PHOSPHORUS IN THE FEEDING OF PIGS

Effect of diet on the absorption and retention of phosphorus by growing pigs

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in de energiehuishouding der dieren.

A.W. Jongbloed

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Proefschrift
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ABSTRACT

Jongbloed, A.W. (1987). Phosphorus in the feeding of pigs; effect of diet on the absorption and retention of phosphorus by growing pigs.
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XVI, 343 p, 149 tbs, 24 figs, 599 refs, Eng. and Dutch summaries,
32 appendices.

An extensive review is given of the literature concerning phosphorus feeding of pigs. Subjects dealt with are: 1. physiological background, regulation and effect of diet composition and nutrient supply on phosphorus absorption and retention; 2. estimation of the amount of P present in the bodies of pigs using several models and 3. estimations of the P requirements of slaughter pigs from results of balance and slaughter experiments.
In the own experiments -using balance, slaughter, digestibility and feeding trials- on growing pigs the following aspects were studied: a) accuracy of measurements ; b) P absorption and retention as related to diet composition and nutrient supply; 3) the effects of reduced P supply on performance and, possibly, on locomotory disturbances. It was shown that in phosphorus balance studies, because of carry-over effects, the adaptation period should be at least 21 days when there is a substantial change in phosphorus supply. Effects of dietary energy and protein on P absorption and retention could best be explained by their effect on the daily amount of protein and fat retention. The retention of P measured by the balance was only six per cent (25 $\pm$ 17 g P) higher than measured by the comparative slaughter technique. Animals with a normal type of daily gain retained 5.0 to 5.1 g P/kg live weight gain, those with a leaner gain 0.2 to 0.3 g P/kg live weight gain more.
A technique was described to measure the digestibility of P in various feedstuffs and feed phosphates; substantial differences in digestibility of P between various feedstuffs and feed phosphates were observed. Maximal utilization of P was found at a dietary Ca/digestible P ratio between 2.9 and 3.5.
In various feeding trials, leg weakness was not observed any more frequently when slaughter pigs from 30 kg live weight onwards received diets with very low concentrations of phosphorus (g/kg feed) and calcium. However, calcification of the bones was poorer than that of the control animals.
Both optimal and just sufficient P requirements for slaughter pigs, were derived. These were expressed as the concentration of digestible P per kg diet.
Keywords: *phosphorus, pigs, calcium, phytate, phosphates, feeding, diet composition, bone mineralization, adaptation, balance technique, slaughter technique, leg weakness.*

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STELLINGEN

1. Bij de calcium- en fosforbalansproeven met varkens van Vipperman et al. (1974) was de aanpassing aan de proefvoeding veel te kort om inzicht te krijgen in effecten op de lange termijn.

   Vipperman et al. (1974). Effect of dietary calcium and phosphorus level upon calcium, phosphorus and nitrogen balance in swine. J. Anim. Sci. 38 : 758-765.

   Dit proefschrift.

2. Een overmaat aan calcium in het rantsoen van landbouwhuisdieren is nadelig voor de benutting van fosfor en diverse spoorelementen.

3. Het hanteren van een vaste fosfor/stikstofverhouding in varkenskarkassen als uitgangspunt voor de schatting van vervluchtiging van stikstof, vanaf uitscheiding door het dier tot het moment van uitrijden van varkensdrijfmest, is onjuist.

4. Het verschil tussen totaal P en fytine-P wordt ten onrechte met beschikbaar P aangeduid.

5. De E.G. dient bij de declaratie van de energiewaarde van mengvoeders rekening te houden met verschillen in verteerbaarheid tussen grondstoffen.

6. De consequenties uit de goedgedocumenteerde rapporten van de N.R.L.O.-werkgroep "Mineralen in krachtvoer in relatie tot bemesting en milieu" uit 1975, 1979 en 1985 kwamen erg laat en in onvoldoende mate in beleid van het Ministerie van Landbouw en Visserij tot uiting.

7. Voor een goede analyse van tegenvallende produktieresultaten in de varkenshouderij dient de praktiserende dierenarts goed op de hoogte te zijn van veranderingen en vorderingen op het terrein van de veevoeding.

8. De normen ten aanzien van P-giften per ha als maatstaf voor de milieubelasting leiden bij de huidige fosfor/stikstofverhoudingen in drijfmest bij varkensmest tot een grotere vermindering van de N-belasting dan bij rundermest.

9. Het verlagen van het kopergehalte in mengvoeders voor mestvarkens heeft helaas niet geleid tot verlaging van het zinkgehalte, die daardoor mogelijk is geworden.

M.I.K. (1985). De gehalten aan enkele spoorelementen in mengvoedergrondstoffen en voordroogkuilen en de gehalten aan enkele mineralen en spoorelementen in mengvoeders. Rapport werkgroep "Mineralen in krachtvoer in relatie tot bemesting en milieu" N.R.L.O.

10. Bij fokzeugen is een hoge index bij de bedrijfsprestatietoets wel een aanwijzing voor de kwaliteit van de nakomelingschap, maar niet voor een lange levensduur van de zeug en een hoge produktie aan biggen.

11. Gezien het feit dat vrouwen gemiddeld per uur op de schaats een kleinere afstand afleggen dan mannen, verdient het aanbeveling dat vrouwen voortaan bij de elfstedentocht in de vroege startgroepen kunnen vertrekken.

A.W. Jongbloed

Phosphorus in the feeding of pigs. The effect of diet on the absorption and retention by growing pigs.

Wageningen, 29 april 1987

VOORWOORD

Het gereedkomen van dit proefschrift is slechts mogelijk door velen die hebben bijgedragen tot het uiteindelijke resultaat.
Het onderzoek werd uitgevoerd op het Instituut voor Veevoedingsonderzoek, eerst te Hoorn en daarna te Lelystad. De oud-direkteur, ir. F. de Boer, ben ik zeer erkentelijk voor de outillage en mankracht die ik voor dit onderzoek mocht gebruiken en de huidige direkteur, dr.ir. Y. van der Honing, die mij in de gelegenheid stelde het onderzoek ook echt af te ronden.
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De uitvoering van het onderzoek zou onmogelijk zijn geweest zonder de hulp van J.Th.M. van Diepen, de medewerkers van de Stofwisselingseenheid onder leiding van R. Terluin en van de Varkenseenheid onder leiding van T. Koorn.
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De vele suggesties voor het onderzoek die ik van collega's buiten het instituut kreeg heb ik bijzonder op prijs gesteld. Hierbij wil ik met name noemen dr.ir. P.C.M. Simons van het Centrum voor Onderzoek en Voorlichting voor de Pluimveehouderij. Veel dank ben ik verschuldigd aan mijn Franse collega's dr. L. Guéguen en dr. A. Pointillart. Zij hebben het manuscript nauwgezet bestudeerd en veel waardevolle opmerkingen gemaakt; daarnaast ben ik hen zeer erkentelijk voor de stimulerende discussies op het gebied van fosfor bij varkens.
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De engelse tekst werd in korte tijd gecorrigeerd door mevr. A. Chadwick.
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Tenslotte betuig ik mijn dank aan alle anderen die door hun hulp of belangstelling een bijdrage hebben geleverd aan het tot stand komen van dit proefschrift.

Aan Alie,
Pietronella, Auke en Wieteke

C O N T E N T S

E X P E R I M E N T S
(part two)

List of symbols and abbreviations

A	= ash
a,b,c,	= regression coefficients
abs %	= absorption percentage
1A	= highest but one grading of carcass
Ca	= calcium
CP	= collection period
Cu	= copper
CV	= coefficient of variation of $x = s_x/\bar{x}$
d_B	= apparent digestibility of component B
df	= degrees of freedom
dig. P	= digestible phosphorus
DL	= Dutch Landrace breed
DXP	= digestible crude protein
E	= heat of combustion, calorific value
EAA	= highest grading of carcass
EBW	= empty body weight
EW	= 8.79 MJ NE_f
f	= growing and fattening
FCR	= feed conversion ratio
FFEBW	= fat-free empty body weight
FFW	= fat-free weight
Fyt	= phytate phosphorus
GY	= Dutch Yorkshire breed
ln	= natural logarithm
M	= maintenance
ME	= metabolizable energy
Mg	= magnesium
n	= number of sample units
N	= nitrogen
NE_f	= net energy of fattening for pigs
NW	= nitrogen weight
O	= organic matter
P	= level of probability * = $0.01 < p \leq 0.05$ ** = $0.001 < p \leq 0.01$ *** = $p < 0.001$
ns	= not significant ($p > 0.05$)
Pi	= inorganic phosphorus
PO	= optimal phosphorus content
PO_c	= optimal phosphorus content corrected for NE_f value of the diet
PP	= preliminary period
r	= correlation coefficient
R^2	= coefficient of determination
ret. P	= retainable phosphorus
ret %	= retention percentage
rsd	= residual standard deviation from regression
se	= standard error of the regression coefficient
sed	= standard error of difference of means
$s_x = sd_x$	= standard deviation of $x = \sqrt{(x-\bar{x})^2/(n-1)}$
$s_{\bar{x}}$ = sem	= standard error of the mean
T	= dry matter
VVm	= digestion or balance trial number m
W	= live weight; mass of live animal (kg)
$W^{0.75}$	= metabolic body size ($kg^{0.75}$)
x	= value of a sample unit
$\bar{x}$	= sample mean
XF	= crude fibre
XL	= crude lipid
XP	= crude protein, usually 6.25N
XX	= nitrogen-free extract

GENERAL INTRODUCTION

In 1974 a research project was started at the I.V.V.O. institute in order to study various aspects of phosphorus feeding in pigs. There were several reasons for doing this:

1. the price of feed phosphates usually added to mixed feeds had increased enormously;
2. the considerable uncertainty concerning the recommendations of the phosphorus requirement for pigs due, for example, to the improved performance levels of modern pigs;
3. the use of more by-products instead of cereals in the feeds for pigs. There was at that time hardly any information available on the nutritive value of phosphorus in these by-products;
4. a possible relationship between the phosphorus supply and the frequency of leg weakness;
5. the increase in the number of animals per hectare of land, resulting in so much pig slurry and poultry manure being applied in certain areas, that a high accumulation of phosphorus in the soil, together with leaching-out and run-off takes place. The effect is eutrophication of the water in ditches and other waterways (Gerritse and Zugec, 1977; Lexmond et al., 1982).

The eutrophication is reason why, in the Netherlands, legislation will be enforced in 1987 in order to limit the amount of phosphorus in the manure which can be applied per hectare of land. Up to 1983, phosphorus accumulation in cultivated fields was still increasing mainly due to the fact that nearly all feedstuffs and thus their phosphorus, and feed phosphates in the Netherlands are imported (Olsthoorn, 1986). Pig farming is concentrated in the south and east of the Netherlands, mostly on sandy soils, and in these regions the problem of phosphorus accumulation is greatest. When the farmer produces more phosphorus in the pig slurry per hectare of land than is permitted in the legislation, he will be fined. Many efforts are therefore being made to reduce the surplus of phosphorus as much as possible. A reduction of phosphorus in the feed results in less phosphorus in the excreta, but it is not well known how this affects the animals' production and metabolism. Phosphorus has many functions in the animal and is an essential nutrient. Therefore, a lower dietary phosphorus level may lead to reduced performance, which is not desirable.
In this thesis, several aspects of phosphorus nutrition, mainly in growing pigs, will be described. First, in the literature review, a survey will be given of the physiological processes, diet composition, nutrient supply and aspects other than dietary composition, that affect the absorption and retention of phosphorus and the phosphorus requirement of growing pigs. Our experiments will then be presented in which the effect of various nutritional factors on the absorption and retention of phosphorus was studied using digestion, balance and feeding trials. In a final discussion it is argued, that without any negative side-effects, growing pigs can be fed lower amounts of phosphorus than is so far being used in practice.

Literature review

(part one)

1. SOME PHYSIOLOGICAL CONSIDERATIONS WITH REGARD TO ABSORPTION AND RETENTION OF PHOSPHORUS

1.1. INTRODUCTION

A survey of the literature shows that up to ten years ago little attention was paid to the absorption and retention of phosphorus in animals, this in contrast to calcium.
Phosphorus has more known functions than any other mineral element in the animal body. In addition to its vital participation in the development and maintenance of skeletal tissue, it functions as a component of nucleic acids which are essential in cell multiplication, growth and differentiation. In combination with other elements, it helps maintain osmotic and acid-base balance. It plays a vital role in a host of metabolic functions, including energy utilization and transfer (ADP, ATP), phospholipid formation and, therefore, fatty acid transport and amino-acid and protein formation (N.R.C., 1980). Phosphorus is further involved in the control of appetite, in a manner not yet fully understood, and in the efficiency of feed utilization.
Much is known about the hormonal feedback system responsible for calcium homeostasis; comparable information with regard to phosphorus is still limited and incomplete. In this chapter, attention will first be paid to the site of absorption of phosphorus in the digestive tract, to the manner in which the absorption takes place and to the role of hormones in it. The roles of the kidneys, the skeleton and metabolites of vitamin D will also be discussed. Most of the information has been gained from experiments on rats and chickens; so far, work on pigs in this field is not abundant.

1.2. INTESTINAL ABSORPTION OF PHOSPHORUS

Most phosphorus is absorbed from the gut as inorganic phosphate either present in the diet as such or liberated from organic components before absorption. In addition to phosphosugars, phosphorylated amino acids and phosphonucleotides are hydrolyzed at the brush border of the enterocyte by alkaline phosphatase to liberate inorganic phosphate. The phosphorus present in certain phospholipids, however, may be absorbed in the organic form (Wilkinson, 1976).

1.2.1. Site of intestinal absorption

1.2.1.1. In laboratory animals

To locate the site of phosphorus absorption in rats, Cramer (1972), using radiophosphorus, showed that of the total absorption of phosphorus, 29 per cent took place in the duodenum, 25 per cent in the jejunum, 38 per cent in the ileum and 8 per cent in the colon. The absorption rate in the duodenum was much greater than in the other segments of the gut, but due to the shorter retention time, the amount absorbed in the duodenum was about equal to that in the jejunum. Also working on rats, McHardy et al. (1956) found higher absorption rates for phosphorus in the duodenum and jejunum than in the ileum. Kowarski and Schachter (1969), however, using the everted sac technique, found a more rapid uptake of phosphorus in the jejunum than in the duodenum, and Walling (1977) found that active absorption of phosphorus in rats was highest in the jejunum, lower in the duodenum and lowest in the ileum. This was also found by Harrison and Harrison (1961) and by Chen et

al. (1974). In three week old chickens, Hurwitz and Bar (1972), using yttrium-91 as a non-absorbable reference substance, showed that most of the absorption of phosphorus occurred in the upper jejunum. Wasserman and Taylor (1973), demonstrated that phosphorus in chicks was more rapidly transferred than calcium across the duodenum. In the duodenum, radiophosphorus was absorbed twice as quickly than in the jejunum and ileum.

1.2.1.2. In pigs

In experminents with growing pigs, Moore and Tyler (1955) incorporated labelled calcium and phosphorus in the diet. The animals were slaughtered four hours after feeding and the digesta in the gut sampled and analysed. They concluded that the absorption of phosphorus took place in the proximal half of the small intestine and the absorption of calcium in the proximal quarter of the small intestine. On the other hand, both phosphorus and calcium were secreted into the lumen of the upper small intestine, but were reabsorbed from the lower segments of the small intestine. They did not find any secretion of phosphorus and calcium into the lumen of the large intestine. Gueguen et al. (1968) infused labelled phosphorus into the large intestine, but could not prove the existence of any absorption of phosphorus from the large intestine. This finding is in agreement with the results of Partridge (1978[a]), who worked with a reentrant fistula in the ileum of pigs and used a cereal mixture as diet. With a semi-synthetic diet, however , Partridge (1978[a,b]) found that some phosphorus was absorbed beyond the ileum fistula.
Sauer et al. (1982) found in pigs with ileo-caecal reentrant cannulas that not less than 22 per cent of the total amount of phosphorus absorbed was absorbed beyond the small intestine. These values of Sauer et al. (1982), however, are not reliable due to experimental problems (Jørgensen, 1986). Recent research with pigs, fitted with simple T-cannulas about 5 cm proximal to the ileo-caecal junction, by the same group (Jørgensen and Fernandez, 1984; Jørgensen et al., 1985), showed that no more phosphorus was absorbed distal to the cannula. This was also found by Partridge et al. (1986) and at our laboratory (Metz, 1986) using pigs fitted with simple T-cannulas proximal to the ileo-caecal junction. However, a few experiments indicate that in the large intestine, a considerable amount of phosphorus can be absorbed. Drochner (1984) showed this in mini-pigs fitted with ileal reentrant cannulas or with simple T-cannulas in the caecum, and Guéguen et al. (1981) also concluded from their experiment with labelled phosphorus administered into the caecal cannula, that the absorption of phosphorus in the large intestine should not be neglected. Also, experiments done by Den Hartog et al. (1985) with an ileo-caecal reentrant fistula, showed that a substantial amount of phosphorus (40 per cent) was absorbed in the large intestine.

1.2.1.3. Discussion

From the studies on rats, chicks and pigs it is clear that the proximal half of the small intestine is the principal site for the absorption of phosphorus. Unfortunately, for rats little information is available as to whether much phosphorus is absorbed in the large intestine, due to the fact that the studies were focussed more on the mechanism of absorption.
Although in experiments with pigs having reentrant cannulas at the end of the ileum some absorption of phosphorus from the large intestine has been

found, there are still a few doubts concerning these results, because of the fine grinding of the diets in such studies and the possibility that digesta flow back from the large to the small intestine. In this respect, high dietary inorganic phosphorus levels may also influence the results; in most studies, two to four times the phosphorus requirement was offered, inducing higher errors.

1.2.2. Mechanism of the absorption of phosphorus

1.2.2.1. In laboratory animals

From the first experiments in the 'fifties it was concluded that transport of phosphorus through the intestinal wall was passive and that the absorption rate decreased when the sodium concentration in the lumen was low (Mc Hardy and Parsons, 1956). However, it is now accepted that the absorption of phosphorus in the gut is an active process (Wasserman, 1981). This was clearly demonstrated in vitro by Harrison and Harrison (1961) and by Borle et al. (1963). The latter authors were of the opinion that the transport of phosphorus across the intestinal wall consisted of several steps: uptake from the mucosal side, transport from mucosa to serosa and transport from serosa to the body fluid. The absorption of phosphorus in the intestinal tract seems to be independent of the presence of calcium in the luminal fluid (Carlsson, 1954; Kowarski and Schachter, 1969; Clark and Rivera-Cordero, 1973; Peterlik and Wasserman, 1978), although some relationship between calcium and phosphorus absorption is suggested by Walling (1977).
In chicks, Wasserman and Taylor (1973) found that the absorptive process could reach a maximum only in the ileum but not in the duodenum or jejunum. Radiophosphorus accumulated in the mucosa, so probably absorption proceeded at a more rapid rate than the release of the radionuclide to the blood, and the latter was the rate-limiting step. Vitamin D was found to stimulate the absorption of phosphorus. The greatest response was found to occur in the jejunum of the chick, where the phosphorus uptake in the mucosal cell layer proved to be saturable, an indication of an active transport mechanism (Peterlik and Wasserman, 1978). The transfer of phosphorus from tissue to the serosal compartment appeared to be by diffusion and was not dependent on vitamin D.
Kinne et al. (1977) and Quamme (1985) demonstrated (see also Figure 1) that transport of phosphorus occurred as an electroneutral cotransport with sodium through the luminal cell membrane and as a sodium independent efflux across the contra luminal cell membrane. The downhill movement for sodium into the cytoplasm provides the energy for the transport of phosphorus against a gradient in the same direction. Kowarski and Schachter (1969) showed that in the rat, absorbed phosphate does not enter the general phosphorus pool of the intestinal cell. This was verified in chick intestine (Peterlik and Wasserman, 1978). Absorbed phosphorus could hypothetically maintain its "exclusive" status by incorporation into a vesicle, traversing the cell through channels or as a phosphorylated derivative. Inhibition of the transport of phosphate by arsenate and sodium depletion takes place at the luminal cell membrane and the inhibition of phosphate transport by ouabain can be explained by the inhibition of the Na-K-ATP ase.

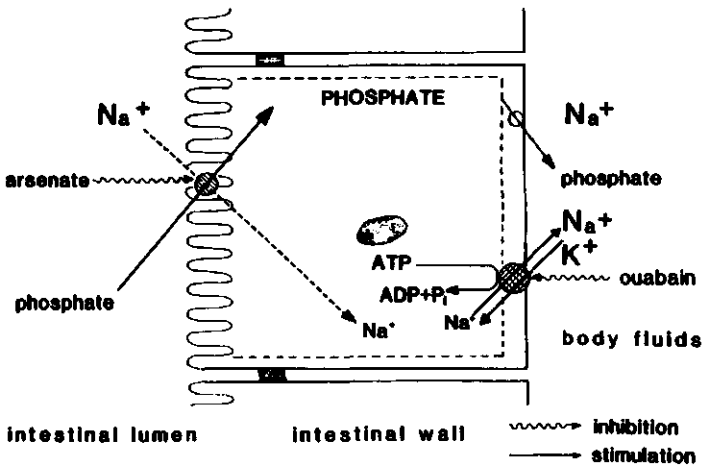

Figure 1. Schematic representation of the transport systems and driving forces involved in active phosphate transport by the small intestine (adapted from Kinne et al., 1977 and Wasserman, 1981).

Phosphate is transported against a gradient across the brush border of the intestinal cell by a Na^+ dependent process. Phosphate moves through the cell without entering the cytoplasmic phosphate pool, and diffuses from cell to lamina propria, possibly by facilitative (mediated) diffusion. The low intracellular Na^+ concentration is maintained by Na, K extrusion pump on the basal-lateral membrane.

1.2.2.2. In pigs

There have been only a few experiments on pigs concerning the mechanism of phosphate absorption.
According to Guéguen and Rérat (1967), the rate of phosphorus absorption is much faster than that of calcium. The peak of absorption after an oral dosage of radiophosphorus (as Na_2HPO_4) was only 30 minutes after administration and absorption was practically complete within three hours. However, when phytate phosphorus from wheat bran was given they found a much slower absorption; only after three to four hours was there a peak in the plasma. Fox et al. (1978[a]) demonstrated an increase in the jejunum of pigs, in the net absorption of phosphate from a perfusate, as the phosphate concentration increased. With further increases in phosphate concentration, the rate of increase of phosphate absorption slowed down, indicating a saturation process. At concentrations from 0 to 6 mM/l calcium in the solution, the net phosphate absorption increased, but at higher calcium levels hardly any effect on phosphate absorption was found. The work done by McKercher and Radde (1981) on gut segments of young pigs showed that in the duodenum and jejunum, active absorption of phosphorus could be demonstrated but not in the ileum.

1.2.2.3. Conclusion

The transport of phosphate across the intestinal wall probably consists of several steps, which could explain why the dependence of the absorption rate upon metabolism, hormonal action or electrochemical gradient is not always the same.
Most experiments indicate that the transport of phosphate through the gut wall is an active process. Lack of complete agreement between results could perhaps partly be explained by different segments of the intestinal tract being used. It is uncertain whether or not calcium is necessary for the absorption of phosphate. Further investigations are required for the complete understanding of the phosphate transport system.

1.3. RENAL HANDLING OF PHOSPHORUS

The kidney is regarded as a major if not the major organ in the regulation of calcium and phosphorus in blood plasma. The kidney consists of millions of nephrons, which can be divided into different sections. A nephron is composed of a glomerulus, a proximal convoluted tubule, Henle's loop, the distal convoluted tubule and finally the collecting duct. Aqueous, ionic and crystaloid components of blood can pass into the glomerulus, while erythrocytes and most of the plasma proteins do not filter through the glomerular membrane. Phosphorus in blood plasma exists in two main forms, either as organic phosphate, mainly as phospholipids and phosphate esters, or as inorganic phosphate. Most of the plasma phosphorus is in the organic form and is not ultrafiltrable. The inorganic phosphate of plasma, having a divalent and monovalent ion in a ratio of 4:1 at pH 7.4 is almost completely ultrafiltrable through the kidney's glomerular membrane. When the ultrafiltrate has been formed, the glomerular filtrate can be transported across the epithelium of the peritubular space and hence into the vascular system. Phosphorus reabsorption by the kidney has been described as saturable, i.e. characterized by a maximal transport capacity (T_m) above which any further increment in filtered load is quantitatively excreted into the urine. It appears, however, that under certain circumstances the T_m-value can be al-

tered (Geschwind, 1961). In pigs weighing 25 kg, McIntosh and Scott (1975) showed that the amount of phosphorus excreted in the urine increased with the increase in the amount filtered at the glomerulus. A threshold value for phosphorus excretion in these pigs occurred at a plasma phosphorus concentration of 2.03 mmol/l, while over a wide range of filtered load (0.21 - 1.14 mmol/min) phosphorus was reabsorbed at a mean maximum rate of 0.19 mmol/min.
The site of phosphorus reabsorption is predominantly in the proximal convoluted tubule. There is still a lot of debate about the cellular mechanisms of phosphate transport in the kidney, which reflects the complexity of this subject. A general consensus concerning the mechanisms that regulate phosphate transport does not yet exist. In this section, only some general remarks will be made. For more details, the reader is referred to recent reviews by Mizgala and Quamme (1985), and Gmay and Murer (1986). Phosphate reabsorption in the proximal tubule is highly dependent on the presence of sodium ions in the lumen and can be considered as being linked to active sodium ion transport (Barrett et al., 1980). The reabsorption of phosphate in the kidney is affected by several factors (Mizgala and Quamme, 1985). It has been established that the dietary phosphorus supply in relation to requirement, adaptation, renal function, intrarenal calcium concentration, acid-base balance, extracellular volume, and the presence of steroids (including glucocorticoids) and diuretics must be taken into account when the role of renal handling of phosphate is evaluated (see e.g. Madsen et al., 1977; Gmay and Murer, 1986). The effect of parathyroid hormone (PTH) and vitamin D on the reabsorption of phosphate is described elsewhere (see sections 1.4.1 and 1.4.4.5. respectively), while some aspects of the effect of pH and acid-base balance, especially in relation to phosphate reabsorption will be described below.

It is clear that, contrary to other cellular membranes, there is a preferential reabsorption of the divalent form of phosphate in the renal brush border (Kinne et al., 1977; Amstutz et al., 1985). The cause of this is not clear but it is most probable that hydrogen ions may directly decrease the affinity of the sodium phosphate cotransport system for sodium ions.
The effect of acidosis and alkalosis on urinary phosphate excretion cannot easily be explained. Acute acidosis, resulting in intraluminal acidosis, inhibits net phosphate reabsorption, whereas intracellular acidosis may increase phosphate transport. Therefore, the balance between intraluminal pH and intracellular hydrogen ion generation must be considered before predicting appropriate responses to acid-base disturbances. Chronic acidosis may adjust renal phosphate transport processes, resulting in a decrease in reabsorption and an increase in urinary phosphate excretion.
The association of an elevation of urinary phosphate exretion with urinary alkalinization is a well-known clinical observation, while it is also known that chronic alkalosis increases phosphate reabsorption. This contradiction might be explained by the fact that on a relatively high phosphate diet, an elevated urinary phosphate excretion is found with induction of alkalosis, while on a low phosphorus diet this is not the case. Thus it seems that three main factors directly controlling renal phosphate reabsorption should be considered: dietary phosphorus content, acid-base influences and also PTH as we will see later (Mizgala and Quamme, 1985). Gmay and Murer (1986) summarized the effects as follows: the responses to acid-base alterations are critically dependent on the concentration of phosphate in the lumen and in the cell. At concentrations of phosphate in the lumen below saturation, the effects of luminal pH on phosphate carrier interaction seem to

dominate, whereas at a high concentration of phosphate in the lumen the effects of intracellular pH become apparent.
Most of the hydrogen ions excreted by the kidney to maintain acid-base equilibrium during acidosis must be bound to bases; the most important of these are divalent phosphate and ammonia. Bases are defined as substances that tend to accept and bind hydrogen ions from a solution: this means that divalent phosphate (HPO_4^{2-}) is a base and monovalent phosphate ($H_2PO_4^-$) is a (weak) acid. To understand the mechanism in the kidney some of it will be outlined here (see also Houpt, 1984).
When acids or bases are added to body fluids, chemical buffers are the first to react (including bicarbonate and plasma protein). In the case of acids, the anions are usually electrically balanced with cations (mainly sodium). In the tubular fluid of the kidney, the cation is reabsorbed in exchange for hydrogen ions, which are actively secreted. Mobilization of hydrogen ions for tubular secretion is derived from carbonic acid formed from carbon dioxide and water. In this way the urine is acidified. The quantity of acid which can be excreted as free hydrogen ions is limited. This means that most of the hydrogen ions excreted must be bound to bases (divalent phosphate and ammonia). In the case of divalent phosphate, it takes up and binds a hydrogen ion to form predominantly monobasic phosphate. Part of the cation (mostly sodium ions) that electrically balances divalent phosphate in the glomerular filtrate is thus exchanged with the secreted hydrogen ion. The ammonia which is formed in the distal renal tubular cells is diffused into the tubular fluid and buffers the hydrogen ion to form ammonium ions.
It may be clear that the renal handling of phosphate is a complicated matter, the mechanisms of which, also with regard to acid-base balance, are not well understood.

1.4. HORMONAL EFFECTS ON PHOSPHORUS ABSORPTION AND EXCRETION

1.4.1. Parathyroid hormone

The parathyroid hormone (PTH) is produced by the ultimo branchial cells of the parathyroids. The porcine PTH, isolated by Woodhead et al. (1971) had a calculated molecular weight of 9423, with serine as a terminal amino acid. PTH is probably the most important hormone in the control of calcium homeostasis through its action on bone, kidney and intestine. The rate of secretion of PTH is inversely dependent on the concentration of extracellular calcium (see also review by Habener et al., 1984). PTH also plays a role in phosphorus metabolism, mainly through its influence on kidney functioning (e.g. Clark and Rivera-Cordero, 1973 and Lau et al., 1980).
There is some evidence that PTH may directly or indirectly influence the absorption of calcium and phosphorus from the intestine, but the effect on phosphorus absorption is minor. Wasserman and Comar (1961) found no difference in phosphorus absorption in parathyroidectomized rats, when compared with normal rats, which was in agreement with the results of Carlsson (1954). Cramer (1972) came to the conclusion that with regard to increasing the net flow of calcium, phosphorus and magnesium into the plasma, PTH has an immediate effect on bone and apparently a delayed effect on the intestine. In their studies, Borle et al. (1963) found that parathyroid extract increased the transfer of phosphorus from mucosa to serosa by 70 per cent and uptake by the tissue from the mucosal site by 30 per cent. Secretion of phosphorus from serosa to mucosa was unaffected by parathyroid

extract. Clark and Rivera-Cordero (1974), however, in their experiments on rats, found no effect of parathyroidectomy on the absorption of phosphorus or on the urinary phosphorus excretion when compared with control animals. This is not in accordance with the results of Mayer et al. (1968) who found that parathyroid extract decreased faecal phosphorus but increased urinary phosphorus in cows. In pigs, Fox and Care (1978) and Fox et al. (1978[b]) demonstrated an increase in intestinal absorption of phosphorus in response to dietary restriction of phosphorus and concluded that the parathyroid glands were not essential for this adaptation. However, PTH was capable of increasing the absorption of phosphorus from the jejunum.
Phosphorus reabsorption in the tubules of the kidney is depressed by an increased concentration of PTH. Sie et al. (1974), and Clark and Rivera-Cordero (1973; 1974) showed that an increase of dietary phosphorus at the same level of calcium resulted in an increase of PTH production. Studies by Bonjour et al. (1977) indicate that in addition, dietary phosphorus activates an important mechanism for regulating the reabsorption of phosphorus other than PTH and plasma phosphorus concentration. They showed marked differences in phosphorus excretion rates in thyroparathyroidectomized rats on low and high phosphorus diets, even though plasma phosphorus was controlled by phosphorus infusions. It has been reported by Meyer and Meyer (1974) that when PTH was given, phosphorus which came from soft tissues such as muscle, liver and red blood cells, was excreted in the urine.
In the skeleton, PTH stimulation leads to the simultaneous resorption of bone mineral and matrix, resulting in the subsequent release of calcium and phosphorus into the circulation.
For pigs, there is some evidence that PTH does not play such an important role as in the rat (McIntosh and Scott, 1975; Pointillart et al., 1978[b]; 1979) and probably calcitonin (see section 1.4.2.) might be more important. The possible effect of PTH on phosphorus absorption may be explained by a stimulating effect on 25-hydroxycholecalciferol-1α- hydroxylase in the kidney.

1.4.2. Calcitonin

Calcitonin (CT) is a hormone composed of 32 amino acids and has a molecular weight of about 3500 (Copp et al., 1962; Brewer et al., 1968). It is formed in the thyroid and has a very rapid hypocalcaemic action by inhibiting bone resorption without acutely affecting bone mineralization. In addition, it has been shown that gastrointestinal hormones (either gastrin or cholecystokinin) stimulated by the presence of food in the stomach and intestine, stimulate CT secretion (Dickson, 1984). Pointillart et al. (1978[b]) showed on pigs that high levels of magnesium in the diet stimulated CT secretion.
Little is known about any effect of CT on the intestinal absorption of phosphorus. So far, there is no evidence that CT has a direct effect on the absorption of phosphorus from the intestine (Cramer, 1972); this has been confirmed in experiments with young pigs (McKercher and Radde, 1981).
In contrast to the CT-PTH antagonism on bone, CT is similar to PTH in its effects on renal phosphorus reabsorption. CT, however, inhibits phosphorus reabsorption in the ascending loop of Henle and the distal convoluted tubule (Knox et al., 1973; Yoshinobu et al., 1976). It results in a reduced plasma phosphate level but a significant rise in phosphate uptake by the liver has also been reported (Meyer and Meyer, 1974; 1975).
Some workers suggest that CT may also be involved in the regulation of the

vitamin D metabolism in the kidney, but this is not certain (DeLuca and Kleiner-Bossaler, 1973; Rasmussen et al., 1972; Fraser, 1980).
It looks as though CT has no direct effect on phosphorus absorption in the gut, and that this hormone decreases the tubular reabsorption of phosphate in the kidney.

1.4.3. Thyroxine and growth hormone

Little is known about the effect of thyroxine on phosphorus metabolism. Thyroxine may also have an indirect influence through its effects on the growth rate of bone and body. Effects on bone mean that both calcium and phosphorus are involved. Irving (1973) suggested that thyroxine increases the bone turnover rate and thyroidectomy seems to slow down the rate of bone growth and differentiation. Noble and Matty (1967) indicated that when rats were given a daily injection of 1 mg thyroxine per kg body weight for seven days, the rate of transport of phosphorus from mucosa to serosa was depressed in the duodenum but not in the jejunum or ileum. The treatment had little or no effect on mucosal uptake values, but thyroxine exerted its influence on infusion or release of phosphorus. Administration of thyroxine (Espinoza et al., 1984) and growth hormone (Hammerman et al., 1984) increased phosphate reabsorption and the activity of the sodium-phosphate cotransport system in the brush border membranes in the kidney.
Growth hormone stimulates endochondral bone formation and increases skeletal mass by accelerating subperiostal bone apposition. The effect of growth hormone on bone seems to be dependent on thyroxine. An anonymous review (1979) suggested that one of the functions of growth hormone is to stimulate the absorption of intestinal calcium. This was concluded because plasma levels of 1,25-dihydroxycholecalciferol decreased significantly after hypophysectomy and were restored to normal by growth hormone. This effect might, however, have been mediated by PTH. Westby et al. (1977) concluded from their experiments with dogs, that growth hormone affected calcium and phosphorus homeostasis only slightly. Massry et al. (1973) found that, with regard to renal handling, growth hormone has an opposite effect to that of PTH, while Spencer et al. (1979) reported that growth hormone, injected into hypophysectomized rats, stimulated the renal conversion of 25-hydroxycholecalciferol into 1,25-dihydroxycholecalciferol. They suggested that this effect could be relevant to the long-term stimulation of renal hydroxylase during growth.
It can be concluded that there is no clear evidence of significant direct effects of thyroxine and growth hormone on phosphorus metabolism, but there are some data suggesting indirect effects.

1.4.4. Metabolites of vitamin D

1.4.4.1. Introduction

For several years we have known that vitamin D (cholecalciferol; CC) is important for calcium and phosphorus metabolism (DeLuca and Schnoes, 1983 and DeLuca, 1979). The best understood function of vitamin D is that it elevates plasma calcium and phosphorus concentrations to levels required for the support of normal mineralization of bone and that it prevents tetany (DeLuca, 1980).

1.4.4.2. Metabolism of vitamin D and its metabolites

In the intestinal mucosa a provitamin D_3 (7-dehydrocholesterol) is formed from cholesterol. This provitamin D_3 is transported to the skin where it is converted into previtamin D_3 by the action of ultraviolet radiation (Holick and Clark, 1978). Previtamin D_3 thermally isomerizes to vitamin D_3. After binding to an appropriate carrier protein, the vitamin can be transported to other tissues. Provitamin D_2 (ergosterol) in feedstuffs of plant origin is similarly converted to vitamin D_2 (ergocalciferol). In mammals, vitamin D_2 and vitamin D_3 have the same biological activity, but in birds the activity of vitamin D_2 is about ten times lower than vitamin D_3, due to a lower absorbability in the gut. Vitamin D can also be ingested with the diet. The absorption of ingested CC occurs with the aid of bile salts in both jejunum and ileum, where a linear relationship was found between the absorption rate of the vitamin and its intraluminal concentration (Hollander et al., 1978). In the lymphatic system, most of the vitamin is transported in the chylomicron fraction (Dueland et al., 1983).
Investigations (e.g. DeLuca and Kleiner-Bossaler, 1973) have shown that after absorption by the liver, CC is mainly hydroxylated in the hepatic mitochondria, but also in the hepatic microsomes, to 25-hydroxycholecalciferol (25-HCC) after which it is secreted into the circulation linked to a specific α-globulinprotein. This 25-HCC is the major circulating form of CC in the blood.
In the kidney, some of the 25-HCC of the blood is converted into 1,25 dihydroxycholecalciferol (1,25-DHCC), probably in the mitochondria of proximal tubular cells by means of 25-HCC-1α-hydroxylase. This has been confirmed in pigs by Sommerville et al. (1978) who observed that in homogenates of pig kidney, the cortex carried out its conversion more efficiently than the medulla. Apart from the kidney, some 1,25-DHCC can also be produced in the placenta (DeLuca and Schnoes, 1983).
The 1,25-DHCC is returned to the blood where it is removed by cells of the main target tissues: the small intestine, bone and the kidney itself. In the small intestine, 1,25-DHCC is selectively localized in the nucleus of the intestinal mucosal cells, where it actively facilitates the synthesis of calcium-binding protein.
During isolation and identification of 1,25-DHCC, other metabolites of vitamin D_3 were detected, but their function is not quite clear (e.g. Zucker and Rambeck, 1981). For example, DeLuca and Schnoes (1983) found that if animals are hypocalcaemic or hypophosphatemic, the 25-HCC is hydroxylated to 1,25-DHCC, but when the serum levels of calcium and phosphorus are normal and the animal has been given a source of vitamin D, predominantly 24,25-DHCC is formed (see also the review of Kumar, 1984). The biological action of 24,25-DHCC is not yet clear.
In human blood plasma, 25-HCC has a half-life of 15 to 30 days, whereas 1,25-DHCC is present at a 500 to 1000 fold lower concentration and disappears with a half-life of only 5 to 8 hours (Fraser, 1980). In pigs 25-HCC values in plasma seem to be more important than those of 1,25-DHCC (Thomasset et al., 1979). These authors found a plasma concentration of 25-HCC in control pigs from 16 to 22 μg/l, while on vitamin D deficient or calcium deficient diets this concentration dropped to 5μg/l or less. In blood plasma of non-gravid pigs, the physiological concentration of 1,25-DHCC lies between 60 and 80 pg/ml (Horst and Littledike, 1982), but Kaune and Harmeyer (1984) found a wider range with values from 35 to 90 pg/ml. In young piglets up to six weeks old, the concentration decreased from 160 to 90 pg/ml, while in gravid sows the concentrations gradually

increased (Lachenmaier-Currle, 1985).
The liver is particularly efficient at removing vitamin D from the circulating blood, and may inactivate its metabolic action; the inactivated vitamin is excreted, via the bile, with the faeces.
Finally, the metabolism of vitamin D is schematically given in Figure 2.

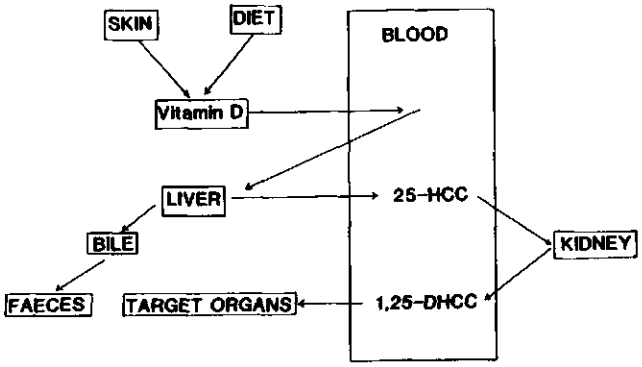

FIGURE 2 Scheme for the metabolism of vitamin D in relation to its function in the maintenance of the extracellular calcium concentration; 25-HCC, 25-hydroxy-vitamin D; 1,25-DHCC, 1,25-dihydroxy-vitamin D (adapted from Fraser, 1975)

1.4.4.3. Regulation of the vitamin D metabolism

The concentration of 25-HCC in blood plasma appears to be related to the input of CC and its production does not seem to be regulated according to need. Large amounts of CC cause a subsequent increase in the concentration of 25-HCC in the blood, but the rate of output of 25-HCC from the liver is not proportional to the input of vitamin D substrate (Fraser, 1975; 1980).
To regulate the activity of 25-HCC-1α-hydroxylase, there is possibly a feedback mechanism which is very probably active at low concentrations of CC. During the last decade, many studies have been published about how the conversion of 25-HCC to 1,25-DHCC is regulated. Most of the work, predominantly done on rats and chicks, has recently been reviewed by Kumar (1984). From the studies of Holick et al. (1976) and Sommerville et al. (1978), it can be concluded that chickens have a more rapid metabolism and excretion of vitamin D than rats, and that in pigs the conversion of 25-HCC to 1,25-DHCC is almost as efficient as in chicks.
During the onset of vitamin D deficiency, the activity of 25-HCC-1α-hydroxylase might be 20 times greater in chickens than when the supply is adequate (Fraser, 1975) and 5 to 10 times greater in pigs (Engstrom et al., 1984). The ability of the enzyme increases according to the severity of the vitamin D deficiency.
In their experiments on rats, Tanaka and DeLuca (1973) found that the concentration of 1,25-DHCC in serum and intestine was more than twice as high for rats on a diet with 0.1 per cent phosphorus when compared with 0.3

per cent phosphorus; the calcium supply was sufficient. This has been confirmed by many other experiments. In pigs, diets with a low phosphorus or calcium concentration resulted in an increase in renal 25-HCC-1 -hydroxylase activity and in circulating and intestinal 1,25-DHCC, but the same level of plasma 25-HCC, when compared with diets with a normal concentration of phosphorus and calcium (Sommerville et al., 1978; 1985; Engstrom et al., 1985). Haussler et al. (1977), who found a rise in 1,25-DHCC plasma concentration of 3 to 5 times in pigs, due to a low phosphorus diet, suggested that phosphorus depletion apparently accelerates the formation or retards the degradation of 1,25-DHCC. Fox and Ross (1985) concluded from their experiments with young pigs that the metabolic clearance rate of 1,25-DHCC was unchanged when a low phosphorus diet (0.30 per cent P) was given compared to one with 0.70 per cent P, but a diet low in calcium (0.07 per cent Ca) increased the metabolic clearance rate somewhat. The production rate of 1,25-DHCC increased by 2.3 and 4 respectively when a diet low in phosphorus or calcium was given. According to Tanaka and DeLuca (1973) a low phosphorus concentration in the renal tubule cell stimulates the production of 1,25-DHCC.
There is a lot of debate about the role of PTH in vitamin D metabolism. Some authors suggest a direct role in 1,25-DHCC synthesis, others are of the opinion that PTH is not necessary for the production of 1,25-DHCC (see review by Kumar, 1984), while Trechsel et al. (1980) concluded from their experiments that both a PTH dependent and a PTH independent response can be demonstrated.
It has more or less been admitted (DeLuca, 1979) that CT inhibits the synthesis of 1,25-DHCC. It is not certain whether, in mammals, sex hormones have any influence, which certainly seems to be the case in egg-laying birds (DeLuca, 1979).
Metabolic acidosis might impair the conversion of 25-HCC to 1,25-DHCC (Lee et al., 1977; 1986; Sauveur and Mongin, 1978) but Gafter et al. (1981) found, on the contrary, a higher plasma level of 1,25-DHCC in rats fed NH_4Cl when compared with controls. Edwards (1984), also found no evidence of an impaired conversion of 25-HCC to 1,25-DHCC by metabolic acidosis. Other factors which might regulate 25-HCC-1α-hydroxylase activity such as hydrogen ion concentration, potassium ion concentration, prolactin, growth hormone, glucocorticoids and insulin are extensively discussed in an excellent review by Fraser (1980).
Synthesis of 1,25-DHCC is controlled by numerous factors. The major ones, however, are the serum or extracellular fluid phosphorus concentrations, circulating levels of 1,25-DHCC itself, the circulating amounts of PTH and perhaps serum calcium directly.

1.4.4.4. Effect of vitamin D on intestinal transport of phosphorus

The results of experiments done by Carlsson (1954), Harrison and Harrison (1961), Kowarski and Schachter, (1969) and many others, leave no doubt that 1,25-DHCC stimulates the transport of intestinal phosphate. (DeLuca and Schnoes, 1983). The effect of 1,25-DHCC is on the mucosal surface and it stimulates the entry of phosphate at the mucosal border; the mucosal to blood step is 1,25-DHCC independent (Peterlik and Wasserman, 1978). Using the technique of everted sacs of intestinal tissue in adult vitamin D deficient rats, physiological doses of 1,25-DHCC increased the (^{32}P) phosphate uptake in the duodenum considerably, to a lesser extent in the jejunum but not in the ileum or colon (Lee et al., 1981).
In chickens, Wasserman and Taylor (1973) and Peterlik and Wasserman (1978)

observed that the intestinal absorption of phosphorus was stimulated by vitamin D in all segments of the intestine, but most of all in the jejunum. Moreover, Hurtwitz and Bar (1972) found, that as a result of vitamin D in the diet, there was an increase in phosphorus transport in the jejunum but not in the duodenum of chicks, when compared with vitamin D depleted animals.
Information about the action of 1,25-DHCC on intestinal transport of phosphorus in pigs is not abundant. From the work of Fox and Care (1976; 1979) we learn that an enhanced absorption of phosphorus also occurs from the inclusion of hydroxylated derivatives of vitamin D in the perfusate. Also, Fontaine et al. (1985) found that absorption of phosphorus in vitamin D depleted pigs was only half of that found in pigs fed with vitamin D supplemented diets (1 000 IU D_3/kg diet).

Effect on intestinal alkaline phosphatase and phytase
There is still a lot of debate about the effect of dietary vitamin D on the activity of the enzymes phytase and alkaline phosphatase of the mucosa of the small intestine, enzymes which might also be involved in the absorption of phosphorus. Günther (1966) suggested that through its effect on alkaline phosphatase activity, dietary vitamin D might enhance the absorption of phosphorus from feedstuffs containing phytate. In fact, Peterlik and Wasserman (1980) found that an injected dose of 1,25-DHCC, stimulated the alkaline phosphatase activity in chicks. The correlation between phosphorus transport and alkaline phosphatase activity was 0.99, thus it also could be suspected from their work that there is a good relationship between phosphorus absorption and alkaline phosphatase activity. In their experiment, the induced higher phosphorus transport tended to reach its maximal level sooner than the activity of alkaline phosphatase, and so they suggest that there are possibly two mechanisms, one on phosphorus transport and one on alkaline phosphatase activity. Also with broiler chickens Teunis and Versteegh (1982) found that at 30 000 IU vitamin D_3/kg more phytate phosphorus was hydrolyzed than at 1 000 IU vitamin D_3/kg.
In pigs, Pointillart et al. (1984) observed a close positive relationship between phytase and alkaline phosphatase activities along the intestine. However, for the same group (Fontaine et al., 1985), vitamin D supplementation of vitamin D depleted pigs had no effect on the activity of phytase and alkaline phosphatase, which was also found by Moore and Veum (1982, 1983[a,b]) with rats. In experiments on pigs, Boyd et al. (1981) and later Koch et al. (1984) and Koch and Mahan (1985) showed that plasma alkaline phosphatase activity merits more attention as a criterion for estimating available phosphorus. However, this is only of use when the phosphorus level in the diet is suboptimal. Pointillart et al. (1985[a,b]) never found any correlation between plasma alkaline phosphatase activity and phosphatemia in pigs, but in some phosphorus-deficient pigs hyperactivity of alkaline phosphatase was found.

1.4.4.5. Effect of vitamin D on renal handling of phosphorus

As we have seen (section 1.4.4.2.), synthesis of 1,25-DHCC occurs in the kidney by means of 25-HCC-1α-hydroxylase. The activity of this enzyme is, amongst other things, regulated by vitamin D status, calcium and phosphorus status and PTH (section 1.4.4.3.).
There is not much evidence of a direct (short-term) effect of dietary vitamin D on renal tubular reabsorption of phosphate (Mizgala and Quamme, 1985) but, as shown by Kurnik and Hruska (1984), concentration of PTH and

vitamin D metabolites is important for the effect observed. The latter authors came to the conclusion that under physiological conditions a direct stimulatory role of 1,25-DHCC on renal phosphate reabsorption could be observed.
It is suggested by Bonjour et al. (1978) that vitamin D affects the intrinsic adaptation to high dietary phosphorus levels. The renal cell is able to adapt to phosphorus intake in the absence of vitamin D but does so more efficiently when vitamin D is present.
The long-term effects of vitamin D intake are generally accepted. Vitamin D stimulates intestinal phosphorus absorption which may result in a positive phosphorus balance. The renal cell responds to abundance of phosphorus by decreasing fractional phosphate reabsorption.
Although 1,25-DHCC is a potent regulator of calcium and phosphorus transport in intestine and bone, its renal effects may be secondary to more general changes of calcium and phosphorus metabolism and PTH status.

1.4.4.6. Effect of vitamin D on bone

In growing animals, bone is continuously being renewed by a combination of formation and resorption. Bone has a dual function: mechanical support and maintenance of mineral homeostasis. Vitamin D plays a role in both functions through its role in the mineralization of the organic matrix of bone (Gonnerman et al., 1976) and in bone resorption. Bone is therefore a target organ for the action of vitamin D.
Lack of vitamin D causes rickets in young animals and osteomalacia in the adult, and administration of vitamin D results in rapid healing. It is, however, not quite certain whether vitamin D participates directly in the process of mineralization (Omdahl and DeLuca, 1973) but certainly, when vitamin D is given, in an increased turnover of calcium and phosphorus, where the deposition exceeds the removal. In hypophosphatemia and hypocalcaemia bone resorption occurs, preferently from older bone and not from recently deposited bone (Irving, 1973).
Little is known about the mechanism of 1,25-DHCC in bone; several investigations are currently in progress.
The overall response to 1,25-DHCC for the mobilization of calcium from bone requires the presence of PTH, and both 1,25-DHCC and PTH act together on this system (DeLuca and Schnoes, 1983)

1.4.4.7. The vitamin D requirement of pigs

In the preceeding sections it has been shown that vitamin D is important in regulating calcium and phosphorus metabolism. We will now discuss the requirement of vitamin D for pigs. The requirement of vitamin D is expressed in International Units (IU) where 1 IU = 0.025μg crystalline vitamin D_3.
To establish the vitamin D requirement of pigs one should consider that it is influenced by several factors. Some of these factors are given below, but not all have yet been proved:

1. the concentration of calcium and phosphorus in the diet and the Ca/P ratio. The requirement is higher when low concentrations of calcium and phosphorus are present in the diet, or when the Ca/P ratio is sub-optimal;
2. the age and weight of the animal and the level of production of the animal;

3. animal differences, as pointed out by Johnson and Palmer (1939) who found that white pigs stored about twice the amount of vitamin D of coloured pigs when kept outdoors;
4. the existence of body stores;

and possibly

5. the quantity of vitamin A in the diet;
6. the level of phytate in the diet.

The literature about the vitamin D requirement of pigs is far from abundant. Assuming that the animals are not kept outdoors, it has been definitely proved that there is a requirement for vitamin D (a.o. Günther, 1966; Miller et al., 1965[a]; Combs et al., 1966[a]). Lack of vitamin D results in decreased performance, lowered bone ash content and breaking strength of bones, hypophosphatemia, hypocalcaemia and hyperphosphatasemia, rickets and very often hyperparathyroidism (Harmeyer et al., 1977). The criteria taken for the assessment of optimal vitamin D requirement are mainly performance, bone ash content, bone strength, calcium and phosphorus balance, alkaline phosphatase activity and calcium and phosphorus level in blood plasma. Some papers will be discussed in which the requirement for vitamin D has been investigated.

Young pigs

Nearly all the experiments have been done with young pigs. Miller et al., (1965[a,b]) found that when no vitamin D was added to a diet, an excessive excretion of calcium and phosphorus and thus a lower absorption and retention percentage for these minerals was observed when compared with an addition of 100 IU vitamin D or more per kg diet. When these authors used a diet containing glucose and soya protein instead of a glucose and casein diet it appeared that more than 100 IU vitamin D per kg was required. It is possible that the concentration of available phosphorus in the glucose and soya protein diet was too low to achieve optimal bone development and mineral balance when compared with the glucose and casein diet. For the diets mentioned, the authors found no differences in mineral balance when more than 100 IU vitamin D was used per kg diet. The differences in the mineral balance between 0 and 100 IU vitamin D per kg diet might have been intensified by the reduced feed intake without the vitamin D addition.
In their experiments on baby pigs, Hendricks et al. (1964) found that 100 IU vitamin D_2 per kg diet was adequate to produce optimum growth rate and skeletal development when compared with 250 or 500 IU. Vitamin A or β-carotene (2 000 IU/kg) in these experiments gave no indication of being rachitogenic. The concentration of vitamin A or β-carotene was probably too low to observe any effect. Combs et al. (1966[a,b]) found that 220 IU vitamin D_3 per kg in diets for pigs weighing from 3 to 20 kg was adequate, while Hendricks et al. (1969) found no differences in animal performance or skeletal development when 250 or 500 IU vitamin D_3 per kg diet was used.

Growing pigs

In experiments on growing pigs, weighing from 10 to 60 kg, Baustad et al. (1967) used 0 or 300 IU vitamin D per kg feed. The feed contained 0.6 or 1.4 per cent phosphorus with Ca/P ratios of 0.25 (only for 1.4 per cent P) and 0.5 or 1.2. Except for a Ca/P ratio of 1.2 the diets without a supplementation of vitamin D caused rickets together with an extremely low growth rate in the animals and a reduced ash content of bones. Stone and

McIntosh (1977) fed barley-pea diets to pigs weighing from 15 to 70 kg with 230 or 2 000 IU vitamin D_3 per kg diet. The level of 2 000 IU vitamin D_3 increased the breaking strength of bone and its ash content when the diet contained 0.34 per cent calcium and 0.39 per cent phosphorus, but not in diets with 0.69 per cent calcium and 0.39 per cent phosphorus. Their conclusion was that for diets with phosphorus from plant origin, vitamin D_3 supplementation should be higher than 230 IU/kg diet when the Ca/P ratio is 1 or lower. Also Pointillart (unpublished) found in a cross-experiment that phytate phosphorus absorption increased with increasing levels of vitamin D_3 (from 0 to 1 500 IU D_3/kg diet). Wahlstrom and Stolte (1958) found hardly any effect of supplementation of diets with vitamin D; only the ash content in the femur was somewhat higher with 200 IU vitamin D. The animals had access to sunlight up to weaning and might have stored vitamin D before they were used for the experiment from 15 to 100 kg.

From the literature mentioned in this section, it appears that the vitamin D requirement of young and growing pigs can be met using diets containing between 100 and 200 IU per kg. The effect of the level of phytate in the diet is not yet clear, but there are indications that this will increase the vitamin D requirement (Davies, 1979). If we assume that the minimum requirement lies between 100 and 200 IU, then for practical applications a safety margin will be necessary because of losses during manufacture and storage of the feed, possibly of higher phytate contents and because not always a balanced feed is given (unfavourable Ca/P ratio); moreover animal health might be suboptimal.

In the studies of Goff et al. (1984) on sows it was shown that parenteral cholecalciferol treatment of sows protected young piglets against vitamin D deficiency via the sow's milk. A high correlation was observed between 25-HCC plasma levels of sows and piglets but not of 1,25-DHCC.

Günther (1969) recommends 4 to 10 IU vitamin D per kg body weight, while A.R.C. (1981) gives values of 120 IU per kg diet for pigs up to 20 kg and 105 IU/kg diet from 20 to 90 kg. The daily requirement of vitamin D per kg body weight was estimated by A.R.C. (1981) to be 4.8 to 5.2 IU. N.R.C. (1979) gives values per kg diet of 220 IU for 5 to 10 kg pigs, of 200 IU for 10 to 35 kg pigs, of 150 IU for 35 to 60 kg pigs and of 125 IU for 60 to 100 kg pigs. The basis for the vitamin D requirement for gestating and lactating sows is weak because no experiments have yet been performed to establish it. N.R.C. (1979) recommends 200 IU/kg diet. In the Netherlands, usually 2 000 IU vitamin D_3/kg diet is used.

1.4.4.8. Hypervitaminosis D in pigs

There have also been some experiments concerning hypervitaminosis D in pigs. Hypervitaminosis D is predominantly characterized by the mobilization of calcium and phosphorus from bones. The blood levels of calcium and phosphorus increase, resulting in the calcification of various soft tissues, primarily involving the cardiovascular system, the urinary tract and the kidneys. It results in fragile and deformed bones and cessation of growth (Günther, 1966; Reiland, 1975; Haschek, 1978).

In a field trial, Burgisser et al. (1969) observed that the addition of a vitamin mix in the trough for pigs suffering from pneumonia, resulted in death losses within two or three days. It was shown that these pigs, weighing approximately 25 kg, were getting 1 400 000 IU vitamin D_3 per day. Vitamin D_2 however proved to be less toxic.

Quarterman et al. (1964) found that 250 000 IU vitamin D per day for pigs with a body weight of 20 kg was toxic. Haschek (1978) found that 825 000 IU

vitamin D/kg diet was toxic, while even 165 000 IU/kg diet resulted in reduced bone ash. Reiland (1975) observed toxic effects when weekly doses of 15 000 IU vitamin D per kg bodyweight were given intramuscularly. In their research, Peo et al. (1986) found that in diets for pigs from 6 to 17 kg live weight, 22 000 IU vitamin D_3/kg diet resulted in lower performance when compared with 11 000 IU/kg. At levels of 180 000 IU/kg diet or greater it was toxic.
Clearly, very high levels of vitamin D have to be fed before toxicity occurs; about 10 000 IU/kg body weight per day or 200 000 IU vitamin D/kg diet is toxic for pigs.

1.5. CONCLUSIONS

Intestinal absorption of phosphorus in pigs occurs predominantly in the small intestine, while it is not certain if any phosphorus is absorbed in the large intestine. Absorption of phosphorus across the intestinal wall probably consists of several steps and is an active process with sodium as the co-ion. The kidneys are important organs in the regulation of the phosphorus homeostasis, mediated by the parathyroid hormone, calcitonin and possibly 1,25-DHCC. Vitamin D and its metabolites have important functions in phosphorus absorption and retention, but present knowledge is still poor.
The main effects have been summarized in Figure 3.

	absorption of P in intestine	reabsorption of P in kidney	bone formation
Parathyroid hormone	0?	--	--
Calcitonin	0	-?	+
Thyroxine	0?	-	+
Growth hormone	0?	+	++
Vitamin D	++	+	++
acidosis	+	-?	-
alkalosis	-	+	+?

Figure 3. Summary of effects on absorption and reabsorption of P and on bone

2. EFFECT OF DIET COMPOSITION AND NUTRIENT SUPPLY ON ABSORPTION AND RETENTION OF PHOSPHORUS

2.1. INTRODUCTION

In this chapter the interrelationship of phosphorus metabolism with several nutritional factors will be reviewed. These factors comprise not only level of feeding and energy supply, dietary protein, fat and crude fibre but also several macro- and micro-minerals. As calcium probably affects absorption and retention of phosphorus to a large extent, it will be discussed in more detail. Because of their frequent interaction with phosphorus metabolism, much attention will be paid to the effect of phytate and phytase content on the absorbability of phosphorus in the pig. Also, knowledge concerning the amount of faecal endogenous secretion by pigs will be reviewed. This is necessary for a better interpretation of experimental results on apparent absorption. Furthermore, some attention will be given to the effect of these dietary factors on calcium and, occasionally, on magnesium absorption and retention.

2.2. LEVEL OF FEEDING AND ENERGY SUPPLY

Much research has been done concerning the effect of the level of feeding upon growth rate and feed conversion ratio in pigs. In some experiments, the effect of the level of feeding on protein and fat deposition or energy utilization has been studied. However, so far very little attention has been paid to the effect of the level of feeding or energy supply on the absorption and retention of minerals. It is of interest to know if at a higher level of feeding a higher or lower concentration of minerals in the diets is required or not. This may mainly depend upon the tissue that is synthesized: bone and muscle or fat. If the higher level of feeding only results in more fat retention, a higher concentration of minerals may not be necessary, even a lower concentration may be sufficient. When mainly muscle and bone are synthesized, it is more difficult to decide upon the required mineral concentration.

In an experiment on pigs receiving the same diet from 20 to 70 kg live weight at two levels of feeding (1.7 or 2.5 times maintenance) and at 25°C and 33°C, Holmes et al. (1975) measured the absorption and retention of some minerals. At 25°C the absorption and retention of phosphorus was higher at the higher level of feeding, but the reverse was found at 33°C. The Ca/P ratio in the retention was abnormally high (3 to 4.5) so that it must be doubted whether their results are of great value.

In an experiment described by Whittemore et al. (1972), 1.20 or 0.60 kg of the same diet was fed daily to pigs of 25 kg. The availability of calcium and phosphorus did not differ. Sauer et al. (1982) did an experiment on pigs weighing some 70 kg, with cannulas in the terminal ileum, which got 1.68, 1.26 or 0.84 kg dry matter a day of the same diet. No differences were observed in the absorption percentage of calcium and phosphorus; the retention was not measured in their studies.

In a study by Stoy (1983), four experiments on pigs from 20 to 100 kg live weight were done, in which the pigs were fed the same diet at a high level of feeding or, on average, 22 per cent less. The retention percentage was calculated by means of the comparative slaughter technique. The growth rate of the pigs at the low and high levels of feeding was, on average, 605 and 813 g/d, respectively. The retention percentages of calcium and phosphorus at the low and high levels were 47 and 43 and 43 and 40, respectively; the differences were not statistically significant.

Fandrejewski and Rymarz (1986) applied different levels of feeding, using the same diet, to boars and gilts from 32 to 100 kg live weight. On average, 2.31 or 2.49 kg/d was fed to boars and 2.40 or 2.68 kg/d to gilts.

At the end of the experiment the animals were slaughtered. The higher level of feeding resulted in an increase in daily gain of 30 and 50 g for the boars and gilts, respectively. The amounts of calcium and phosphorus retained per kg empty body weight were not significantly lower at the higher level of feeding. The retention percentages of calcium and phosphorus were therefore, on average, 2 and 1 units lower respectively at the high level of feeding.
Tran et al. (1983) showed in their slaughter experiment, that a diet with a higher energy concentration (other feedstuffs) but the same dietary calcium and total phosphorus concentration resulted in a higher calcium and phosphorus retention in the pig. Their results might have been affected by the considerable amount of wheat in the high energy diet due to its phytase content, which could have resulted in more available phosphorus.
In some other experiments where the effects of the level of energy supply on mineral retention was measured, the concentration of the minerals was adjusted to intake of energy in such a way that the daily intake of minerals was the same (Moinizadeh, 1975; Chidume, 1977). This means that not the same diet was fed. The energy supply was varied from two to four times the maintenance requirement for pigs from 25 to 98 kg live weight. The growth rate of the pigs varied from 356 g/d at the lowest level to 828 g/d at the highest level of energy supply, and at slaughter bone as a percentage of the empty body weight varied in the opposite direction, from 9.7 to 7.4 respectively. The retention percentages of calcium and phosphorus in their experiments are given in Table 1.

Table 1. Effect of energy supply (times maintenance; M) and the same daily supply of minerals on growth rate, amounts and retention percentages of Ca and P (Moinizadeh, 1975)

energy supply*	growth rate (g/d)	retention % Ca	P	amount at 100 kg Ca (g)	P (g)
2	356	10.0	8.6	1030	591
2.5	511	16.4	14.6	889	542
3	675	17.5	16.0	842	511
3.5	778	20.1	18.2	806	498
4	828	19.0	17.6	792	486

* (multiples of M requirements = $0.65\ W^{0.569}$ MJ NE_f)

From Table 1 it can be concluded that, except for the lowest energy level, there is a slight tendency towards a higher retention percentage of calcium and phosphorus at a higher daily energy (from corn starch) supply and the same mineral supply a day. However, the amount of calcium and phosphorus retained per kg live weight gain decreased (see also Chapter 4.2.).

2.3. PROTEIN

2.3.1. General

The aim in pig production, is to produce animals which achieve a high growth rate, have a favourable feed conversion ratio and good slaughter quality, under the generally accepted production systems. One factor which has a definite effect on these production parameters is the dietary supply of protein or amino acids. Thus, the amount of protein offered to the animal can influence the absorption and retention of phosphorus and calcium through altered growth rate. When more protein is retained, more phosphorus

is needed because of a relatively high concentration of phosphorus in the fat-free soft tissues (mainly protein). In contrast to growing pigs, the protein requirement of adult rats and humans is soon met because hardly any protein is necessary for growth.
First, the effect of the protein supply on the phosphorus and calcium balance in laboratory animals and humans will be described, then the same is done for pigs. Also, some remarks will be made on the effect of phosphorus and calcium supplies on nitrogen balance.

2.3.2. Protein and calcium in laboratory animals and humans

Several experiments on humans and rats have shown that dietary protein can affect calcium absorption and retention. As far back as 1956, Wasserman et al. had reported that the presence of certain amino acids, particularly lysine and arginine, in the intestinal tract improved calcium absorption. Howe and Beecher (1981) found in young growing rats that increasing dietary protein, regardless of dietary phosphorus level, resulted in a decreased faecal calcium output accompanied by increased urinary calcium. The growth rate of their rats was somewhat lower on the high protein diet due to lower food intake, so there may have been an effect due to the lower calcium intake of the high protein diet on the faecal calcium excretion. In some other experiments, an enhancement of the calcium absorption is also observed in adult humans and rats (Pittman and Kunerth, 1939; Chu et al. 1975), but notably in experiments on growing rats and children no effect on calcium absorption is found (Shofield and Morrell, 1960; Shenolikar, 1974).
In all experiments, a higher supply of protein resulted in a higher excretion of calcium in the urine (Allen and Hall, 1978; Hegsted et al., 1981; Calvo et al., 1982). In the experiment described by Howe and Beecher (1981), the calcium balance was not affected by dietary protein level, but in most experiments on adult humans a lower calcium retention is observed when a higher protein supply is given.
In experiments on young rats (Allen and Hall, 1978) with diets of 18 and 36 per cent casein it was shown that after 29 days on the high protein diet the urinary calcium excretion was the same as that of the controls. This was not the case with diets of 25 and 45 per cent casein (Howe and Beecher, 1981). These and other observations lead to the conclusion that the calciuric effect depends on the quantity, duration and type of the protein fed and the age of the subjects (Calvo et al., 1982).
Impaired fractional renal tubule reabsorption of calcium due to the increased excretion of acid as sulphate (from the sulphur-containing amino acids) is currently held to be a major factor involved in protein-induced hypercalciuria of rats and humans (Whiting and Draper, 1980; Zemel et al., 1981). The origin of the higher urinary calcium excretion is not yet clear. Some authors suggest a shift in the route of endogenous calcium from faeces to urine, others an increased absorption of calcium or higher release from bone, though the latter possibility is rather unlikely (Calvo et al., 1982).

2.3.3. Protein and phosphorus in laboratory animals and humans

In contrast to calcium, little attention has been paid to the effect of protein on phosphorus absorption and retention. In their experiment on young growing rats, Howe and Beecher (1981) showed that an increased protein intake had little effect on phosphorus absorption at 0.35 per cent phosphorus in the diet, but at 0.8 per cent phosphorus, absorption was somewhat decreased.
There are few reports in which the effects of separate amino acids on phosphorus absorption is given. However, Chow et al. (1972), found that

lysine inhibited radiophosphorus absorption from ligated intestinal loops of the chick. Another amino acid that was studied is L-phenylalanine, because this is an inhibitor of alkaline phosphatase. Wasserman and Taylor (1973) demonstrated a decreased radiophosphorus transport in chicks, but in a further experiment, Taylor (1974) found no effect of phenylalanine.

2.3.4. Protein and the absorption and retention of phosphorus and calcium in pigs

In balance experiments on baby pigs from 3 to 11 kg, Hendricks et al. (1969) observed that 16 per cent compared with 32 per cent protein in the diet resulted in the same phosphorus and calcium balance. The urinary excretion of these minerals was somewhat higher at 32 per cent protein. In a second experiment (Hendricks et al., 1970), however, it was found that the higher protein diet (16 per cent compared with 32 per cent protein) resulted in a lower absorption and retention percentage for phosphorus when isolated soybean protein was given, but the reverse was found when casein was given as a protein source. The daily gain was not affected by the treatments, but the daily feed intake was higher at 16 per cent protein. One difficulty in interpreting these results is that as the concentration of phosphorus in these diets is the same, in the high protein diet more phosphorus comes from soybean protein. The phosphorus in isolated soybean protein consists of about 60 per cent phytate phosphorus and this is not so readily available as phosphorus from casein or an inorganic source of phosphorus. Moreover, the higher protein diet resulted in a higher feed intake and, therefore, in a higher growth rate of the pigs, which is another disturbing factor. Müller and Kirchgessner (1974) reported from experiments on early weaned piglets, that with diets from 19.5 to 32.5 per cent protein in the dry matter, the retention percentage for phosphorus and calcium increased with an increase in dietary protein intake from 36 to 42 for phosphorus and for calcium from 58 to 68. From the constant Ca/N and the P/N ratios, these investigators concluded that the higher retention percentage could be attributed to the simultaneous changes in growth. This is in accordance with observations made by Livingstone et al. (1962). Florescu et al. (1972) found a higher absorption percentage for phosphorus and calcium using normal diets than from diets in which the protein content was reduced by 30 per cent and, moreover, the lysine content lowered from 0.72 to 0.35 per cent on average from 15 to 40 kg live weight. The growth rate on the lower protein concentration was about half of that using the normal diet.
In ileo-caecal reentrant fistulated pigs of 60 to 80 kg live weight, Jørgensen et al. (1979) fed diets with 16.5, 24.1 and 32.8 per cent protein and found no significant effect on the absorption of phosphorus and calcium. However, the authors did not supply the same daily amounts of calcium and phosphorus with the three diets, so their results might not be due only to differences in dietary protein content.
Reinhart et al. (1976) fed growing pigs from 17 to 55 kg, diets with 14, 18 and 22 per cent protein, but with the same phosphorus and calcium concentration ad libitum. The higher protein levels resulted in a somewhat better performance (on average 3 per cent better growth rate and 4 per cent better feed conversion ratio), lower serum phosphate levels, a higher serum alkaline phosphatase activity and a decreased bone ash percentage. They concluded that a higher total dietary phosphorus level was necessary to achieve maximum bone ash and serum phosphate levels when dietary protein levels are increased. The same tendencies as those found by Reinhart et al. (1976) were also reported by Fammatre et al. (1977) and by Schiefelbein (1979). In a second experiment of Reinhart et al. (1976) it was observed that growth rate increased by 7 per cent as dietary mineral levels were elevated, most notably in the 22 per cent protein diet. When, in pigs, a

higher protein level in the diet results in a better performance, it also results in a lower serum phosphate level and a lower bone ash percentage (Hendricks et al., 1969; 1970; Fammatre et al., 1977; Schiefelbein, 1979). However, it can be remarked for these experiments that at higher protein but constant total phosphorus levels, the higher available phosphorus from feed phosphates is exchanged for the lower available phosphorus from soybean meal. A higher protein level gives a higher excretion of calcium in the urine and, due to the sometimes stimulating effect on growth rate, also a higher absorption and retention of phosphorus and calcium can be observed.

2.3.5. Effect of phosphorus and calcium level in the diet on the nitrogen and energy balance

Although there is abundant information concerning the effect of the level of phosphorus and calcium in the diet and its Ca/P ratio on growth rate, feed conversion ratio and feed intake (see Chapters 5.3. and 5.4.), not much is known about the effect it has on the digestibility and retention of nitrogen.

In experiments on rats, Goto and Sugai (1975) found that a high Ca/P ratio in the diet (4:1), when compared with a normal Ca/P ratio (1:1), resulted in a lower nitrogen retention, which was also the case with excess phosphorus and calcium in the diet. This was confirmed in the work of Suzuki and Goto (1976). Short et al. (1974) noticed after PTH application, not only an increase in phosphorus excretion but also in urinary excretion of several amino acids, which resulted in a lower nitrogen retention. Henry et al. (1979) showed, in growing rats, that the primary effect of a phosphorus deficiency was a decrease in bone mineralization; at a more advanced stage of this deficiency, the tissue phosphorus levels were affected and the resulting metabolic alteration reduced protein retention and subsequently voluntary energy intake.

In experiments on barrows weighing about 30 kg, Vipperman et al. (1974) observed that an increase in dietary phosphorus level from 0.27 to 0.50 per cent at each calcium level in the diet (0.29, 0.53 and 0.73 per cent), resulted in a higher nitrogen digestibility, decreased nitrogen excretion in the urine and, therefore, an increase in nitrogen retention. A further increase in dietary phosphorus level from 0.50 to 0.71 per cent had no effect on nitrogen retention. At the same dietary phosphorus level, only at 0.73 per cent calcium in the diet was the nitrogen digestibility higher, but also the nitrogen excretion in the urine, so that nitrogen retention was the same. Galik (1979[a]) found that at Ca/P ratios in the diet of 1.1, 1.3, 1.5 and 1.8, only the highest Ca/P ratio tended to give a lower N digestibility and N retention in pigs of about 30 kg. Bayley and Thomson (1969), however, did not observe any effect of the phosphorus level in the diet (0.35 and 0.56 per cent P) on N digestibility, which was also the case in the experiments described by Kirchgessner et al. (1960[a]) who, furthermore, found no effect of the Ca/P ratio in the diet on the N retention. Finally, Schenkel and Müller (1984) also found no effect of different phosphorus and calcium concentrations in the diet on N digestibility or N retention in growing pigs of about 24 kg live weight. Only with their diet without any supplementation of phosphorus and calcium (0.52 and 0.12 per cent P and Ca in the dry matter of the diet respectively) was there a tendency towards a lower N digestibility but not of N retention. We can conclude that there seems to be little or no effect of the concentration of dietary phosphorus and calcium on nitrogen digestibility or nitrogen retention.

Little is known about the effect of a low phosphorus intake on the energy balance. Diets deficient in phosphorus may result in a lower intake of energy and can thus affect energy retention. The work of Greene et al.

(1985) on rats showed a lower digestibility of energy due to a diet deficient in phosphorus. Many enzymes contain phosphorus: a severe deficiency might slow down their production which could lead to a less efficient metabolism. So far, no experimental data are available concerning the effect of a low dietary phosphorus concentration on digestibility and retention of energy in pigs.

2.4. FAT

In the intestinal tract, soap formation can take place due to the binding of mainly calcium and magnesium with fatty acids. These soaps are less soluble in the intestinal tract and are thus not absorbed. The extent of soap formation is dependent on the calcium and magnesium concentration in the digesta on the one hand, and the concentration and composition of the fatty acids on the other. Long chain saturated fatty acids such as C16:0 and C18:0 readily form soaps; unsaturated and short chain fatty acids do not (Flanzy, 1969; Häkansson, 1974). As soap formation especially takes place with calcium, one can expect that the absorption or retention of calcium can be lowered by the addition of fat to a diet, and due to the interaction between phosphorus and calcium it is also possible that the absorption and retention of phosphorus is increased.
In experiments on rats, some authors mention hardly any effect; others find a positive effect of added fat on phosphorus absorption. The differences in effect can be explained by different levels of feeding, dietary concentration of phosphorus and calcium and the Ca/P ratio, different fats, and the age of the animals (do Amaral, 1969). This author observed in his experiments on rats that the addition of fat to the diet had no effect on the absorption of calcium, but increased the absorption of phosphorus. He concluded that soap formation occurs in the distal part of the intestine, a place where no calcium absorption takes place. Because of the lower concentration of soluble calcium in that area, less phosphorus is conjugated with calcium, and so a higher absorption for phosphorus is possible.
In experiments on pigs, Newman et al. (1967) found that the addition of 10 per cent tallow in the diet decreased the absorption percentage of phosphorus in one experiment, but the opposite was found in another experiment. Nevertheless, their conclusion was that tallow depresses the absorption of phosphorus. In experiments on pigs from 60 to 80 kg, fitted with ileo-caecal reentrant cannulas, diets with 4.5, 17.0 and 26.8 per cent fat were supplied (Jørgensen et al., 1979). The authors found no significant differences in the absorption of phosphorus which amounted to 46, 43 and 50 per cent, respectively. It should be remarked, however, that the intake of calcium was not the same in the three treatments; the diets contained 8.3, 9.3 and 9.6 g/kg dry matter, respectively. In balance studies with early weaned piglets of $\pm$ 3 kg (2 weeks old) 1.6 up to 42.9 per cent butterfat in the diet (Jordan and Weatherup, 1978) had little or no effect on the absorption percentages of calcium, phosphorus or magnesium. These authors calculated a positive relationship within the diets between the apparent absorption of fat and that of phosphorus and calcium. It is not clear whether the mineral concentration in their diets were adjusted for energy concentration, so that the higher absorbability could be due to a lower daily intake of the minerals. Gundel and Kemenes (1980) found that the addition of fat at the same phosphorus and calcium concentration in the diet did not alter the absorption percentage of phosphorus. When the tibia development in young pigs was taken as a criterion, Höller and Hill (1968/69) concluded that the addition of 8 per cent tallow to a diet had no effect on the retention of phosphorus and calcium. In more recent experiments of Jørgensen and Fernandez (1984), there was a tendency towards a higher net absorption of phosphorus at 15 per cent when compared with 3 per cent fat. However, a lower amount of feed was offered at the higher fat

level, so that it is not certain whether the same intake of minerals was realized. Atteh and Leeson (1983; 1985) studied the interrelationship between fat and the minerals calcium, magnesium and phosphorus in more detail. In their first experiment (Atteh and Leeson, 1983) on pigs of 35 kg live weight, corn starch was replaced by cellulose and animal-vegetable blend fat. The mineral levels and ME content of the diets were kept as constant as possible. At the end of the experiment, the animals were slaughtered and digesta collected at several sites in the gut. The pH in the stomach and duodenum tended to increase with more fat in the diet but the reverse was the case in the caecum and colon. More fat in the diet gave an insignificant decrease in absorption percentages of calcium, magnesium and phosphorus, which could be due to the somewhat higher concentration of phosphorus in the diets with fat and a significantly higher intake of the control diets. In their second experiment, Atteh and Leeson (1985) gave pigs of 20 kg live weight diets with up to 10 per cent soapstock (a by-product of soybean oil refining, consisting mainly of salts of fatty acids, glycerides and phosphatides). These diets were adjusted to the same energy and mineral concentration. No differences in absorption percentages of phosphorus and calcium could be demonstrated. After slaughter, it was shown that soap formation was negligible in the stomach because of the acid condition there. With an increase in pH of the contents of the small intestine, there was a gradual increase in the formation of insoluble soaps, mainly palmitates and stearates.

One problem in interpreting the experiments is, that when fat is added to a diet a higher energy concentration is achieved. When the same amount of feed is offered, more energy but less phosphorus and calcium are given due to the dilution with fat. This can lead to a higher growth rate or to a higher absorption percentage for these minerals.

Another aspect is the composition of the fats. In experiments on rats, Calverley and Kennedy (1949) demonstrated that the addition of coconut fat or peanut oil decreased the absorption percentage of phosphorus. Cottonseed oil, however, did not. The retention percentage of the phosphorus in the fat-enriched diets was somewhat lower than in the control diet. Tadayyon and Lutwak (1969), however, found that the absorption and retention of phosphorus was not greatly altered when different fats and oils were fed to rats.

A positive effect of fat on phosphorus absorption might also be explained by the facilitating effect of fat on the intestinal absorption of fat soluble vitamin D.

From the above mentioned experiments it can be concluded that the addition of fat to diets has only a small positive effect, if any, on the absorption of phosphorus. If there is an effect, it may be caused by an alteration in the energy and mineral intake of the fat-enriched diets and by the composition of the fat.

2.5. CARBOHYDRATES, ESPECIALLY THOSE IN PLANT CELL WALLS

2.5.1. General

In sections 1.2.2.1. and 1.3. it was shown that glucose is required for phosphorus absorption or reabsorption. It may only be needed as an energy source for the intestinal cells, rather specifically, to provide direct energy for the phosphorus transport process. In this respect, it is well known that lactose stimulates the intestinal absorption of calcium (e.g. Pointillart et al., 1986). Usually, ordinary diets contain abundant starch and sugar, so it can be expected that there is always enough energy for absorption. Therefore, one is not concerned about the components starch and sugar with regard to mineral metabolism. More interest is paid to the structural carbohydrates of plant cells (fibrous components) due to their

interference with some minerals.
Plant fibre has a very heterogenous composition, which includes cellulose, hemicellulose, pectic substances, other polysaccharides, and lignins. Cereal fibre is closely associated with phytic acid, which has a strong cation binding capacity, so that effects of fibre are often confounded with the presence of phytic acid.
A lower absorption of minerals at a higher fibre concentration in the diet could be due to (see also reviews of Low, 1985 and Drochner and Coenen, 1986):

a) a higher passage rate
b) the greater volume of the digesta reducing the mucosal concentration of the minerals in the digesta
c) an increased intestinal secretion of minerals
d) a reduced release by microbial fermentation of minerals bound to the fibre matrix or a reduced availability of minerals present as a constituent of fibre
e) more potential mineral binding sites and thus a removal of minerals from an absorbable pool, but this is probably not the case for phosphorus (McConnell et al., 1974)
f) the interactive effect of phytase, phytate and fibre in the case of several cereal fibres.

2.5.2. In humans and rats

In human feeding, the effect of cellulose on the absorption and retention of phosphorus has been described by Reinholt et al. (1976), Ismail-Beigi et al. (1977), Drews (1977) and Godara et al. (1981). In general, a decreased absorption and retention of phosphorus is observed. Drews (1977) reported that the effect of dietary fibre on mineral balance was dependent on the chemical composition of the fibre. He fed hemicellulose (from psyllium), cellulose (-cellulose fibre; 99.5 per cent) and lignin to rats and reported that the hemicellulose component was mainly responsible for the increased faecal excretion of phosphorus and calcium; cellulose had a much smaller effect and pectin had no effect. Experiments on growing rats showed that when 10 per cent of starch was replaced by purified cellulose or pectin (degree of esterification 70 per cent), no effect was found on phosphorus absorption or retention (Boisen et al., 1984). In an in vitro study by Bagheri et al. (1982), the binding capacity of various fibre sources for calcium, phosphorus and zinc was determined at a pH of 6.8. With regard to phosphorus this, at 63 per cent was by, far the highest for wood lignin, much less for hemicellulose from 'Sigma' or wheat bran (10 to 14 per cent) and almost non-existant for cellulose 'Sigma', delignified or dephytinated wheat bran.
Batchelor and Compston (1983) reported that the depressed absorption of calcium and phosphorus caused by fibre could be due to an effect on vitamin D metabolism. They observed a reduced plasma half-life of injected radiolabelled 25-HCC in humans fed a high fibre diet (bran). This may involve interference with an enterohepatic circulation of 25-HCC, perhaps by the binding of 25-HCC to dietary fibre.

2.5.3. In pigs

Partridge (1978[b]) was the first who studied the effect of fibre on mineral absorption in pigs. Using a synthetic diet supplemented with 30 or 90 g wood cellulose (Solka Floc) per kg diet, he showed that in pigs of ± 40 kg the absorption percentage for phosphorus decreased significantly from 81 to 74. Also, for calcium, magnesium and sodium the absorption percentages decreased. Working with reentrant fistulas in the ileum, he observed that there was no reduction in apparent absorption anterior to the terminal

ileum but only in the large intestine. Also, in a recent experiment done by Partridge et al. (1986) an increased amount of treated straw meal (ground wheat straw treated with concentrated hydrochloric acid and steam and then neutralized with calcium hydroxide; 302 g cellulose/kg) decreased the total apparent absorption of phosphorus but much less the ileal absorption. It must be remarked, however, that in this experiment the effect of straw meal was confounded with a higher calcium concentration in the diet.

Moser (1980) added, if any, 10 per cent ground oat hulls to both a sorghum-soybean meal and a corn-soybean meal diet. Faecal excretion of phosphorus was higher for pigs fed diets with hulls and a decrease in phosphorus retention was found. The addition of oat hulls also tended to increase calcium excretion in the faeces. However, somewhat less dicalcium phosphate had been added to the diets with oat hulls than to the other diets, so that the effect of oat hulls might be confounded with the phosphorus source. In the experiments of Den Hartog et al. (1985) the effect of either 5 per cent pectin, 5 per cent pure cellulose or 5 per cent straw meal in a diet, on the absorption of minerals in the small and large intestine was investigated. No effect of these carbohydrate sources on phosphorus absorption in either the small or large intestine was observed. Lack of effect might be explained by the rather high phosphorus concentration in the basal diet.

Moore et al. (1986) studied the effect of 10 per cent oat hulls or 20 per cent wheat bran in diets, on mineral retention in pigs. The diets were equalized for total calcium and total phosphorus content by adding limestone and dicalcium phosphate. Oat hulls did not affect phosphorus absorption but somewhat more phosphorus was excreted in the urine. The absorption of phosphorus in the diet with wheat bran was not significantly lower than from the control diet, but it should be mentioned that in contrast to the control diet no supplementary dicalcium phosphate was used in the diet with wheat bran.

Bagheri and Guéguen (1985) studied the effect of 2.5 per cent pectin or 20 per cent wheat bran, in the diet given to pigs, on the absorption and retention of, for example, phosphorus. High-methoxylated pectin had no effect, but low-methoxylated pectin drastically diminished the absorption and retention of phosphorus. This decrease was explained by the strong binding capacity of ionized carboxyl groups of uronic acids. The positive effect of wheat bran on absorption and retention was explained by the presence of phytase and phytate phosphorus in the bran.

Drochner (1984) studied extensively the effect of three fibrous components in the diet on mineral absorption in mini-pigs. These pigs were fitted with ileal reentrant cannulas at the terminal ileum or with simple T cannulas in the caecum. The basal diet contained, per kg dry matter, 8.1 and 17.0 g phosphorus and calcium, respectively; these concentrations are very high. The basal diet was fed either alone or supplemented with 5 per cent crude wood fibre product (cellulose + lignin), or isolated wood cellulose or isolated pectin derived from apples. These experiments indicated that the absorption of phosphorus at the ileum was negative and was depressed by the three sources of fibre but most of all by crude wood fibre. The negative values might indicate that intestinal secretion of minerals is enhanced by fibre. Overall absorption of phosphorus was highest in the diet with pectin.

It can be concluded from the experiments discussed in this section that fibre may sometimes have a small negative effect on phosphorus absorption. The results are conflicting with regard to the component of the fibre which gives the possible negative effect. A better characterization of the fibrous components may help to explain the effects observed; in half of the papers this information is not available.

2.6. CALCIUM

2.6.1. In laboratory animals

Calcium is one of the most important factors that can affect the absorption and retention of phosphorus. As already outlined in section 1.2.2.1., the role of calcium in the mechanism of absorption of phosphorus, when investigated in experiments using intestinal loops, is not yet clear. Some investigators have suggested that calcium is required for the transport of phosphorus from the intestinal lumen to blood (Harrison and Harrison, 1961; Helbock et al., 1966; Fox et al., 1978[a]). Others suggest that the absorption of phosphorus is independent of the calcium concentration in the digestive tract (Carlsson, 1954; Kowarski and Schachter, 1969; Wasserman and Taylor, 1973, Peterlik and Wasserman, 1978). Taylor (1974) suggested that calcium in the medium had no effect on the uptake of phosphorus from the mucosal medium but did have an effect on the transfer to the serosal medium. Finally, Chen et al. (1974) concluded that calcium in the medium increased the absorption of phosphorus in the upper duodenum but not in the jejunum.

It can be concluded that absorption of phosphorus may require the presence of some calcium in the intestine. Under practical circumstances, however, small amounts of calcium are always present in the diet so the interest is directed to the possible effect of increasing the concentrations of calcium in the intestinal tract on phosphorus absorption rather than to the presence or absence of calcium per se.

It has been shown in Chapter 1.4.1. that a low dietary calcium concentration stimulates PTH secretion with, as a result, an increase in phosphorus excretion in the urine. As an example, the effect of the concentration of phosphorus and calcium in the diet and the Ca/P ratio on the phosphorus and calcium absorption and retention in rats, as found by Whittemore et al. (1973), is given in Table 2.

Table 2. Absorption, excretion and retention of Ca and P in rats as affected by varying Ca and P levels in the diet

intake (mg/d)		absorption (%)		availability (%)		faecal endogenous excr. (mg/d)		urinary excr. (mg/d)		retention (mg/d)		retention (%)	
Ca	P	Ca	P	Ca	P	Ca	P	Ca	P	Ca	P	Ca	P
0.9	1.7	75	<0	100	96	0.2	1.9	1.0	0.3	-0.3	-0.5	<0	<0
1.6	59.5	80	93	100	98	0.3	3.3	0.1	42.4	1.2	12.8	75	22
55.8	1.7	41	<0	53	75	6.9	2.9	16.9	0.1	5.9	-1.8	11	<0
54.4	56.0	32	58	47	65	8.2	4.2	0.4	22.3	17.2	9.9	32	18
56.4	114.3	40	78	60	86	11.8	9.6	0.3	62.0	22.0	26.6	39	23
108.2	55.7	20	21	32	43	12.4	12.4	1.1	3.8	20.6	7.9	19	14
111.9	112.3	18	59	38	67	22.1	9.3	0.4	48.1	19.9	18.3	18	16

The term availability is defined by Whittemore et al. (1973) as the percentage of the element supplied by the food that can be used by the body to make good endogenous loss or promote storage. However, in practice, availability is usually considered as true digestibility. As excretion in the urine is low, this is almost correct for calcium, but not for phosphorus due to the fact that a considerable amount of phosphorus can be excreted in the urine.

From Table 2 the following can be concluded. There is an inverse relationship between calcium intake and calcium availability, and the availability of calcium is not affected much by the intake of phosphorus. Faecal endogenous losses of calcium decline with less calcium in the diet, but they decline even more with a lower phosphorus intake. The urinary excretion of calcium is low except when the intake of calcium is normal and that of phosphorus inadequate. When the intake of calcium is adequate but, that of phosphorus inadequate, the retention of calcium falls.
Availability of phosphorus does not appear to be related to phosphorus intake but is inversely related to calcium intake, probably due to the formation of insoluble calcium phosphates in the intestinal tract. Faecal endogenous excretion of phosphorus is somewhat higher when the calcium intake increases. Loss of phosphorus in the urine is partly dependent on the intake of phosphorus but is mediated by the calcium intake. The retention of phosphorus falls with increased intake of calcium. These results agree with those of several other experiments (Hansard and Plumlee, 1954; Jenkins and Phillips, 1960; Clark and Rivera-Cordero, 1973; 1974); Kaye, 1974; Goto and Sugai, 1975; Cramer and McMillan, 1980).
In general, at higher dietary calcium, phosphorus absorption and retention decrease, whereas an increased intake of phosphorus results in higher phosphorus absorption and urinary excretion and a rise in phosphorus retention.

2.6.2. In pigs

In nearly all experiments on pigs, the same tendencies are found as shown for rats (Whiting and Bezeau, 1958; Kirchgessner et al., 1960[a]; Berry et al., 1961; Morgan et al., 1969; Vipperman et al., 1974; Bayley et al., 1975[a]; Frape et al., 1979; Galik, 1979[b]). The relationship between the calcium level in the diet and the absorption and retention percentage of phosphorus is illustrated in Figures 4 and 5. In all these experiments, the phosphorus content was kept constant (from 0.34 to 0.79 per cent phosphorus in dietary dry matter).

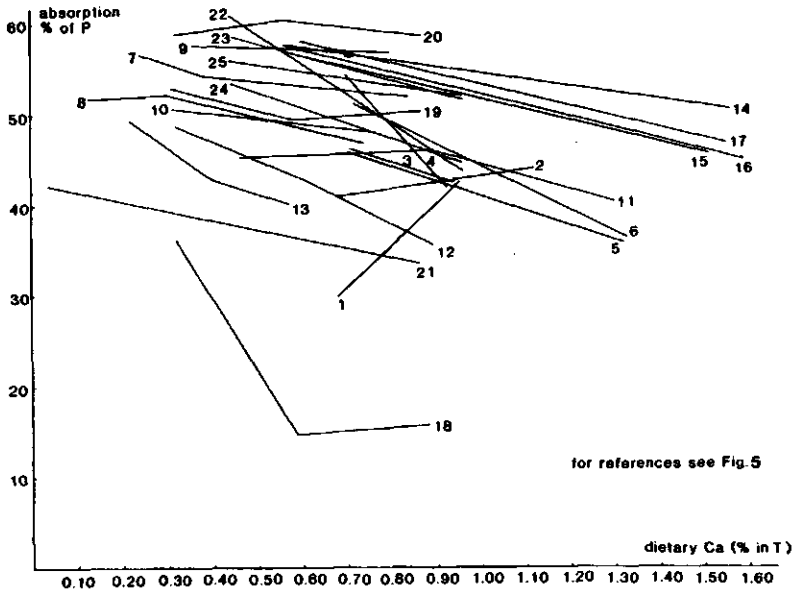

Figure 4 Relationship between Ca level in diet and absorption % of P

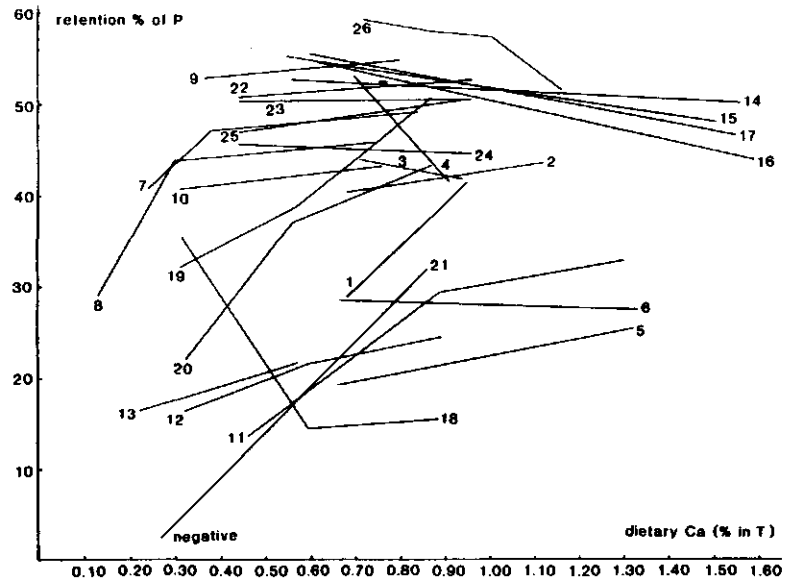

Figure 5 Relationship between Ca level in diet and retention % of P

	Reference	P (% in T diet)
1.	Bayley et al. (1975[a])	0.34
2.	,,	0.38
3.	,,	0.52
4.	,,	0.52
5.	Berry et al. (1976)	0.61
6.	,,	0.62
7.	Frape et al. (1979)	0.53
8.	,,	0.49
9.	,,	0.53
10.	,,	0.50
11.	Kirchgessner et al. (1960[a])	0.79
12.	,,	0.74
13.	,,	0.73
14.	Morgan et al. (1969)	0.72
15.	,,	0.72
16.	,,	0.72
17.	,,	0.74
18.	Vipperman et al. (1974)	0.29
19.	,,	0.53
20.	,,	0.76
21.	Weigand and Kirchgessner (1980)	0.43
22.	Whiting and Bezeau (1958)	0.51
23.	,,	0.51
24.	,,	0.51
25.	,,	0.51
26.	Galik (1979[b])	0.64

In nearly all experiments, more calcium leads to a lower absorption percentage for phosphorus. With regard to the retention percentage of phosphorus, it can be seen in Figure 5 that up to a calcium level of 0.90 to 1.00 per cent there is a positive relationship, but at a higher calcium level a slight negative effect on the retention percentage of phosphorus is observed. This was also found in recent experiments by Pointillart et al. (1987), in which no significant effect could be demonstrated of calcium excess (14.1 g/kg vs 9.1 g/kg diet) on phosphorus absorption and retention of marginally poor phosphorus fed pigs (5.5 g/kg diet, no added inorganic phosphorus).
From the results of the studies mentioned, we calculated within each diet the relationship between the calcium level and the absorption and retention percentage of phosphorus, after which the mean of all regression coefficients and constants for all experiments together were calculated. In this calculation, we omitted the results of Vipperman et al. (1974) with the diet of 0.29 per cent phosphorus and those of Bayley et al. (1975[a]). This was done because of the experimental design (very short adaptation period) in these experiments. The relationship was also calculated separately for calcium concentrations in the dry matter of the diet below 1.0 per cent. The following results were obtained (mean ± sem):

absorption%P=	-11.0 ± 1.6 Ca% + 58.4 ± 1.4	n = 20	all Ca levels;	p <0.001
retention%P =	8.9 ± 3.7 Ca% + 36.1 ± 4.9	n = 21	all Ca levels;	p <0.025
absorption%P=	-9.6 ± 2.2 Ca% + 56.2 ± 1.8	n = 14	Ca < 1.0%;	p <0.001
retention%P =	15.5 ± 4.4 Ca% + 30.9 ± 5.8	n = 15	Ca < 1.0%;	p <0.005

From these equations it can be seen that with regard to the absorption percentage there is not much difference in the negative effect of the calcium concentration when this level is either higher or lower than 1.0 per cent. However, as to the retention percentage of phosphorus, the regression coefficient only increases when calcium levels below 1.0 per cent are used, although there is also a small decrease in the regression constant, which somewhat diminishes the difference of the retention percentage.
The optimum Ca/P ratio, that is the ratio at which a maximal phosphorus retention percentage at the given dietary phosphorus level was obtained, was also calculated for each experiment separately. From these results, the mean optimum Ca/P ratio was derived by simple averaging. For all experiments, the Ca/P ratio was 2.10 ± 0.16 (n=20). For the experiments with a calcium concentration below 1.0 per cent it was 1.86 ± 0.08 (n=14) and for those above 1.0 per cent, it was 2.64 ± 0.44. The difference was statistically significant (p <0.01). From the equations given, a Ca/P ratio of 1.84 for all experiments and 1.75 for those below 1.0 per cent dietary calcium was calculated. These values are somewhat lower than calculated earlier (2.10 and 1.86, respectively). The Ca/P ratios calculated here are higher than those recommended on the basis of feeding trials (see Chapter 5.4.).
We also calculated the optimum of calcium to inorganic phosphorus (Ca/Pi) in the diet for a maximal phosphorus retention percentage, because Jenkins and Phillips (1960) suggest that this ratio might be a better parameter for estimating the optimum than the Ca/P ratio. Moreover, the Ca/Pi ratio is used in practice for broiler chicken diets for which a ratio of 2.0 is recommended. The calculated mean optimum Ca/Pi ratio for all experiments was 4.53 ± 0.61 and for the diets with calcium concentrations below 1.0 per cent it was 4.82 ± 0.84. These results indicate a wide variation in the optimum Ca/Pi ratio. This is mainly caused by including the experiments of Frape et al. (1979) who worked with diets which consisted of more than 90 per cent of wheat bran. When their results are omitted, the optimum Ca/Pi ratio is 3.32 ± 0.28 for all diets and 2.99 ± 0.22 for the diets with

calcium concentrations below 1.0 per cent. These values are still considerably higher than those for chickens, but we have no clear explanation for it.
In this chapter, it has been shown clearly that the calcium concentration in the diet has a significant effect on the absorption and retention of phosphorus. When the calcium concentration increases by 0.1 per cent in diets with a phosphorus concentration from 0.34 to 0.79 per cent the absorption percentage of phosphorus is depressed by one percentage-unit. Calculations concerning the optimal Ca/P ratio for a maximal phosphorus retention percentage reveal a higher level than the recommendations for swine based on feeding trials. The calculated optimal Ca/Pi ratio shows a greater variation than the Ca/P ratio, which for a large part could be explained by the diets with 90 per cent wheat bran of Frape et al. (1979).

2.7. MAGNESIUM

In several experiments, it has been shown that there is a relationship between magnesium and phoshorus with regard to the absorption and retention of these elements in animals. Parker (1985) found that in magnesium deficient weanling rats an increase in phosphorus supply greatly reduced growth rate, but little effect of additional phosphorus was seen when adequate magnesium was given.
In their experiments on rats, Lifshitz et al. (1967) observed that the transport of phosphorus in loops incubated in a magnesium-containing buffer was less than in loops incubated in a magnesium-free buffer. Loops from rats on a magnesium-free diet also showed a greater transport of phosphorus than loops from rats fed on diets containing magnesium. The authors suggested that magnesium deficiency directly affects the phosphorus transport system. They also found that magnesium deficiency reduced the concentration of serum phosphorus and increased the excretion of phosphorus in the urine.
In balance experiments on rats, Clark (1968) found that magnesium, as $MgCl_2$, had no effect upon phosphorus absorption when dietary phosphorus was suboptimal and the dietary calcium content was normal, but it increased it when dietary Ca/P ratio was low. The increase in phosphorus absorption might be due to a stimulation of calcium absorption by magnesium and so decreasing the amount of calcium available for precipitation of phosphorus in the intestine. When the dietary level of magnesium was raised using magnesiumoxide for adult rats, a depressed absorption of phosphorus was found up to 0.50 per cent magnesium, but at higher magnesium levels it was increased (Clark and Bélanger, 1967). Pointillart and Guéguen (1973) concluded from their experiments on rats, that a surplus of magnesium in the diet decreased phosphorus absorption. Moreover, there was an increase in faecal endogenous loss of phosphorus due to the surplus of magnesium. O'Dell (1960) is of the opinion that the lower absorption of phosphorus due to more magnesium in the diet might be explained by the formation of a magnesium-phosphorus complex in the gastrointestinal tract, which makes both magnesium and phosphorus unavailable for absorption. Günther and Mohme (1985) fed pigs weighing 60 to 100 kg a control diet without supplemented magnesium (2.0 g/kg), and the control diet supplemented with 1.7 g magnesium per kg either as magnesium oxide or as magnesium fumarate. Their balance experiment showed that the absorption percentage of phosphorus was significantly depressed by the magnesium additions from 42 to 29 and 34 respectively. However, in growing pigs Pointillart et al. (1985[a]) demonstrated that magnesium excess or deficiency had little or no effect on phosphorus absorption and retention. Magnesium excess decreased phosphaturia and magnesium deficiency increased phosphaturia and the reverse was also true.

In most experiments, a higher level of dietary magnesium decreases the excretion of phosphorus in the urine (Clark and Bélanger, 1967: Clark, 1968; Bellavia and Wallach, 1973; Pointillart and Guéguen, 1973; Rogel and Chenoweth, 1976). Thus, there seems to be a strong antagonism between phosphates and magnesium ions at renal level. Also, Günther and Mohme (1985) observed that the daily excretion of phosphorus in the urine was greatly depressed from 1.0 to 0.2 g due to the magnesium supplementations, so that the daily retention of phosphorus was not affected by magnesium fumarate but it was lower with magnesium oxide.
Pointillart and Guéguen (1973), observed on rats, that the retention of phosphorus was not greatly affected; only the addition of magnesium lactate, giving a more alkaline acid-base balance, increased the retention of phosphorus.
The effect of magnesium on phosphorus absorption is contradictory, but there appears to be some positive effect on phosphorus absorption at very low magnesium concentrations in the diet, that are not likely to occur in pig feeding. The excretion of phosphorus in the urine decreases at higher levels of dietary magnesium.

2.8. PHOSPHORUS

2.8.1. Organic and inorganic phosphorus in feedstuffs

In most feedstuffs of plant origin, phosphorus is present both in organic and inorganic form. The organic part, a small part of which is in the form of phospholipids, consists mainly of phytate, the mixed calcium-magnesium-potassium salt of hexainosit phosphoric acid (phytic acid). Phytic acid readily forms complexes with several essential minerals such as calcium, zinc, manganese and iron, and also protein (Nelson, 1967). The primary role of phytate in plant growth may be storage of phosphorus; the stored phosphorus is gradually utilized during seed germination (Williams, 1970). Tabekhia and Luh (1980) demonstrated for various kinds of beans that soaking them at 24°C for 12 hours decreased the phytate content by 12 per cent and their germination for 96 hours by 44 per cent with corresponding increases in inorganic phosphorus. During the growth of corn, Shinoda et al. (1983) found that phytate was found in the grain from the late yellow stage onwards, which means from about 14 days before full maturity.
In Table 3, some data are given concerning the concentration of phosphorus and phytate phosphorus in some feedstuffs. In Appendix 1, detailed data on most feedstuffs are given. However, one should bear in mind that different methods were used for determining the concentration of phytate phosphorus, so that the results of the various authors are not always completely comparable. For methods, the reader is referred to, amongst others, Mazzola et al., 1986 and Bos, 1986.

Table 3. Concentration of total P and phytate P in some feedstuffs (g/kg T)

	total P	phytate P	phytate P as % of total P	reference
cereals	4.1	2.7	67	Schulz and Oslage (1972[a])
wheat bran	12.3	10.3	84	Simons et al. (1981)
beans (Phaseolus spp)	4.5	3.1	69	Lolas and Markakis (1975)
soybean meal	7.9	5.0	62	Schulz and Oslage (1972[a])
groundnut expeller	6.9	4.5	66	Simons et al. (1981)
alfalfa	2.5	0.4	16	Simons et al. (1981)

From Table 3 it can be seen that in the feedstuffs from plant origin (apart from alfalfa), most of the phosphorus consists of phytate phosphorus. There seems to be a close relationship between total phosphorus and phytate phosphorus, as found by Nahapetian and Bassire (1976) for wheat (r=0.93) and by Lolas et al. (1976), where for wheat, barley, oats and soybean meal r was 0.97, 0.96, 0.91 and 0.98, respectively. Simons et al. (1981) also found close relationships between total and phytate phosphorus for several groups of feedstuffs. The close relationship does not always occur. This was demonstrated by Michael et al. (1980), who found that additional late applications of phosphorus fertilizer resulted in an increase of total phosphorus and phytate phosphorus by 58 per cent and 80 per cent, respectively. About 93 per cent of the phosphorus which accumulated additionally in the grain due to the late phosphorus application was found to be phytate phosphorus.

2.8.2. Endogenous loss of phosphorus in the faeces

For a good interpretation of the absorption of phosphorus in pigs, it is important to know how much phosphorus of endogenous origin is excreted in the faeces. The available information for pigs is rather scarce and, also, not much is known about the effect of several dietary factors. Determination of the quantity of endogenous phosphorus excreted in the faeces is almost always done using labelled phosphorus; feeding a phosphorus-free diet is also done sometimes.
The origin of faecal endogenous phosphorus is, amongst other things, from the secretion of digestive juices containing enzymes (bile, pancreas juice, mucosal juice) and from mucosal cells, which are continuously renewed. However, most of the endogenous phosphorus secreted can be reabsorbed again. From experiments on rats, it has been shown that an increase in phosphorus intake results in an increase in phosphorus absorbed but also in a slight increase in the faecal endogenous losses of phosphorus (Clark, 1968; *Cramer and McMillan*, 1980; *Whittemore et al.*, 1973). Also, the *Ca/P* ratio in the diet has an effect on the faecal endogenous secretion of phosphorus (Whittemore et al., 1973; Hermes et al., 1983). The first authors found some decrease when the Ca/P ratio in the diet was lowered while the phosphorus level was kept constant, but the latter authors found the reverse.
In Appendix 2, detailed data on faecal endogenous phosphorus excretion in pigs are given. For further calculations, the values of diets, to which calcium phytate was added, are omitted. This was done because there was only one observation per treatment (except for Vemmer and Oslage, 1973) and the nutritional value of phosphorus in calcium phytate is not clear. Furthermore, the endogenous excretion of phosphorus in the faeces is expressed per kg live weight and not per kg dry matter intake, because the intake of dry matter was not given in all experiments. In Table 4, a summary of results is given of experiments on pigs in which the endogenous faecal excretion was determined.

Table 4. Daily loss of endogenous P in the faeces of pigs

live weight range	range of P level in diet (% in T)	mean and range of daily loss of endogenous faecal P (mg/kg body weight)
15 to 80 kg	0 - 0.33	2.9 (1.3 - 4.8)
14 to 80 kg	0.58- 0.83	8.8 (1.8 -17.6)
> 140 kg	0 - 0.63	4.5 (3.0 - 7.1)

The results in Table 4 show that there is a great variation in the values for the excretion of faecal endogenous phosphorus. Vemmer and Oslage (1973), who supplied diets with a rather low concentration of phosphorus, came to the conclusion that about 10 per cent of total faecal phosphorus excretion was of endogenous origin. On the basis of their own results, and those reported in the literature, Guéguen and Perez (1979) came to the conclusion that, under normal conditions of feeding and mineral intake, the minimum endogenous loss in faeces varies from 5 mg/kg/d in diets poor in phosphorus to 15 mg/kg/d in diets with a normal phosphorus content. In experiments using diets with a high phosphorus content, not only the excretion of endogenous phosphorus in faeces increased, but also the excretion of phosphorus in urine.
In some experiments, it appears that the animal can adapt to low phosphorus diets by altering its endogenous excretion of phosphorus (Günther et al., 1978) and that it can take quite a long time before the adaptation is complete (Gütte et al., 1961; Vemmer and Oslage, 1973).
From Table 4 we can conclude that the faecal endogenous excretion of phosphorus is lower when less phosphorus is supplied to the animal than it requires. Under normal feeding conditions, a faecal excretion of about 10 mg endogenous phosphorus per kg live weight can be assumed, a quantity also suggested by Guéguen and Perez (1979).

2.8.3. Phytate phosphorus and its breakdown

2.8.3.1. Phytase and factors affecting its activity

General
Phosphorus from phytate cannot be absorbed in its original form by animals so it must first be released by hydrolysis. Only soluble phytate can be hydrolyzed (Hill and Tyler, 1954[a,b,c]). These authors observed that the solubility of phytate largely depends on pH; it increased considerably for wheat bran when the pH was lowered from 6.0 to 3.5. A further decrease in pH was of little influence. It was also found that the effect of pH on phytate solubility differed among feedstuffs and that the calcium concentration also played an important role, as will be discussed further in this section (McCance and Widdowson, 1944; Hill and Tyler, 1954[b]; Nelson, 1967; Nahapetian and Young, 1980).
The enzyme, phytase, is necessary for the hydrolysis of phytate to inositol and phosphoric acid (Nelson, 1967). Almost all feedstuffs from plant origin which are used in animal feeding possess phytase, although with different activity (McCance and Widdowson, 1944; Hill and Tyler, 1954[b]; Nelson, 1967). According to Bagheri et al. (1982) the activity of phytases in feedstuffs is in the following order: wheat > barley > rye > oats and soybean meal > sorghum and maize > cottonseed. This order must not be regarded as completely definite because other authors give different orders. It is generally accepted that wheat has powerful phytase(s), barley less powerful phytase(s) while maize has phytase(s) with little enzyme activity. Williams and Taylor (1985) showed that with a diet free of phytase (maize and soybean flakes) the hydrolysis of phytate in the stomach of rats was very low (5 per cent), but with a wheat-based diet a substantial hydrolysis of phytate occurred (49 per cent), presumably due to the influence of wheat phytase.
Besides being present in the feedstuffs, phytases are produced by the microbial flora in the intestine and are probably also secreted by the intestinal tract, where they are present in the brush border of the small intestine (Spitzer and Phillips, 1945; Davies et al., 1970; Ivey and Shaver, 1977; Davies and Flett, 1978; Cooper and Gowing, 1983; Williams and Taylor, 1985). Also, intestinal alkaline phosphatase can hydrolyze some phytate.

Davies and Flett (1978), and Williams and Taylor (1985) demonstrated in rats that the activities of phytase and alkaline phosphatase were greatest in the duodenum and lowest in the terminal ileum. This was also found in pigs (Pointillart et al., 1984). The latter authors, and also Williams and Taylor (1985), concluded however that intestinal phytase does not seem to be of great significance for the hydrolysis of phytate.
It is known, that in ruminants phytate is hydrolyzed to a large extent by the microflora in the forestomachs, so that also phosphorus from phytate can be very well utilized by these animals. In pigs, some fermentation takes place in the stomach but it is doubtful whether phytate is hydrolyzed by phytases of bacteria present there. In the large intestine, with its rich microbial flora, phytate can be hydrolyzed to a great extent by microbial phytases. However, whether the pig can absorb the phosphorus in the large intestine or not is still uncertain (see Chapter 1.2.1.2.).
Moore and Tyler (1955) and Schulz and Oslage (1972[b]) observed a great variation during the day in phytate content of the faeces. In particular, faeces excreted in the morning contained less phytate than those excreted at other times of the day, probably due to longer retention in the large intestine. The composition in the feed's phosphorus (more or less phytate) does not seem to influence the organic phosphorus content of the faeces, ranging between 15 and 25 per cent of total phosphorus (Gerritse and Zugec, 1977), as also found by Schulz and Oslage (1972[b]).

Factors affecting activity of phytase
Several factors affect the activity of phytase, the most important of which (pH, temperature, duration of incubation, metal ions and vitamin D) are discussed below.
The optimum *pH* for plant phytase is about 5.0 (Hill and Tyler, 1954[c]). At a pH of 2.5 and lower these authors could not detect any plant phytase activity and reported that the enzyme was irreversibly inactivated. So plant phytase can probably not survive the acid conditions in the stomach to resume its activity in the small intestine. The optimum pH for intestinal phytase activity depends on animal species and varies from 7.2 to 8.5 (Spitzer and Phillips, 1945; Davies et al., 1970; Firenzuoli and Zanobini, 1975), while for rabbits and guinea-pigs even higher levels were found (Cooper and Gowing, 1985).
At a pH of 5.1 Hill and Tyler (1954[b]) demonstrated a positive linear relationship between the *incubation temperatures* between 15 and 50°C and plant phytase activity. The optimum temperature for wheat phytase activity was about 55°C. Boiling water destroys the enzyme but it can resist dry heating very well (McCance and Widdowson, 1944; Ranhotra and Loewe, 1975). Sandberg et al. (1986) also observed that extrusion cooking of a bran diet destroyed phytase activity.
In their experiment, Hill and Tyler (1954[b]) found that most of the phytate was hydrolyzed during the first hours of *incubation*. In wheat bran at 37°C 15.8, 27.0, 33.7 and 38.5 mg phytate was hydrolyzed after 2, 4, 6 and 8 hours, respectively. About the same was found by Frape et al. (1979), and Takemasa and Hyikuro (1984) in vitro, and by Schulz and Oslage (1972[b]) in the stomach and small intestine of pigs. It is possible that lack of sufficient substrate is responsible for the lower rate of hydrolysis.
Several *metal ions* affect the activity of phytase, although it is not always clear if it is a direct or an indirect effect (Hill and Tyler, 1954[b]; Nelson, 1967). A high calcium concentration in the diet, and so in the incubation fluid, depresses the activity. An indirect effect of calcium can be explained by the formation of less soluble phytate, but how calcium can directly influence phytase activity is not known. Davies and Flett (1978) showed that in rats, zinc supplemented diets enhanced phytase activity in duodenal mucosal homogenates, while Cooper and Gowing (1983) demonstrated with their in vitro experiments a clear quadratic effect of the concentra-

tions of either $ZnCl_2$ or $MgCl_2$ on the activity of intestinal phytase in rats. Their conclusion is that the activity of intestinal phytase is affected by the same factors as alkaline phosphatase but to a greater degree. In chicks, high dietary levels of calcium and magnesium reduced the activity of intestinal alkaline phosphatase; high phosphorus levels had no effect but low dietary phosphorus levels greatly increased the activity of intestinal alkaline phosphatase (McCuaig and Motzok, 1973; 1974[a,b]).
According to some investigations, the positive effects of *vitamin D* on phytase activity is probably an indirect one, because of its effect on calcium and phosphorus absorption (Taylor, 1965; 1974; Fontaine et al., 1985). Others have established that vitamin D stimulates the activity of intestinal phytase directly (Steenbock et al., 1953; Roberts and Yudkin, 1961). Further information can be found in Chapter 1.4.4.4.

2.8.3.2. Absorption of P and phytate P from single feedstuffs and simple feeds in pigs

General
Using the knowledge given in section 2.8.3.1. a synthesis will now be made about the hydrolysis of phytate in pigs. When the diet for pigs is mixed with water, the pH of the slurry will be between 5.5 and 6.5. So when the food is soaked for some time before feeding, and phytase is present, the hydrolysis of phytate can take place. In practice, soaking is done at environmental temperature, thus far below the optimal temperature for activation of phytase. Therefore, the duration of soaking needs to be long to obtain a large enough effect. Indeed, Frape et al. (1979) observed only a small increase in the absorption of phosphorus in pigs after soaking the meal for 11 hours before feeding. However, Takemasa and Hyikuro (1983[b]; 1984) found in chicks that it was very beneficial to soak barley, wheat or wheat bran for 6 to 20 hours. The difference in effect might be due to drying the soaked feedstuffs at 40°C as described by Takemasa and Hyikuro. Most absorption of phosphorus is from the small intestine, so in view of low pH activating phytase, the activation will take place in the stomach and not in the large intestine (Moore and Tyler, 1955; Kidder and Manners, 1978). Since probably most of the plant phytases are destroyed by the low pH in the stomach, no significant effect of these in the small intestine can be expected. Also, the effect of intestinal phytase and alkaline phosphatase seems small (see also section 2.8.3.1.). In the large intestine, hydrolysis of phytate of bacterial phytases can be considerable, but there is a lot of doubt concerning the possibility of absorption of the released phosphorus (see also Chapter 1.2.1.2.).
In experiments on pigs, Schulz and Oslage (1972[b]), determined the site of the hydrolysis of phytate using Cr_2O_3 as an indigestible marker. When barley was fed, digesta were sampled four and five hours after feeding, but only at four hours after feeding when a feed mixture was fed. Their results indicated that in the stomach the hydrolysis of phytate ranged from 20 to 50 per cent, while in the small intestine, on the whole, hardly any hydrolysis was observed. It is surprising that in their experiment hydrolysis of phytate in the stomach was about the same in the barley and the feed mixture. There were substantial differences in hydrolysis of phytate between barley and feed mixture in the large intestine. This, according to Schulz and Oslage (1972[b]), can be explained by the dietary calcium concentration, because no calcium was added to the barley diet, while the calcium concentration in the feed mixture was 8.8 g/kg T. In another experiment Schulz and Oslage (1972[b]) found that the hydrolysis of phytate in the stomach and small intestine of pigs receiving a feed mixture (6.1 g Ca and 5.1 g P/kg T) was, 3, 6 and 9 hours after feeding, 34, 37 and 42 per cent, respectively. However, determination of phytate in digesta is difficult, so their data may not be correct.

It can be concluded, that the presence of plant phytases and possibly the dietary calcium concentration are important for the rate of hydrolysis of phytate, and that for the absorption of phosphorus from phytate hydrolysis in the stomach seems to be most important.

Absorption of P and phytate P from single feedstuffs and simple feeds.
In practice, general opinion is that only about one third of plant phosphorus can be absorbed by the pig. It is assumed that two thirds is in a hardly absorbable organic form and therefore useless as a phosphorus source. In the following we will see in how far this view is correct.
First we collected data from the literature of studies with feed mixtures of two feedstuffs and with feedstuffs to which no supplementary phosphorus was added, in which the absorption or availability of phosphorus was measured.
In Appendix 3, detailed data are given for the mixtures, and in Appendix 4 they are given for the separate feedstuffs. A summary of these data is given in Table 5.
With regard to the studies with the single feedstuffs, it should be mentioned that different experimental techniques have been applied; where necessary this is also indicated in Appendix 4. It was not possible to correct for the calcium concentration in the diet, because this was often not given. Data about the phytate phosphorus concentration were frequently lacking, so in these cases the values were estimated using the data in Appendix 1. In order to gain some insight on the absorption of phosphorus from phytate, the absorption of inorganic phosphorus has to be estimated and also the faecal endogenous excretion of phosphorus. For this the following assumptions were made and used in the calculations:

a) when 100 per cent absorption (apparent) of the inorganic phosphorus is assumed
b) when 80 per cent absorption of the inorganic phosphorus is assumed
c) similar to b) but with an additional 5 mg faecal endogenous excretion of phosphorus per kg live weight

The figure of 80 per cent for absorption of the inorganic phosphorus from diets not supplemented with inorganic phosphorus was suggested by Günther (1978). The amount of 5 mg faecal endogenous excretion of phosphorus per kg live weight is estimated from the results given in the literature and was further outlined in section 2.8.2. In those experiments where the true absorption of phosphorus was measured (Brüggemann et al., 1962; Guéguen et al., 1968; Vemmer and Oslage, 1973), the data of these authors were used. In Table 5, a summary is given of the absorption percentages of phosphorus from phytate estimated in this way. In most cases, the standard error is high probably due to experimental design, insufficient data on phosphorus and phytate phosphorus content in the feedstuffs and the limited number of observations. More detailed information is also given in Appendices 3 and 4. Some remarks should be made about the calculations. The determination of availability of total phosphorus using the slope ratio technique with monosodium phosphate as a reference, gives a value that is higher than the absorption percentage. It is assumed that phosphorus from monosodium phosphate is 100 per cent available. The data obtained with the slope ratio technique using monosodium phosphate as a reference could be corrected with 0.9, but this was not done in our calculations.

Table 5. Absorption percentage of P and phytate P in diets and feedstuffs (mean and sd)

	absorption % of total P		calculated absorption % of phytate P assumed absorption % of Pi		
diet or feedstuff	n		100	80	80+5mg**
barley + soybean meal	2	34	-18	-8	2
corn + soybean meal	13	30 ± 10	-14 ± 10	-2 ± 12	5 ± 12
corn + rapeseed meal	2	24	6	11	14
sorghum + soybean meal	1	36	-7	6	13
alfalfa	1	100	-	-	-
barley	6*	32 ± 14	-10 ± 20	2 ± 20	12 ± 22
cottonseed	2	21	-13	-4	-3
corn	9	18 ± 9	-23 ± 15	-13 ± 14	-6 ± 15
corn moist (ensiled)	4	47 ± 8	19 ± 12	30 ± 13	35 ± 13
milo	1	25	-7	1	7
oats	2	30	-18	-4	1
palm kernel cake	1	11	-48	-35	-33
peanut meal	1	12	-33	-23	-20
rice bran	1	25	-50	-30	-29
sorghum	2	11	-26	-18	-10
sorghum moist (ensiled)	2	42	18	26	32
soybean meal	6	26 ± 9	-23 ± 15	-9 ± 15	-6 ± 15
wheat	5	48 ± 5	28 ± 8	36 ± 7	40 ± 7
wheat bran/middlings	6	44 ± 10	25 ± 14	32 ± 14	34 ± 14

* value of Vemmer and Oslage is omitted because of extremely high P content in barley

** additionally 5 mg endogenous excretion of P per kg live weight

From Table 5 it can be concluded that the absorption percentage of total phosphorus in most dry feedstuffs is low except for alfalfa, barley, oats, wheat and wheat by-products. Those of corn, cottonseed, palm kernel cake, peanut meal and sorghum are very low.

It is remarkable that so many values for the absorption percentage of phytate are negative. This is probably caused by the assumptions made for the absorption of inorganic phosphorus. As a very high negative effect of phytate on absorption of inorganic phosphorus is not very likely, the assumptions of the last column of Table 5 might be closest to the truth. Ensiling, i.e. permitting phytase to exert its effect, clearly helps. This was also found by Cornelius and Harmon (1974), Abrams et al. (1975), and Trotter and Allee (1979[a]). The phytase for hydrolysis of phytate phosphorus in ensiled corn and sorghum does not come from corn and sorghum itself but probably from microbes which develop during the ensiling process.

The absorption percentages of phytate are also positive for wheat and wheat bran/middlings. This is probably due to the higher activity of phytase in these feeds. In agreement with this are the low figures for corn, usually having a low activity of phytase.

It is surprising that the absorption percentages of total phosphorus in the corn-soybean meal diets of Table 5 are considerably higher than from corn and soybean meal separately. Assuming 18 per cent soybean meal and 79 per cent corn in these diets, then an absorption percentage for phosphorus of 21 can be calculated, whereas percentages of 30 ± 10 were found. When the results of Vipperman et al. (1974) are not taken into account (because of experimental design and low content of soybean meal in the diet) then an absorption percentage for phosphorus of 33 instead of 30 can be calculated.

The difference between the absorption percentage of phosphorus in the complete diet and of the feedstuffs separately gives rise to the question of whether the values measured with the separate feedstuffs are correct or whether, in a complete diet they are additive or not. With regard to corn and soybean meal, phytase cannot be responsible, as in these feeds its activity is low. When wheat or wheat products are present in the diet it might be due to their higher activities of phytase, an aspect which deserves more attention because results of experiments concerning this have not been published.

2.8.3.3. Addition of phytase to a diet

Many fungi, bacteria and yeasts produce phytase. Several studies with chicks have demonstrated that the addition of phytase-producing organisms to the diet can result in a marked improvement in the utilization of phytate phosphorus. Nelson et al. (1968) were the first to add phytase, produced by a culture of Aspergillus ficuum, to soybean meal. The feed was incubated for 2 to 24 hours at 50°C. After drying, it was fed to one day old chicks. The birds showed a considerable increase in bone ash percentage when compared with control animals. In a second experiment (Nelson et al., 1971), a preparation of phytase produced by Aspergillus ficuum was added to a complete diet for chickens (4 g crude phytase per kg diet, which contained 3 800 phytase units per kg diet). The supplemented diet containing 0.30 per cent and 0.18 per cent total and phytate phosphorus respectively, gave the same ash percentage in the tibia as a control diet with an addition of 0.16 per cent phosphorus from disodium phosphate. In a third experiment by Nelson et al. (1971), an addition of 2 800 phytase units per kg diet hydrolyzed all the phytate phosphorus, and a fourth experiment confirmed once more these results. Their conclusion was that the addition of phytase to diets for chicks can improve the absorption of phytate phosphorus.
Encouraging results from added phytase have not yet been reported for pigs. Cromwell and Stahly (1978) performed an experiment in which a dried live yeast culture of Saccharomyces cerevisiae was added to a corn-soybean meal diet for pigs (15 g/kg). It was concluded that the yeast culture probably did not improve the availability of phytate phosphorus because performance and bone strength were not influenced. Chapple et al. (1979[b]) concuded the same from the results of an experiment with 2 per cent live yeast culture in a diet for growing pigs; only performance was the criterion. However, an improvement in growth rate was observed in another experiment with pigs from 65 to 100 kg live weight. Shurson et al. (1984) were also unable to improve phytate phosphorus utilization by including a yeast phytase in the diet in balance studies and feeding trials with piglets. The reason for the failures of added phytase to pig diets is not clear.
New technology in genetic engineering offers hope for producing additives with high phytase activity. Adding these to the diet might result in much greater usage of the phosphorus from plant feedstuffs which, at present, is being wasted.

2.8.4. Phosphorus from inorganic phosphorus sources

In pig feeding, the basal diet, mainly composed of various feedstuffs, does not usually contain enough phosphorus to meet the pig's requirement for this element. Therefore, the basal diet is supplied with phosphorus from inorganic origin. A wide variety of phosphorus sources is available for supplementation. Which phosphorus source is most suitable for pigs, also from the economic point of view and the presence and content of undesirable contaminants, is still under discussion.
In many experiments on pigs, different phosphorus sources were compared

with regard to their value in satisfying phosphorus requirements. In these experiments, not always the same criteria are used on which conclusions were based, sometimes leading to differences in interpretation (Mulder and Jongbloed, 1983).
Bones are often used in order to evaluate the phosphorus sources, but the choice of bone is not clear. Early experiments by Evans (1930) showed that from weaning to about 35 kg live weight, due to a higher calcium supply, the amount of dry weight of the carpal and tarsal bones, femur, tibia fibula and patella increased the least when compared with other bones.
Günther's group extensively studied the effect of different mineral supplies on various bones (Günther et al., 1966/1967; 1967/1968; Günther and Rosin, 1970/1971). Most of the effect of the mineral concentration in the diet for pigs from 21 to 56 days old was noted on the femur, tibia, ribs, vertebrae, sternum, carpals and tarsals. The bones of the head and shoulder were relatively independent of the mineral content of the diets. Between these two groups of bones were the pelvis, humerus, radius and ulna placed. In pigs from 20 to 100 kg live weight the greatest relative increase in ash was noted in the scapula and carpals.
Recently, comparisons between several bones (femur, humerus, third and fourth metatarsal and metacarpal bones) have been made in order to evaluate the response to dietary phosphorus supply (Koch et al., 1984; Koch and Mahan, 1985; 1986). They concluded that metacarpal and metatarsal bones were to preferred, and that the metacarpals gave a slightly better response than the metatarsals.
Friedel et al. (1973) and Gabel et al. (1974[a,b]) showed, using a radiological and photometric technique, that bone ash determination of the fifth tail vertebra could be used for controlling the mineral supply of slaughter pigs and breeding sows. They also demonstrated that the tail vertebra was very sensitive in indicating differences in mineral supply. In their experiment on new-born piglets, however, they showed that the amount of ash in the front and hind legs was more affected by the mineral supply of the sows than the tail vertebra (Friedel et al., 1973).
There are several factors which can affect the results. In an excellent review, in 1961, Guéguen discussed these factors, which will be only briefly mentioned here. First, the factors related to the animal (species, physiological state), then those related to the composition of the diet (amount of phosphorus intake, Ca/P ratio, vitamin D) and later different aspects related to the phosphorus source (fineness, concentration of other elements, crystallinity, the presence as anion or cation).
To give some idea of the complexity of these factors, some results of the work done by Huyghebaert et al. (1980; 1981) can be mentioned. They found that for chicks a Na/Cl ratio of 1:3 decreased the availability of phosphorus when compared with a ratio of 1:1. However, at different concentrations of fluorine the effect of the Na/Cl ratio altered completely.
When considering the phosphorus sources, one should be aware of differences between batches, as shown by Latimier et al. (1982), while also in the work done by Waibel et al. (1984) on turkeys and by Huyghebaert et al. (1980) on chickens, it was shown that there is a wide range in bioavailability of various dicalcium phosphates and defluorinated phosphates.
In Appendix 5 a survey of the results with phosphorus sources, mostly in feeding experiments, with pigs is given. For each criterion measured, the ranking order is stated. It can be seen that there are substantial differences in ranking order, even in the same experiment, depending on the criterion chosen. In most experiments, it seems clear that soft phosphate ($Ca_5(PO_4)_3F$) is one of the less well utilized phosphorus sources. However, in the majority of experiments, no significant differences between the various phosphorus sources could be shown. Growth rate and feed conversion ratio do not seem to be very sensitive criteria, while bone ash percentage and bone breaking strength appear to be more sensitive (Koch et al., 1984;

Koch and Mahan, 1985). It is suggested that serum mineral concentrations and also alkaline phosphatase activity are good indicators (Wise et al., 1961; Boyd et al., 1981; 1983; Koch et al., 1984; Koch and Mahan, 1985), but Koch and Mahan (1986) came to the conclusion that this is not the case for pigs over 60 kg live weight.

Günther (1966) found that the availability of phosphorus from primary, secondary and tertiary phosphate decreased in that order for rats and chicks and probably also for pigs. The order quoted is said to be due to their intermediary hydrolysis equilibrium and so the buffer system between acids and bases. He developed the so-called "Transponierungstest". In his experiments the phosphorus source is given to piglets from 21 to 56 days old and, using Röntgenphotos, the area of the epiphysial plate of the tibia is measured. The smaller the area, the better the phosphorus source should be. In the final evaluation, besides the "Transponierungstest", the growth rate of the piglets is also taken into account. Whether or not the results obtained with piglets can also be used for older slaughter pigs is uncertain, because the acid secretion in the stomach of piglets up to five weeks is not optimal (Cranwell, 1978). An indication for that was found by Grimbergen et al. (1985) who observed a higher absorption percentage for phosphorus from dicalcium phosphate in older pigs than in younger ones of 6 to 10 kg.

After the promising results with poultry, the slope ratio technique has recently also been introduced in pigs to assess the availability of phosphorus (Cromwell, 1983). In these experiments, monosodium phosphate is mainly used as the reference and the availability of phosphorus is assumed to be 100 per cent. In most experiments, the criterion is the bone breaking strength or bone ash percentage. Taking digestibility of phosphorus as the criterion, Grimbergen et al. (1985) found, in pigs, evidence of a somewhat better availability of phosphorus from hydrated dicalcium phosphate than from non-hydrated dicalcium phosphate. They also applied the slope ratio technique. Furthermore, they found that monocalcium phosphate was more readily available than the dicalcium phosphate.

Due to the difficulties of finding good animal criteria there have been many attempts to determine the availability of phosphorus from phosphorus sources using chemical methods (Wicke, 1972; Guéguen, 1977, Jensen et al., 1977; Huyghebaert et al., 1980). However, the problem still remains; what criterion on the target animal with which it should be compared. It appears that solubility in water and the solubility of phosphorus in ammonium citrate are not good indicators of the availability of phosphorus for pigs. The solubility of phosphorus in diluted hydrochloric acid might be more valuable (Guéguen, 1977); however, calcium pyrophosphate is, for 97 per cent, soluble in 0.4 per cent HCl but its availability to chicks and pigs is low. Guéguen (1977) proposed a method in which first the solubility of the phosphate in water is determined followed by extraction with a 2 per cent citric acid solution. This method was applied for sheep, but whether it is also suitable for pigs is not yet known. In chicks, however, Yoshida et al. (1979) found a high correlation between solubility in 0.5 per cent citric acid and the biological availability of phosphorus in various inorganic phosphorus sources.

Jensen et al. (1977) proposed dissolving the phosphorus sources at 37°C and pH 2.7 in a pH stat, an apparatus in which the pH is kept constant and the hydrogen ion is the only acid neutralizing the phosphate ion coming into solution. In this method, the solution curves are determined and the solution rate can be calculated at any given time. However, the results obtained by this method have not yet been compared with data on phosphorus availability from studies with animals.

2.8.5. *Conclusion*

The endogenous faecal phosphorus excretion seems to depend upon the amount of phosphorus supplied in relation to the phosphorus requirement. At low phosphorus intake levels, the endogenous faecal phosphorus excretion is about 5 mg/kg live weight/d, but under normal feeding conditions it amounts to about 10 mg/kg/d.
From the literature concerning phytate phosphorus, it can be concluded that the pH and probably the concentration of calcium are important factors in the hydrolysis of phytate by phytase. For pigs, the stomach seems to be the principal place for the hydrolysis of phytate so that its phosphorus can be utilized. Intestinal phytase does not play an important role, while it is doubtful whether, in the large intestine, much hydrolyzed phytate phosphorus can be utilized. In feedstuffs containing a substantial amount of phytase, some of the phytate phosphorus can be utilized by pigs (a.o. wheat). More attention should be paid to differences in the absorption percentage of total phosphorus among feedstuffs. More work should be done to investigate the effect of microbial phytases added to the diets of pigs. With regard to inorganic phosphorus sources, a good comparison is only possible if more standardization in criteria and methods is applied. It is not certain whether results obtained with chicks can also be applied to pigs and, furthermore, it is doubtful whether results with piglets can be compared with those of older pigs. The use of chemical methods in vitro should be stimulated. A further chemical analysis and determination of the structure of the phosphates might be helpful in explaining the differences in availability of inorganic phosphorus. Results of in vitro methods should always be checked with studies on animals.

2.9. SODIUM AND POTASSIUM

In Chapter 1.2.2.1. it is clearly shown that sodium is required for the transport of phosphorus through the intestinal wall and tubule cells of the kidney. At a low dietary concentration of sodium, therefore, the phosphorus absorption is decreased (McHardy and Parsons, 1956; Harrison and Harrison, 1961; Taylor, 1974; Lee et al., 1986). In chicks, significant effects of the level of sodium in the diet on phosphorus absorption and retention have been demonstrated (McCuaig and Motzok, 1974[b]; Huyghebaert et al., 1981; Simons, 1985). In his experiments with chickens, Simons (1985) showed that 0.30 per cent sodium in a diet containing 1.40 per cent potassium drastically reduced performance when compared with 0.17 per cent sodium, suggesting an interaction between sodium and potassium. Huyghebaert et al. (1981) showed that the Na/Cl ratio in the diet is important for the utilization of phosphorus in chicks, which might be explained by the acid-base balance ($Na^+ + K^+ - Cl^-$).
The only report on the effect of sodium on phosphorus absorption in pigs is given by Partridge (1978[b]). He observed a somewhat lower absorption for phosphorus at 0.27 per cent sodium in the diet than at 0.09 per cent sodium anterior to the terminal ileum; no data were given based on faecal collection.
To date, there is hardly any information available concerning potassium and phosphorus availability. Results of experiments by Harrison and Harrison (1961) indicated that more potassium in the medium enhanced the transport of phosphorus in everted loops of the rat gut. Also, Suttle and Field (1967) observed an enhanced phosphorus absorption in sheep when more potassium was given. It is not known, however, whether the retention of phosphorus was also higher.

2.10. DIETARY ACIDITY AND ACID-BASE BALANCE

According to Hays and Swenson (1984), absorption of phosphorus and calcium is facilitated by a low intestinal pH which increases their solubility. Lee et al. (1986), with in vitro studies on rat jejunum, also demonstrated that when the pH was dropped from 7.4 to 6.0 the phosphorus influx was markedly increased. Thus, normal gastric secretion of hydrochloric acid or hydrogen ion concentration is necessary for efficient absorption. The low pH of the duodenum accounts for the greater absorption in that part of the small intestine compared with more distal parts. This view is supported by Cramer (1972), who concluded from his experiments on rats that the pH only affected phosphorus absorption to a limited extent. A contrasting view is held by McHardy and Parsons (1956) who observed a markedly elevated phosphorus absorption in ligated guts of rats with a decreasing hydrogen concentration in the pH range of 4.4 to 7.9. Chow et al. (1972) also demonstrated that NH_4Cl, which has a lowering effect on the pH of the medium, inhibited the absorption of phosphorus in ligated duodenal loops of chicks. In their experiments on rats, which were given 2 per cent NH_4Cl in the diet, Newell and Beauchene (1975) showed significant increases in urinary phosphorus and calcium excretion, depressed serum phosphorus and calcium levels, but a reduction of minerals in the tibia was not observed. Unfortunately they did not measure the phosphorus balance to show a possibly enhanced phosphorus absorption due to NH_4Cl in the diet. These authors suggested that rats can adapt to an acid load and maintain acid-base balance without loss of minerals from the skeleton. Goulding et al. (1984) worked with $NaHCO_3$ which tends to increase the pH. They found in rats which got 4.5 mmol $NaHCO_3$ per day, less phosphorus in the faeces, more phosphorus excreted in the urine, but no effect on the phosphorus balance. However, Gafter et al. (1983) demonstrated that $NaHCO_3$ depressed duodenal absorption of labelled phosphorus.

Little is known about the effect of changing the acid-base balance on phosphorus absorption and retention in pigs. Some work has been done on chickens in this field where it was shown by Mongin (1981) that the $Na^+ + K^+ - Cl^-$ balance should be close to 25 meq/100 g diet to get maximal phosphorus retention. This author stated that for the acid-base balance the divalent ions Ca^{++} and Mg^{++} should also be taken into account. In pigs of 48 to 58 kg, Scott (1971) found that when 200 mmol NH_4Cl per day was given there was little or no increase of phosphorus excretion in the urine, even supplying extra $NaHCO_3$ had hardly any effect. A reduction in faecal excretion of phosphorus due to acidosis (with NH_4Cl) was not observed. In an experiment by Jambor and Prochazka (1977), however, a negative effect of acidosis on phosphorus retention in pigs was observed.

Information on the effect of pH and acid-base balance on absorption and retention of phosphorus is often contradictory. However, in most cases the effects appear to be small, but for getting a better insight some experiments might be done.

2.11. TRACE ELEMENTS

2.11.1. Introduction

It is obvious that lack of essential trace elements in the diet will cause deficiency symptoms and so also affect the absorption and retention of phosphorus in the animal. This has been demonstrated in several experiments. In any case, at least a certain amount of all essential trace elements should be included in the diet so that the requirements for these are met. If somewhat more than the requirement is given no clear negative effects on the absorption and retention are to be expected.

The elements copper, zinc and iron are usually supplemented to pig diets in

considerable concentrations, usually more than the requirement, so these elements could interfere with phytic acid and inorganic phosphate resulting in insoluble phosphorus-containing salts. Such salts might also be formed at a higher aluminium content. Therefore, the effect of these elements on phosphorus absorption and retention will be discussed in more detail. Also, some attention will be paid to fluorine because of its effect on bone formation.
No information is available in the literature concerning the effect of other trace elements, such as manganese or cobalt on the phosphorus balance.

2.11.2. Copper

Since about 1960, in most European countries, 100 to 250 ppm copper is added to the diet of slaughter pigs because of its favourable effect on growth rate and feed conversion ratio. Some research workers have studied the effect of the copper level in the diet on the mineral balances.
In their experiments on pigs (17 and 32 kg), Kirchgessner et al. (1963) fed diets with or without 125 and 250 ppm copper as $CuSO_4.5H_2O$. Balance experiments indicated that the absorption of calcium, phosphorus and magnesium was somewhat higher at 250 ppm copper than in the diet without copper supplementation, while 125 ppm copper gave an intermediate effect. The excretion of phosphorus and magnesium in the urine at the highest copper application was higher than with the diet without copper supplementation. There was, therefore, hardly any difference in mineral retention. A higher urinary excretion of phosphorus was also found by Galik (1971), who calculated a significant positive correlation between the copper concentration in the diet and the phosphorus excretion in the urine. Again phosphorus retention was not significantly affected.
The shift from faecal to urinary excretion of phosphorus might be caused by the higher acidity of the diet due to the sulphate-ion. Phosphorus retention however does not seem to alter much.

2.11.3. Zinc

It is known that there is some antagonism between calcium and zinc in the intestinal tract, which might also indirectly affect the utilization of phosphorus. When Whiting and Bezeau (1958) fed diets with 34 or 140 ppm zinc to pigs, they found at 0.45 and 0.92 per cent calcium in the dry matter, a higher absorption and retention for calcium at the higher zinc level, but no influence was found on phosphorus utilization. In the experiments done by Berry et al. (1961) and Morgan et al. (1969), the effect of 28 and about 102 ppm zinc on the phosphorus and calcium balance was studied at two levels of calcium. In the first experiment the diets contained 0.66 per cent and 1.32 per cent calcium with 0.61 per cent phosphorus in the dry matter, in the second it was 0.57 per cent and 1.55 per cent calcium with 0.72 per cent phosphorus. With the low calcium diet, extra zinc gave a higher absorption and retention for calcium and a somewhat higher absorption and retention for phosphorus. In the high calcium diet, extra zinc hardly altered the phosphorus and calcium retention. In another experiment, the effect of 50, 70 and 90 ppm zinc in the diet on the calcium, magnesium and phosphorus balance was studied (Kirchgessner and Oelschläger, 1961). These authors found that the higher zinc concentrations gave a lower absorption and retention for calcium, magnesium and phosphorus, while the urinary excretion of calcium was somewhat lower. Galik (1983) performed balance trials on pigs (22 kg live weight), that had been given diets with 25, 50 or 100 mg zinc per kg feed (71, 99 and 154 mg Zn/kg T respectively; 8.9 g calcium and 5.1 g phosphorus/kg T). He observed a positive effect of the zinc concentration on the retention of phosphorus and calcium.

When the results of the experiments mentioned here are compared, we can conclude that at a calcium concentration of 0.45 to about 0.65 per cent in the dry matter, raising the zinc concentration from about 30 to 80 ppm and higher, the absorption and retention of calcium and, in most cases, also that of phosphorus, is raised. At higher calcium concentrations, raising the zinc concentration from 30 to 80 ppm and higher, has little effect on the phosphorus and calcium balance. From the data of Kirchgessner and Oelschläger (1961), it seems that 60 ppm zinc results in an optimal phosphorus and calcium balance and that a zinc concentration of about 30 ppm, which was used in the other experiments, might be too low to meet the zinc requirement and, therefore, results in a lower phosphorus and calcium balance.

2.11.4. Iron

In experiments on rats 0.1 and 0.3 per cent iron (as $FeSO_4$) was added to a diet with 0.26 per cent phosphorus for five weeks. As a result of the addition of iron, weight gain and bone ash, as a percentage of the fat-free dry femur, were considerably reduced, which was partially, but not completely, overcome by additional dietary phosphorus (Arrington et al., 1968). The lower weight gain and bone ash percentage were also found in the experiments done by Harmon et al.(1968), who worked with concentrations of iron from 38 to 4 510 ppm (as $FeSO_4$) in rats. The mineral balances showed that with increased iron concentrations in the diet, faecal phosphorus excretion increased, urinary phosphorus loss was reduced and less phosphorus was retained. Also, in chickens, 800 instead of 189 mg iron per kg diet reduced the ash and phosphorus content in the tibia (Findrik and Roset, 1971).
In experiments on young pigs, O'Donovan et al. (1963) found that a high concentration of iron in the diet was more toxic at low than at high levels of phosphorus in the diet. This was confirmed by an experiment done by Furugouri (1972) who found a decreased bone ash percentage and phosphorus deficiency symptoms at 5 000 ppm iron added as $FeSO_4$.
Iron presumably interacts by precipitating the phosphorus as an insoluble phosphate within the intestinal tract. Only the more soluble iron sources are capable of impeding phosphorus utilization, as shown by Alsmeyer et al. (1963).

2.11.5. Aluminium

Aluminium interferes in the same way with phosphorus as iron does. This was shown in experiments on rats, where 0.1 and 0.3 per cent aluminium as $AlCl_3.6H_2O$ was added to a diet with 0.26 per cent phosphorus for five weeks (Arrington et al., 1968). The weight gain and bone ash were considerably reduced, which was partly overcome by additional dietary phosphorus. The same has been reported by Findrik and Roset (1971), whose work was done on chickens. Also using pigs, Guéguen and Rérat (1965) showed that aluminium-iron phosphates had a low availability of phosphorus.

2.11.6. Fluorine

Fluorine is an important element in the formation of bones and teeth and might, therefore, interact with phosphorus and calcium utilization. The reports on the effect of fluorine on phosphorus and calcium utilization, however, are conflicting. At low levels, fluorine seems to have a beneficial effect on bone. Both stimulation of bone formation and increased bone resorption are effects of fluorine at higher levels of intake (Ramberg et al., 1970; Forsyth et al., 1972[a,b]). In their experiments, high concentrations of fluorine, 450 ppm, caused shorter and thicker bones. At levels of

250 and 500 ppm fluorine, Huyghebaert et al. (1981) found a slight inhibition of the organic bone mass growth, a considerable decline in bone strength but an increase in bone ash percentage in broiler chicks. It is recommended for pigs that the content of F (as fluorine) in the diet should not exceed 220 mg/kg (A.R.C., 1981). Some phosphorus sources contain a considerable amount of fluorine, so that such a content might be exceeded if no attention is paid to the kind of phosphorus source added.

2.11.7. Conclusion

With regard to trace elements, it can be concluded that the absorption and retention of phosphorus will hardly be affected by variations in the concentrations of these elements in the diet. Only at dietary concentrations of these elements lower than the requirement, or when the requirement for these elements is far exceeded, may a negative effect on the absorption and retention of phosphorus be obtained. This happens if severe mistakes are made when mixing the premixes in the diets. In practice, copper, zinc and iron are added to the diets of pigs, usually as sulphates. The amounts of these elements added to the diet are from 10 to 160, from 100 to 150 and from 50 to 80 mg/kg, respectively. Aluminium and fluorine are not added to the diets of pigs but may be present as contaminants.

2.12. VITAMINS

Vitamins should be given in adequate amounts with the diet because hypo- or hypervitaminosis affect various aspects of phosphorus metabolism in the animal. This was shown by Kirchgessner et al. (1962) in experiments on pigs, where 45, 99 and 198 μg vitamin B_6/kg body weight was fed (in practical diets for pigs usually 700μg/kg is added). The lowest level of vitamin B6 resulted in a lower absorption and retention of phosphorus. Irving(1973) found in the absence of vitamin A, involved in bone formation, that the action of osteoblasts became uncontrolled. Also, in hypervitaminosis A, abnormalities occur: bone formation ceases, possibly due to suppression of osteoblast activity, while bone resorption continues in a normal way. Experiments on broiler chickens showed that hydrolysis of phytate phosphorus was higher on diets with 5 000 IU vitamin A/kg than at 100 000 IU vitamin A/kg (Teunis and Versteegh, 1982). Also, an interaction between the levels of vitamin A and D in the diet was observed; no negative effect of the high level of vitamin A could be demonstrated, when the level of vitamin D in the diet was raised from 1 000 to 30 000 IU/kg. The role of vitamin D in phosphorus absorption and retention is reviewed in Chapter 1.4.4.

2.13. ANTIBIOTICS

The bacterial flora in the digestive tract can affect the utilization of various minerals; the hydrolysis of phytate by bacterial phytases being the most typical example. Application of antibiotics might reduce the bacterial population as a whole or some strains of it; the effect of this is not immediately clear. If the strains producing phytases are reduced in number, a negative effect would be expected. However, the microbes competing with those producing phytases may also be harmed by the antibiotic, so that more phytases might be made. Some authors, in experiments on rats and chickens, have sometimes found an improvement in the intestinal absorption of phosphorus when oral administration of antibiotics was given (see i.e. Guéguen, 1976). Recent experiments by Boisen et al. (1984) on rats have shown that the antibioticum, Nebacitin, increased the absorption of phosphorus.
When 33 mg chlortetracycline per kg diet was given to pigs, Kirchgessner et al. (1960[5]) observed some improvement in the retention of phosphorus at 42 kg live weight, but not at 62 or 82 kg. The excretion of phosphorus in the

urine was lower when the antibioticum was given. In their paper, the Ca/P ratio of the retention differed considerably from 1.6:1 so that their experiment must be regarded with some caution. In an experiment on pigs, Bauer et al. (1978) reported no effect of the growth promotor, Nitrovin, on phosphorus retention except at 70 kg, where an improvement in absorption and retention was found. The experiments of Moore et al. (1986) showed that the addition of 82 mg Salomycine per kg diet resulted, in three different diets, almost always to a significant increase in the absorption of phosphorus, but phosphorus retention was not affected due to an increase in the excretion of phosphorus in the urine. The higher absorption was explained by these authors as an enhancement of phytate degradation. From most of these results, it would appear that if the application of antibiotics improves conditions for bacterial strains that produce phytases, some improvement of absorption and retention of phosphorus may be induced.

2.14. CONCLUSIONS

It has been shown that at a higher level of feeding there is a slight tendency towards a lower retention percentage of phosphorus.
A higher protein concentration in the diet results in a higher excretion of calcium in the urine and, due to a stimulating effect on growth rate, a higher absorption and retention of phosphorus and calcium can also be observed.
The addition of fat to diets has little or no positive effect on the absorption of phosphorus. The effect is often confounded with a change in the mineral content of the diet and in the composition of the fat. Fibre may sometimes have a slightly negative effect on phosphorus absorption. The results are conflicting with regard to the component responsible for the possible negative effect. Factors which might cause this negative effect were discussed.
The calcium concentration and the Ca/P ratio of the diet have a significant effect on phosphorus absorption and retention. It was calculated that an increase in dietary calcium concentration by 0.1 per cent, results in a decrease in the absorption percentage of phosphorus by 1 percentage unit. Levels above 0.9 per cent calcium in the diet also depress phosphorus retention. Calculations concerning the optimal Ca/P ratio for a maximal phosphorus retention percentage reveal a higher level than that recommended for swine, based on feeding trials. No satisfactory relationship between dietary calcium and inorganic phosphorus could be derived to predict the highest phosphorus utilization. No clear conclusion can be drawn concerning the effect of ordinary magnesium concentrations of the diet on phosphorus absorption. At higher levels of magnesium, less phosphorus is excreted in the urine.
The endogenous faecal phosphorus excretion seems to depend upon the amount of phosphorus supplied in relation to the phosphorus requirement. At low phosphorus intake levels, the endogenous faecal phosphorus excretion is about 5 mg/kg live weight/d, but under normal feeding conditions it amounts to about 10 mg/kg/d.
Phytate phosphorus must be hydrolyzed by the enzyme, phytase, before absorption of phosphorus from phytate can take place. In pigs, the stomach seems to be the principal place for the hydrolysis of phytate, with regard to the absorption of phytate phosphorus. It is shown, that in feedstuffs with high phytase activity, some of the phytate phosphorus is hydrolyzed and absorbed by the pig (e.g. wheat). Due to the variation in phytase and phytate concentration, there is a large variation in phosphorus absorption percentage between feedstuffs. More effort could be made to improve the phosphorus absorption by studying the effect of supplementary microbial phytase in pig diets.

Comparing inorganic phosphorus sources with regard to phosphorus supply to the pig is hampered by the lack of standardization of methods and criteria. The use of chemical methods should be stimulated.
The effects of sodium and potassium on phosphorus absorption and retention cannot be considered apart from the acid-base balance. Experimental data on pigs are lacking, but research on chicks suggests that more attention should be paid to this acid-base aspect.
Essential trace elements and vitamins should be offered in sufficient quantities, otherwise phosphorus absorption and retention might be negatively influenced, often indirectly by retarded growth. At excessive amounts of iron, aluminium and fluorine, the absorption and retention of phosphorus is depressed. The addition of antibiotics to pig diets results in little, if any, positive effect on phosphorus absorption. The positive effect may be due to their stimulatory effect on growth rate.

3. EFFECT OF PROCESSING FEEDS AND OF ENVIRONMENTAL TEMPERATURE ON ABSORPTION AND RETENTION OF PHOSPHORUS

3.1. INTRODUCTION

This chapter deals with the effect of processing a diet or feedstuff on absorption and retention of phosphorus. Several technological treatments (e.g. pelleting, extruding) can be applied to diets nowadays that might affect the availability of phosphorus. The influence of soaking will also be considered.
Unfortunately, although the environmental temperature in pigsties can very considerably and affect the performance of pigs, hardly any information is available about how it influences phosphorus metabolism.
Animal effects are discussed in subsequent chapters, because it is more appropriate to consider this subject while discussing phosphorus requirements.

3.2. EFFECT OF PROCESSING DIETS OR FEEDSTUFFS

3.2.1. In vitro experiments, and experiments on chicks

O'Dell (1962) found that autoclaving isolated soybean meal, markedly increased the content of inorganic phosphorus. Lease (1966) observed the same with sesame meal, although the change was not as great as that found by O'Dell. Summers et al. (1967) autoclaved four wheat by-products and found that the concentration of phytate phosphorus decreased with time of exposure. Extrusion cooking of a high-fibre cereal diet, had a slight negative effect on the availablity of phosphorus to humans: it did not change the phytate phosphorus concentration but lowered phytase activity (Kivistö et al., 1986; Sandberg et al., 1986).
In experiments on chicks, Summers et al. (1967) found an increase in the availability of phosphorus from steam-pelleting a diet containing 25 per cent wheat bran. In a second experiment, however, steam-pelleting or dry pelleting wheat bran had no effect (Summers et al., 1968). When compared with extrusion cooking, phytase activity does not seem to be destroyed by steam-pelleting which might be explained by the shorter time of exposure. In another experiment done by the same group, steam-pelleting a corn-soybean meal diet or a corn-wheat bran-soybean meal diet enhanced the bone ash content in chickens and thus a higher availability of phosphorus was achieved. It was surprising that pelleting the corn or soybean meal separately had no effect on growth or bone development (Bayley et al., 1968).
In more recent experiments on chicks, no advantage of steam-pelleting on phosphorus availability is reported. Corley et al. (1979) found no improvement in the availability of phosphorus from steam-pelleting rice bran or wheat bran, and neither did Takemasa and Hyikuro (1983[a]) from dry or steam-pelleting a corn-soybean meal diet. Harrold et al. (1982) even reported a reduction in phosphorus availability due to pelleting either barley, oats, corn or soybean meal separately.

3.2.2. Experiments on pigs

The promising results of the early experiments of steam-pelleting diets for chicks, led to an experiment using pigs (Bayley and Thomson, 1969). The basal diet in their experiment was composed of corn and soybean meal. Later, a second experiment was done (Bayley et al., 1975[a]). The main results of both experiments are given in Table 6.

Table 6. Effect of steam-pelleting and dietary composition on performance and P absorption percentage in pigs

in diet (g/kg) Ca	P	added P (g/kg)	pelleted or meal	feed intake (kg/d)	growth rate (g/d)	feed conv. ratio	ash% bone (ffdm)	breaking strength (kg)	abs% of P	reference
9.0	3.5	-	meal	2.09	595	3.52	55.4	-	19	a
9.0	3.5	-	pelleted	2.15	706	3.04	58.0	-	29	"
8.9	5.6	2.4	meal	2.40	785	3.06	61.6	-	33	"
8.9	5.6	2.4	pelleted	2.24	828	2.71	61.3	-	29	"
6.2	3.1	-	meal	1.94	590	3.29	55.9	364	30	b
6.2	3.1	-	pelleted	1.75	720	2.43	54.1	345	41	"
9.7	3.4	-	meal	1.87	633	2.96	54.7	382	43	"
9.7	3.4	-	pelleted	1.83	583	3.12	56.9	384	44	"
6.3	4.7	1.6	meal	2.40	903	2.65	61.7	672	46	"
6.3	4.7	1.6	pelleted	2.21	913	2.42	61.0	641	55	"
9.2	4.6	1.6	meal	2.36	847	2.79	62.2	672	43	"
9.2	4.6	1.6	pelleted	2.00	843	2.37	60.7	670	42	"

a = Bayley and Thomson (1969)
b = Bayley et al. (1975[a])

From Table 6 it can be concluded that in the first experiment, steam-pelleting the diet not supplemented with phosphorus resulted in a higher absorption percentage of phosphorus, but not in the supplemented diet. Also, the performance and bone data were better due to pelleting the non-supplemented diet. In the second experiment at 0.62 per cent calcium, pelleting resulted in a higher absorption percentage of phosphorus for both the non-supplemented and supplemented diets, but no improvement was seen at a calcium concentration in the diet of 0.92 or 0.97 per cent. The higher absorption percentage of phosphorus due to pelleting is, however, not supported by better bone data. This could be due to more phosphorus being offered than required. Also, Harmon et al. (1970) could not find any differences in the ash percentage of some bones in either non-supplemented or supplemented corn-soybean meal diets due to pelleting.
Trotter and Allee (1979[b]) evaluated the effect of steam-pelleting and extruding on the absorption percentage of phosphorus. In their experiments, they used two phosphorus levels (none or 0.12 per cent added P) at a calcium concentration of 0.60 per cent. From performance, bone measurements and balance studies they concluded that pelleting or extruding a sorghum-soybean meal diet slightly increased the absorption percentage of phosphorus for pigs, when the diet was not supplemented with phosphorus.
Ross et al. (1983) studied the effect of pelleting and reconstituting corn on the availability of phosphorus. They found that pelleting gave no improvement and that reconstituting improved the availability of phosphorus from 16 to 25 per cent in the first experiment and from 18 to 26 per cent in the second. No information was given about the effect on performance.

3.2.3. Soaking a diet in water

It has already been discussed in Chapters 2.8.3.1. and 2.8.3.2. that soaking a diet gives the opportunity for phytase to hydrolyze phytate and thus enhance the absorption percentage of phosphorus.
Takemasa and Hyikuro (1983[b]; 1984) used chickens to study the effect of soaking in water in more detail. In their first experiment, three types of barley were soaked for 16 hours at room temperature (16 to 20°C) after which time the batches were dried in a forced-draft oven at 40°C. Analysis

showed that soaking had hydrolyzed 35 to 59 per cent of the phytate phosphorus to inorganic phosphorus. Feeding soaked barley improved performance and tibia ash content as much as an addition of 0.05 to 0.07 per cent P from monocalcium phosphate to the unsoaked diet. In their second experiment, wheat was soaked for 6 and 20 hours and wheat bran for 20 hours after which time the batches were dried at 40°C. In wheat, total phosphorus contained 71, 48 and 36 per cent phytate phosphorus after 0, 6 and 20 hours of soaking, respectively. As in the first experiment, performance and ash content of the tibia were improved. However, some of the improvement by soaking could be due to drying the soaked material at 40°C.
For pigs, Frape et al. (1979) showed that soaking wheat bran for 11 hours before feeding, slightly increased the absorption percentage of phosphorus in one experiment, but not in the other. Unfortunately, more data about the effect of soaking on the absorption of phosphorus for pigs not been reported.

3.3. ENVIRONMENTAL TEMPERATURE

In some experiments, it has been shown that exceptional environmental temperatures can influence calcium and phosphorus absorption and retention. Brown and Hacker (1974) found that when pigs were kept at 2 or 20°C for 80 days, exposure to cold resulted in increased calcium and phosphorus excretion in the urine. This might be due to the lower growth rate (250 vs 500 g/d) and the much worse feed conversion ratio (3.6 vs 2.1) at 2°C.
Examination of bone data showed that the bone matrix from cold, stressed animals had a composition similar to that of younger animals, suggesting that ageing may have been retarded. Therefore, calcium and phosphorus in the diet could not be utilized and was thus excreted. In their experiment on pigs from 20 to 70 kg, Holmes and Grace (1975) noticed that more calcium, and a tendency for more phosphorus, was excreted in the urine at 33°C when compared with 25°C, but no significant effect on the daily retention was found.
Lack of sufficient information makes it impossible to say any more about the effect of the environmental temperature on phosphorus absorption and retention.

3.4. CONCLUSIONS

Although in less recent research a positive effect of (steam) pelleting on the absorption percentage of phosphorus is often found, in more recent research no positive effect on phosphorus absorption is observed. The effect on phosphorus absorption of pelleting, may depend on the dietary calcium concentration, the feedstuffs used, the amount of supplemented inorganic phosphorus and possibly the conditions during the pelleting process. In experiments on pigs, a negative effect on the phosphorus absorption due to pelleting has not yet been reported. The cause for the higher absorption percentage of phosphorus due to pelleting is not given in the mentioned papers.
There are too few observations to be able to draw conclusions about the effect of extruding and reconstituting on the absorption of phosphorus. The effect on phosphorus absorption of soaking the diet in water merits more attention in pigs, as can be concluded from the positive results on chicks; these are probably due to phytase activity.
Clear conclusions of the effect on phosphorus absorption and retention due to different environmental temperatures cannot be drawn, but there may be indirect effects due to low rate of growth at low temperatures and also at high temperatures if these reduce the intake.

4. THE RETENTION AND CONTENT OF PHOSPHORUS AND CALCIUM IN GROWING PIGS

4.1. INTRODUCTION

In this chapter, the amount of phoshorus and calcium retained in growing pigs is discussed. First, factors which affect the total amounts of phosphorus and calcium in the bodies of pigs are described. Then the results obtained with balance experiments are reviewed and, at the same time, attention is also given to the course of the absorption and retention during the growing period. Instead of measuring total retention of phosphorus and calcium in the body from intake and retention percentages measured in balance experiments during the growth period, one can also calculate this retention using the comparative slaughter technique. In this way, information can be obtained on the variation in mineral retention in the course of the growth period when animals are slaughtered at different live weights. However, such figures will have a considerable error when they apply to a narrow weight range, because of inevitable errors made in assessing the mineral content of an entire animal. We also tried to calculate several relationships between the amounts of the minerals present in the body using other parameters such as live weight and amount of protein. Finally, the results obtained with balance and slaughter experiments are compared.

4.2. FACTORS WHICH INFLUENCE THE TOTAL AMOUNT OF BODY PHOSPHORUS AND CALCIUM IN PIGS

In the preceeding chapters, it has been shown that the composition of the diet can affect absorption and retention. In practice, however, many of the components in the diet vary little or only have an effect at concentrations that, in practice, do not occur. In this section, the effect of these factors, which can be regarded as being of practical relevance, is described. For illustration, we use examples from slaughter experiments, because these reflect long-term effects better than balance experiments which are of too short a duration.

a) The concentrations of phosphorus and calcium in the diet
As can be seen in the experiments of Blair and Benzie (1964), Mudd et al. (1969[b]) and many other research workers, the concentration of phosphorus and calcium in the diet has a significant effect on the retention of these minerals in the pig (see also Chapters 2.6 and 2.8). The results of Mudd et al. (1969[b]) are given in Table 7 to illustrate this.

Table 7. Influence of dietary concentration of Ca and P on retention

live weight (kg)	in diet (% of T)		in body (g)	
	Ca	P	Ca	P
23 (start)	-	-	211	128
41 (at slaughter)	0.30	0.38	309	197
41 "	0.58	0.68	360	223
41 "	0.94	1.13	396	236
41 "	1.16	1.47	426	249

In general, at higher concentrations of phosphorus and calcium in the diet, somewhat more of these minerals are retained in the body of the animal; the efficiency of the utilization of the dietary phosphorus, however, diminishes.

b) The level of feeding
In Chapter 2.2, it was concluded that the feeding level tends to lower the retention percentage when the feeding level was increased but, at a higher feeding level, the amounts of phosphorus and calcium retained per kg live weight are decreased, as can be concluded from the results of Stoy (1983) and Fandrejewski and Rymarz (1986). This is especially so when the daily supply of phosphorus and calcium is kept constant (Moinizadeh, 1975; see Table 1).

c) Breed of pigs
Weniger and Funk (1953[b]), in their slaughter experiments, observed that the Cornwall breed had a lower bone content than animals of the German "Edelschwein" and "veredeltes Landschwein" and, therefore, also lower contents of phosphorus and calcium. Differences in mineral content between breeds were also shown by Rymarz et al. (1982). Günther and Rosin (1970), showed that even within the same breed, the lean type of pig contained considerably more phosphorus and calcium at 100 kg live weight than the fattier type of pig. Some reasons can be given for the differences. First, a fat pig has more fat, and fatty tissue contains hardly any phosphorus. Furthermore, there is a rather close relationship between muscle and bone growth and the higher activity of lean pigs might also stimulate bone growth (Bauer and Grimminger, 1983).

d) The live weight of the pig
Some publications show that the live weight of the pig influences the degree of phosphorus and calcium retention per kg live weight gain. A first indication of this can be derived from the literature concerning the growth coefficients for several tissues. In his review of the literature and from his own experiments, Walstra (1980) concluded that bone growth has the lowest growth coefficient, varying from 0.69 to 0.92. This means that there is a decrease in bone percentage of the body with increasing live weight. Whether the trends found for total bone weight can also be applied to the total amounts of phosphorus and calcium retained is doubtful because of the following considerations. Young pipe bones contain red bone marrow which, with increasing age, is gradually replaced by marrow fat which has a lower specific gravity and also a lower phosphorus content. Moreover, during growth, cartilage is formed first and mineralization takes place later. Furthermore, it is not clear whether the mineral concentration in the bones changes after their initial formation as the animals become heavier. Brown et al. (1972) and Richmond and Berg (1972) showed that bone formation was less intensive at 100 kg than at 30 kg live weight. This was confirmed, amongst others, by Mudd et al. (1969[a]) who, from their slaughter experiment using only eight animals, gave the following relationship between empty body weight (EBW; kg) and the amounts of calcium (g) and phosphorus (g) in the body: $Ca = -111.22 + 16.80\ EBW - 0.07\ EBW^2$ with a rsd of 33 g and $P = -64.9 + 9.98\ EBW - 0.05\ EBW^2$ with a rsd of 16 g. From these equations, it can be calculated that there is a decrease in the retention of phosphorus and calcium per kg EBW as the pigs became heavier. In section 4.4.3., the relationship between the amount of phosphorus and calcium in the pig to other parameters, such as live weight and empty body weight, will be discussed in more detail.

e) Individual variation (see section 4.4.2.)

f) Analytical errors or experimental errors
Nielsen (1972) performed balance experiments using pigs from 20 to 90 kg live weight and analysed the same pigs for their mineral content at the end of the experiment. He found that the retention of phosphorus and calcium, calculated from the balance experiment, exceeded the results from compara-

tive slaughter by 39 and 15 per cent respectively. Hendriks (1981) also concluded from his experiments at the Agricultural University in Wageningen, that there was a great discrepancy in results between balance and slaughter techniques. Explanation for the differences obtained were not given by these research workers. It is, however, well known that in balance trials inevitable small errors (spilled feed, incomplete collection of excreta) lead to an overestimation of the retention. The results of the slaughter technique may also contain errors, especially when homogenizing is not done carefully. Often, only one carcass half is used, and both halves might not have the same bone content. Moreover, analysis of minerals in samples high in fat might easily lead to either overestimation or underestimation. The figures given for average daily feed intake for slaughter trials are usually less reliable than those for balance trials in which, due to the shorter length of the experiment, often containing only one weekend, more attention is paid to feed administration.

4.3. BALANCE EXPERIMENTS

4.3.1. The course of the absorption and retention percentages of P

Many experiments show that young animals can adapt to widely varying amounts of phosphorus and calcium in the diet by varying their intestinal absorption (Whittemore et al., 1973; Fox and Care, 1978; Armbrecht et al., 1982). The latter authors, using rats showed that there was a decrease in the adaptation of the intestine to dietary phosphorus and calcium restriction with increasing age. According to them, this decreased intestinal adaptation is probably due to a decrease in the capacity of the adult kidney to produce sufficient 1,25-DHCC in response to dietary restrictions of phosphorus and calcium. However, renal adaptation to a low phosphorus diet could be demonstrated at all ages. It is not clear whether such a decline in the absorption and retention percentage of phosphorus also occurs in growing pigs. There is not much information about this in the literature, because during the growing period, absorption and retention, using the same diet, are seldom measured more than once.
From experiments in which the same diet was fed during successive balance periods, we calculated the relationship between live weight and the absorption and the retention percentage of phosphorus. This was done using a linear model. When different diets were used by one author in the same experiment, the regression coefficients were calculated for each separate diet, after which a mean regression coefficient and constant for all diets was calculated. In the experiment described by Vemmer (1982), this model did not fit well because, from the ten measurements done, it appeared that the absorption and retention percentages for phosphorus were almost constant from 40 to nearly 70 kg live weight, after which time a considerable decline was found. The results of all calculations are shown in Figure 6. It can be seen that at a higher live weight there is a decline in the absorption and retention percentages for phosphorus and that in most cases the retention percentage is much lower than the absorption percentage. Only Newton et al. (1983) reported that the absorption percentage of phosphorus from the same diets fed to 35 kg pigs was significantly lower than in the same pigs at 85 kg (45 and 49 per cent resp.). It is not clear whether the decrease in intestinal absorption at a greater weight is caused physiologically by age or is due to a surplus in the amount of phosphorus offered in relation to the requirement. According to Vemmer (1982) the latter explanation is more likely.

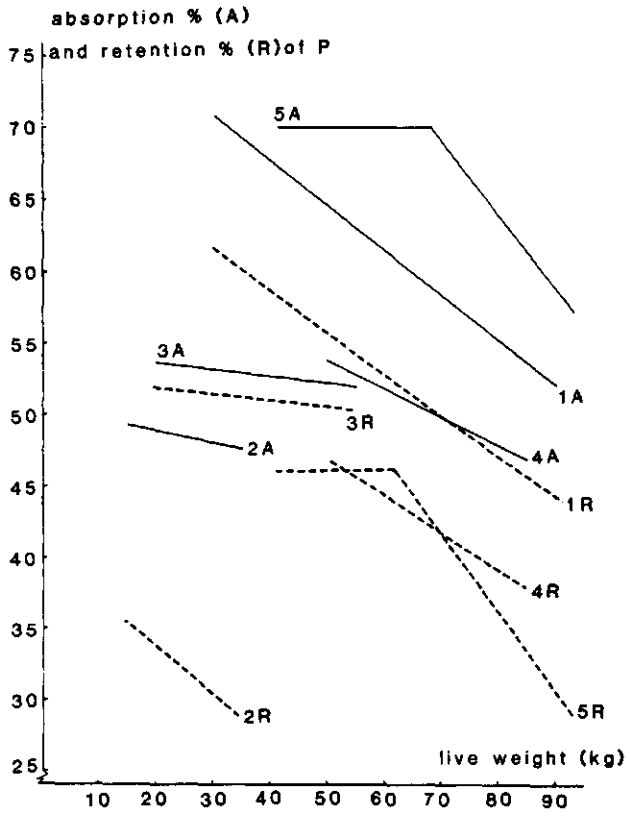

Figure 6 Relationship between live weight and the absorption and retention% of P of pigs

1 = Jambor and Procházka (1977)
2 = Kirchgessner et al. (1963)
3 = Morgan et al. (1969)
4 = Nielsen (1972)
5 = Vemmer (1982)

We also plotted the daily retention of phosphorus at increasing live weights as found by the same authors (Figure 7). Clearly, there is a considerable increase in phosphorus retention between 10 and 50 kg live weight from 1.5 to 5 g/d, while after 50 kg the retention is between 5 and 6 g/d.

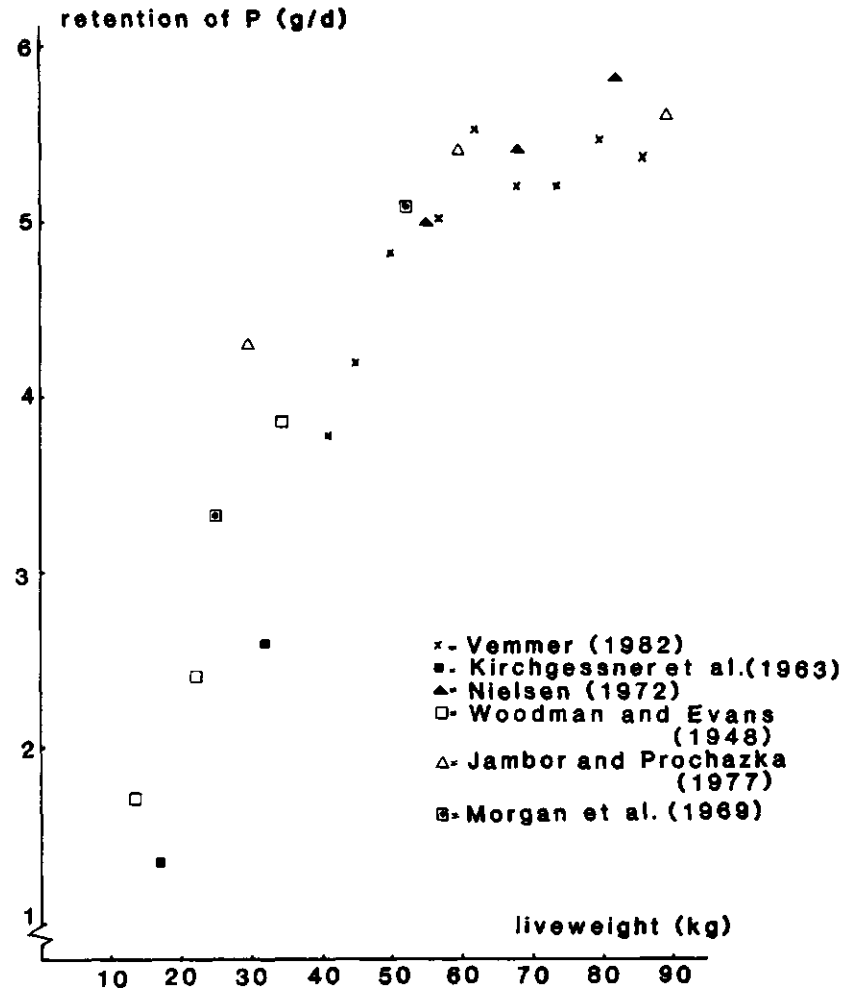

Figure 7 Effect of live weight on retention of P in pigs

4.3.2. Retention of phosphorus and calcium from 5 to 110 kg live weight

There have been quite a lot of balance experiments done on pigs in which the daily retention of phosphorus and calcium was measured. There are, however, great differences in the results due to differences in mineral concentration in the diet, level of feeding and live weight range. Therefore, in the next calculations only those diets in which the inorganic phosphorus concentration in the dry matter was 0.15 per cent or more were taken into account, because 0.15 per cent must be regarded as a minimum level. For the same reason, 0.45 per cent calcium or more in the dry matter was taken as the lower level of acceptance. Further, the level of feeding had to be 628 kJ $NE_f/W^{0.75}$ or more, i.e. at least twice maintenance, to permit a reasonable growth rate. The retention of phosphorus and calcium was calculated according to the technique of weighted mean and according to the number of observations. Next, the results mentioned in the literature were divided into two groups. One group contained all observations according to the criteria mentioned above. In the second group, only those data of the first group were taken which were regarded as being reliable. Data were not regarded as being reliable if the Ca/P ratio in retention was lower than 1.0 or higher than 2.2, when the experimental design was unsatisfactory or when, within the same experiment, great differences appeared between the results of total carcass analysis and the results of the balance experiments using the same animals.
The results of the calculations for the phosphorus and calcium retention per day and per kg live weight gain for the reliable data are given in Appendix 6a. The results of the calculations for all data were not clearly different from those for the reliable data; only the standard deviation was higher as might be expected (Appendix 6b).
From Appendix 6a it can be seen that the phosphorus retention per day slightly increases from 1.7 g at 9 kg live weight to 4.2 g at about 55 kg, after which it remains fairly constant up to 100 kg. This is also seen in Figure 6, but there the level of phosphorus retention above 60 kg live weight is between 5 and 6 g/d. That there is a difference in daily phosphorus retention between these two estimates is not so surprising in view of the factors already mentioned; the relatively high standard deviations show this clearly. Over the whole range of 15 and 110 kg live weight, the phosphorus retention per kg live weight gain is between 5.5 and 6.0 g. At a lower live weight it seems to be higher than 6 g.
The daily calcium retention increases from 2.6 g at 9 kg live weight to 6.4 g at about 55 kg live weight, after which it varies from 6 to 8 g/d. The retention of calcium per kg live weight gain is about 10 g.
The ratio of the calcium and phosphorus retention was on average 1.59. We also calculated the ratio of phosphorus and calcium retention per kg nitrogen retained. In most cases, however, the number of observations were too small to draw reliable conclusions. The P/N ratio (g/kg) varied from 156 to 190 with a mean of 181; the Ca/N ratio (g/kg) varied even more, from 236 to 318, with a mean of 292.

4.4. SLAUGHTER EXPERIMENTS

4.4.1. General

First, all possible information on the individual data of slaughter experiments, such as live weight, empty body weight, dry weight, amount of nitrogen, fat, ash, phosphorus and calcium and age at slaughter, was collected, so that the growth rate could be calculated. At the same time, data on the concentrations of phosphorus and calcium in the diet and on analytical techniques used were also noted. If only the quantity of minerals in the bones was given, it was assumed that 99 per cent of total calcium and 78

per cent of total phosphorus is retained in bones, in order to calculate the quantity in the whole animal (Moinizadeh, 1975). Excluded from further calculations were more results from experiments in which the diets did not contain adequate concentrations of either calcium or phosphorus (< 0.50 per cent Ca and < 0.50 per cent P in the diet) or a normal Ca/P ratio (1.0 to 2.0). Also, experiments were excluded if the growth rate was very low. When only data on live weight were given, it was assumed, for calculating empty body weight, that the weight of gut-fill and contents of the bladder amounted to 5 per cent of live weight.

Most of the data using animals up to about 20 kg live weight came from suckling piglets, which also received creep feed from a few weeks of age onwards. In the data collected by Freese (1958) and Becker (1976) the results on piglets, which were artificially reared, were included in those of suckling piglets. The pigs from 20 to 25 kg live weight were animals that were being used as zero time controls for slaughter experiments. These animals were mainly obtained from commercial farms, so that no specifications on diets previously fed or level of feeding were available.

Animals from 25 to 55 kg live weight received diets with an average phosphorus concentration of 7.9 ± 1.0 g/kg (n=9). No data were available on diets used in the experiments described by Spray and Widdowson (1950) and Weniger and Funk (1953[a,b]). From 56 to 110 kg live weight, the average concentration of phosphorus in the diets was 6.5 ± 1.2 g/kg (n=10). Pigs slaughtered between 56 and 110 kg live weight had a mean growth rate of 672 ± 46 g/d (n=11) from about 20 kg until slaughter.

There was hardly any information on the level of energy fed to the animals. If this was given or could be calculated, levels of 2.5 or less times maintenance were not incorporated in further calculations.

4.4.2. Variation in amounts of body phosphorus and calcium between animals

From the data given in the literature, the variation in total amounts of phosphorus and calcium between animals was calculated. The mean and standard deviation of these parameters, found in the experiments of some of the authors, are given in Table 8. More information about the mean and standard deviation of these parameters, also for groups of animals, is given in Appendix 7.

Table 8. Total amount of Ca and P in pigs (mean ± sd)

live weight (kg)	number of observations	total amount of Ca(g)	P(g)	reference
7 ± 2	6	58 ± 16	36 ± 10	Spray and Widdowson (1950)
15 ± 1	12	145 ± 29	87 ± 15	Mudd et al. (1969[a])
25 ± 1	7	193 ± 10	116 ± 7	Oslage (1964)
74 ± 5	4	622 ± 35	383 ± 31	Rymarz et al. (1982)
98 ± 2	6	795 ± 52	482 ± 30	Stoy (1983)
110 ± 1	29	767 ± 66	485 ± 40	Oslage (1964)

From Table 8 and Appendix 7, it can be concluded that the coefficient of variation in the amounts of phosphorus and calcium within a group of pigs with the same live weight, varies from 2 per cent to more than 25 per cent per experiment. Of the 41 experiments in which the data for the individual animals were given, the mean coefficient of variation was 8.2 and 8.9 per cent for phosphorus and calcium, respectively. The mean coefficient of variation in the amounts of phosphorus and calcium in the ten experiments of Appendix 7, with data on groups of pigs only, was almost the same, 8.3 and 8.9 per cent, respectively.

4.4.3. Relationship between total amounts of body phosphorus and calcium in pigs to live weight, empty body weight, fat-free weight, etc.

For the calculation of several relationships between the total amount of phosphorus and calcium in pigs and live weight, empty body weight, etc., the means of these parameters within a live weight class per author were used. Results per author were combined when litters were concerned or if there was less than 11 per cent or 2.5 kg difference between the live weights. This was done to avoid strong influence on the final result of one publication and because analyses of phosphorus and calcium in carcasses are rather difficult, which can easily lead to systematic errors. All data used for the calculations are given in Appendix 8.
As already mentioned, Mudd et al. (1969[a]) gave the following relationship between empty body weight (EBW; kg) and the amounts of calcium (g) and phosphorus (g) in the body: $Ca = -111.22 + 16.80\ EBW - 0.07\ EBW^2$ and $P = -64.9 + 9.98\ EBW - 0.05\ EBW^2$. In A.R.C. (1981), other relationships are presented based on data of Oslage (1964), Mudd et al. (1969[a]) and Spray and Widdowson (1950). These data were examined, by (natural) logarithmically relating the amounts of phosphorus and calcium to either live weight or to fat-free body weight. The results are given in Table 9; in the three studies the relationships have the same slope, for calcium as well as for phosphorus. Based on these equations the rate of increment of mineral per unit of fat-free body weight shows a steady and progressive increase from birth to 110 kg, whereas per unit of live weight there is no progression.

Table 9. Relationship of total amounts of Ca and P in the body to live weight (W) and fat-free body weight (FFW) resp. (A.R.C., 1981)

equation no.	equations	reference
1	ln Ca = 2.06 + 0.983 ln W	Oslage (1964)
2	ln Ca = 2.33 + 0.983 ln W	Mudd et al. (1969[a])
3	ln Ca = 2.16 + 0.983 ln W	Spray and Widdowson (1950)
4	ln P = 1.56 + 0.996 ln W	Oslage (1964)
5	ln P = 1.74 + 0.996 ln W	Mudd et al. (1969[a])
6	ln P = 1.65 + 0.996 ln W	Spray and Widdowson (1950)
7	ln Ca = 2.27 + 1.033 ln FFW	Oslage (1964), Mudd et al. (1969)
8	ln P = 1.73 + 1.051 ln FFW	and Spray and Widdowson (1950)

In one slaughter experiment, Rymarz et al. (1982) compared three breeds of gilts, at 11 or 13 weeks old and at 18, 22, 26 or 30 weeks old. The growth coefficients between these breeds did not differ significantly when empty body weight or protein weight were taken as independent variables and ash, calcium or phosphorus as dependent variables. For calcium and phosphorus, these equations were ln Ca = 1.967 + 1.054 ln EBW and ln P = 1.634 + 1.003 ln EBW or ln Ca = 3.961 + 0.991 ln Protein and ln P = 3.549 + 0.991 ln Protein (Ca and P in g; EBW and Protein in kg). They conclude that per kg live weight gain the calcium retention increases from 8.4 g at 25 kg to 9.1 kg, while for phosphorus it remains constant at 5.0 g.
Using the data given in Appendix 8, we also calculated several relationships. For these calculations, the data of newborn piglets and piglets up to seven days old, and furthermore the data as pointed out in section 4.4.1. were excluded. Regression models were fitted with Ca and P as dependent variables and live weight (W), empty body weight (EBW), fat-free body weight (FFW), fat-free empty body weight (FFEBW) and nitrogen weight (NW) as consecutive independent variables. On the basis of plots of residuals, it was decided to carry out weighted regression. The following

models were used:

a) $\underline{y} = c_o + c_1 x + c_2 x^2 + \underline{e}$ with $\underline{e}$ normally distributed, with E $\underline{e} = 0$, var $(e|x) = \sigma^2 x^{3/2}$ for y = Ca, P and x = W, EBW, FFW, FFEBW

b) $\underline{y} = c_o + c_1 NW + c_2 NW^2 + \underline{e}$ with $\underline{e}$ normaly distributed with E $\underline{e} = 0$, var $(\underline{e}|NW) = \sigma^2 NW$ for y = Ca, P

The results of all regressions are given in Appendix 9, so that comparisons can be made with similar calculations in the literature. The results in Appendix 9 indicate that, when compared to the linear component, there is a small but significant effect of the square of all independent variables on the amount of phosphorus in the animal and a small effect of the square of fat-free weight and fat-free empty body weight on the amount of calcium in the body. The effect of a negative coefficient for x^2 means a decline in grams of these minerals per kg as the animals become heavier. In most cases, the percentage of variance accounted for was about 99.
Our calculations show a much lower coefficient for the square of empty body weight than those of Mudd et al. (1969[a]). This means that very probably the decline in retention of phosphorus and calcium per kg empty body weight from 15 to 90 kg is much lower than that found by Mudd et al. (1969[a]). This is given in Table 10, together with the results of Rymarz et al. (1982).

Table 10. Estimated amounts of Ca and P in the body (g/kg EBW) at several EBWs

	empty body weight							
	20		40		65		90	
	Ca	P	Ca	P	Ca	P	Ca	P
Mudd et al.(1969[a])	14.0	8.0	11.2	6.0	7.7	3.5	4.2	1.0
Rymarz et al. (1982)	8.9	5.3	9.2	5.3	9.4	5.3	9.6	5.3
own calculations from literature (equation nos. 2 and 7 in Appendix 9)	9.1	5.6	9.0	5.5	8.8	5.4	8.6	5.2
own calculations from literature (equation nos. 2 and 7a in Table 11)	8.7	5.4	8.8	5.4	8.9	5.4	8.9	5.4

Using the data from the literature (see Appendix 8), the amounts of phosphorus and calcium were also estimated according to the following model:

$\ln \underline{y} = c_o + c_1 \ln x + c_2 (\ln x)^2 + \underline{e}$, with $\underline{e}$ normally distributed,

and E $\underline{e} = 0$, var $(e) = \sigma^2$ for y = Ca, P and x = W, EBW, FFW, FFEBW and NW.

Plots of residuals versus fitted values were acceptable. The structure of the residuals of the fitted values permitted this model. The results of these calculations are given in Table 11, which show that only a small significant quadratic effect (p = 0.05) was found for phosphorus with EBW as independent variable. Therefore, further calculations were performed using only the linear model. On the basis of these results, the retention of phosphorus and calcium per kg EBW was calculated and is presented in Table 10. The results given in this table show that, as was expected, there were hardly any differences between our two methods of calculation.

Preference is given to the model with the natural logarithm because it is the one most commonly used in describing the growth of animals (allometric function). The results of Rymarz et al. (1982) are in good agreement with our calculations.

Table 11. Relationship of Ca and P contents to live weight (W), empty body weight (EBW), fat-free body weight (FFW), fat-free empty body weight (FFEBW) and nitrogen (NW). (W, EBW, FFW and FFEBW in kg; Ca, P and NW in g)

equation number	equation	significance of the variables linear different from 1	square different from 0	R^2	rsd*
1	ln Ca = 2.068 + 1.013 ln W	n.s.	n.s.	0.986	0.138
2	ln Ca = 2.120 + 1.016 ln EBW	n.s.	n.s.	0.986	0.137
3	ln Ca = 2.000 + 1.092 ln FFW	***	n.s.	0.993	0.101
4	ln Ca = 2.057 + 1.100 ln FFEBW	***	n.s.	0.994	0.029
5	ln Ca =-0.988 + 0.991 ln NW	n.s.	n.s.	0.987	0.138
6	ln P = 1.628 + 1.000 ln W	n.s.	n.s.	0.995	0.081
7a	ln P = 1.680 + 1.002 ln EBW	n.s.	-	0.995	0.079
7b	ln P = 1.528 + 1.127 ln EBW - 0.022 ln EBW^2	*	*	0.996	0.076
8	ln P = 1.667 + 1.048 ln FFW	***	n.s.	0.996	0.070
9	ln P = 1.721 + 1.056 ln FFEBW	*	n.s.	0.997	0.059
10	ln P =-1.387 + 0.978 ln NW	***	n.s.	0.997	0.061

*) the variance of W is approximately equal to $\sigma^2.e^{2a}.W^2$ when the coefficient b is about 1; where a is intercept and b is slope.

To calculate the rsd at a given W: $rsd_W = rsd\sqrt{e^{2a}.W^2}$.

On the basis of equation nos. 1 and 6 in Table 11, we calculated the amounts of phosphorus and calcium at several live weights; the amount is also given for newborn piglets. These results are given in Table 12, together with the retention of these minerals per kg live weight gain at the given live weights.

Table 12. Amounts (g) of Ca and P at several live weights and retention of Ca and P per kg live weight gain

live weight (kg)	Ca(g)	P(g)	per kg live weight gain Ca (g)	P (g)
1.3 (newborn piglets)	14	8	-	-
10	82	51	8.26	5.09
20	164	103	8.34	5.09
40	332	205	8.42	5.09
60	501	306	8.46	5.09
80	670	415	8.49	5.09
100	840	503	8.52	5.09

We also estimated the amount of nitrogen and fat in the bodies of pigs at

several body weights by means of the allometric function. The number of observations was smaller than for those of phosphorus and calcium (in total 34 and 38 resp.). The amount of nitrogen could be estimated by the following equation ln NW (g) = 3.102 + 1.009 ln W (kg), R^2 = 0.997, rsd = 0.070, that for fat was ln FAT (g) = 4.884 + 0.826 ln W (kg) + 0.067 (ln W)^2, R^2 = 0.971, rsd = 0.244. It can be calculated from these equations that the amounts of nitrogen and fat at 20, 60 and 100 kg live weight are 0.46 and 2.86 kg, 1.39 and 11.94 kg, and 2.32 and 24.51 kg respectively.
From the results given in Table 12, it can be concluded that per kg live weight gain 5.1 g phosphorus is retained. No increase is found because the growth coefficient was equal to 1.00.
Because of the very good relationship between the nitrogen weight and phosphorus and calcium weights, as can be concluded from the low rsd values in Table 11, the daily retention of these minerals was calculated (Table 13). From the equation ln NW (g) = 3.102 + 1.009 ln W (kg), it could be calculated that per kg live weight gain about 23.3 g N was retained. Because the mean growth rate of the pigs slaughtered between 56 and 110 kg live weight was 672 g/d from about 20 kg until slaughter, a mean growth rate from 20 to 100 kg of 700 g/d was assumed. The daily growth at several live weights was derived from the C.V.B. scheme (1983) for a mean growth of 700 g/d.

Table 13. Retention of Ca and P at several body weights, based on N retention, and the Ca/N and P/N ratio

live weight (kg)	growth rate (g/d)	retention of Ca (g/d)	retention of P (g/d)	Ca/N ratio of retention (g/kg)	P/N ratio of retention (g/kg)
20	430	3.5	2.1	350	214
40	620	5.0	3.0	348	210
60	760	6.2	3.7	347	208
80	810	6.6	3.9	346	207
100	790	6.4	3.8	345	206

From 20 to 100 kg live weight, the average daily retention of N amounted from 10 g at 20 kg to 20 g at 80 kg live weight. Rymarz et al. (1982) estimated that per kg nitrogen retention at 20 and 100 kg live weight, 360 and 379 g calcium and 213 and 210 g phosphorus, respectively, was retained. These figures are close to those of our own calculations (350 to 345 and 214 to 206 respectively). Using the results of Stoy (1983), it could be calculated that for 100 kg pigs, the comparable values were 351 and 212 g/kg, respectively, and from those of Fandrejewski and Rymarz (1986) 386 and 222, respectively.
Apart from the close linear relationship between protein weight and phosphorus and calcium weights, a close linear relationship was also found for the fat-free weight or fat-free empty body weight with the minerals. This is clearly due to the fact that the fat-free weight of a pig mainly consists of protein and water in a fairly constant ratio.
The increases in mineral retention per unit of FFW at higher FFW as calculated from equation nos. 3 and 8 in Table 11 were compared with the data of A.R.C. (1981) (see Table 14).

Table 14. Retention of Ca (g) and P (g) per kg fat-free body weight (FFW)

FFW (kg)	A.R.C. (1981) Ca	A.R.C. (1981) P	own calculations Ca	own calculations P
5	10.5	6.4	8.6	5.7
10	10.8	6.7	9.1	5.9
30	11.2	7.1	10.1	6.2
50	11.4	7.2	10.6	6.4
70	11.5	7.4	10.9	6.5
90	11.6	7.5	11.2	6.6

From Table 14, it can be seen that for calcium at the lower FFW a lower retention is found in our calculations, but the increase at higher FFW is less in the A.R.C. calculations. Phosphorus retention per kg FFW is lower in our calculations, but the increase at a higher FFW is about the same.
From the data in Appendix 8 it can be calculated that, except in newborn piglets, the Ca/P ratio in the body is rather constant 1.62 $\pm$ 0.16. When the three observations described by Freese (1958) are omitted because the Ca/P ratio was more than 2.0, and one observation of Berge and Indrebø (1954) at 3.9 kg live weight (Ca/P = 1.15) then the Ca/P ratio in the bodies was, mean and sd, 1.61 $\pm$ 0.09 (n = 47). In newborn piglets, the Ca/P ratio is higher, on average 1.77. Thus, the Ca/P ratio can be used to check the accuracy of the measurements with regard to phosphorus and calcium retention in the whole animal, or measured as g/d in balance experiments.

4.5. COMPARISON OF THE DAILY RETENTION OF P AND CA MEASURED BY BALANCE AND SLAUGHTER EXPERIMENTS

Comparison of phosphorus and calcium retention, as measured in balance experiments, with those in slaughter experiments, is not so easy. Only Nielsen (1972) made a direct comparison with the same animals. He observed that at slaughter, 15 per cent less calcium and 39 per cent less phosphorus was found in the pigs than the amounts calculated from the six balance experiments during their growth period. He did not give any explanation for the difference. The most important factors which can affect the retention of phosphorus and calcium have been discussed in section 4.2., but with regard to the comparison some will be referred to again.
It is probable that the feeding level applied in the balance experiments is lower than in the slaughter experiments. This was, however, difficult to verify because in most cases in the slaughter experiments, the feeding level was not given. The best comparison can probably be made when the retention per kg growth is taken. However, one should be aware that measurement of the growth rate of pigs in metabolism cages is not very accurate, due to the relatively short period (10 to 15 days) in which the weight of the animal is determined. It is also doubtful whether the animals had already adapted to the diet in the balance experiments, while this is not a problem for the (long-term) slaughter experiments. Furthermore, both the balance and the comparative slaughter techniques have their weak points as explained in section 4.2. The former tend to overestimate retention, the latter may not be correct if fat animals are not homogenized correctly prior to analysis.
When comparing the data of Appendix 6a with those of Table 12, it can be concluded that the retention of phosphorus and calcium per kg live weight gain in the balance experiments is considerably higher than in the slaughter experiments. The main phosphorus and calcium retention per kg weight gain in the balance experiments was 6.1 and 9.7 respectively, while those figures in the slaughter experiment were 5.1 and 8.4 respectively.

The mean Ca/N and P/N ratio (g/kg) in the retention was in the balance experiments 292 and 181 respectively, and in the slaughter experiments 347 and 210 respectively.
The cause of these differences is not clear. Just (1982) concluded from several experiments that the nitrogen retention was overestimated in balance experiments by 10 to 15 per cent. Nitrogen loss as ammonia might be responsible, but in the case of phosphorus and calcium, losses of volatile phosphorus and calcium can be excluded. Careful direct comparisons of the two techniques are necessary in order to gain some information about the reliability of the results obtained.
The average Ca/P ratios in the retentions were almost the same in both balance and slaughter experiments: 1.59 and 1.62 respectively. However, it should be mentioned that in the balance experiments, Ca/P ratios less than 1.0 and greater than 2.2 were excluded from the calculations.

4.6. CONCLUSIONS

In this chapter it is shown that also in practice several factors affect the amounts of phosphorus and calcium in the bodies of pigs. Some of these are live weight of the pigs, individual variation (coefficient of variation is about 8 to 9 per cent), the concentrations of phosphorus and calcium in the diet also in relation to its feeding and energy level and the breed.
A decline in absorption and retention percentages of phosphorus and calcium in growing pigs with age can to a large extent be explained by a surplus in the amount of these minerals offered in relation to the requirement. Results with the balance experiments show that up to about 55 kg live weight there is a slight increase in the daily retention of phosphorus and calcium after which time it remains fairly constant.
The relationship between the amounts of phosphorus and calcium with, for example, live weight can best be expressed by relating the natural logarithm of the amount of minerals to the natural logarithm of live weight because this is commonly used in growth studies in view of exponential weight increases. According to these calculations, there is a constant phosphorus retention per kg live weight gain of 5.1 g from 10 kg to 100 kg live weight. However, there is a tendency towards slightly lower values at higher live weights. Except for newborn piglets, there is a close relationship between the amounts of calcium and phosphorus in the body; the ratio is on average 1.62. There is also a close relationship between the amounts of phosphorus and nitrogen in the slaughter experiments; this was on average 210 g/kg. From 20 to 100 kg live weight this ratio decreased from 214 to 206.
The retention of phosphorus and calcium per kg live weight gain found in balance experiments, was about 20 per cent higher than when derived from slaughter experiments. Only part of the difference can be explained by known systematic errors. Few direct comparisons of the two techniques have been made and more such studies are recommended. Therefore, in retention studies very careful direct comparisons are necessary in order to gain enough information about the accuracy of both techniques.

5. THE PHOSPHORUS AND CALCIUM REQUIREMENTS OF GROWING PIGS; FEEDING EXPERIMENTS

5.1. INTRODUCTION

The effect of phosphorus and calcium levels on the performance of pigs has been investigated in many feeding experiments. Even so, there is still considerable controversy about the requirement of these minerals for growing pigs. The controversy could partly be due to the fact that in many experiments the basal diets were not analysed for phosphorus; the intervals between the different phosphorus levels in an experiment were either too great or no additional information of the diets was gathered in digestibility or balance trials on which specific recommendations might be based. Differences in experimental conditions also complicated drawing any conclusions from the results of these feeding experiments. Also, when interpreting the results of their own experiments and those of others, the authors did not use the same criteria and often also considered the importance of these criteria in different ways.

Mineral requirements of pigs in the Netherlands are mainly based on recommendations given by A.R.C. (1967; 1981) and N.R.C. (1973; 1979). They are rather high as the main aim is to prevent too low an intake in all cases. The environmental problems caused by the phosphorus in the excreta of pigs (see General introduction) has emphasized the need to study the phosphorus requirement of pigs more critically. In the Netherlands, no consensus has yet been reached. Although the environmental problem is well recognized, it is feared that a reduction in the supply of phosphorus might lead to a lower rate of gain, higher feed conversion ratio and possibly more leg weakness. Nowadays, pigs have a higher growth potential and lower feed conversion ratio than the pigs of the past on which the A.R.C. and N.R.C. requirements were based. Moreover, the diets currently being used also differ from those of these requirement studies.

In this chapter, a description is given of how the requirements of phosphorus and calcium for pigs were usually derived. This is followed by a survey of the recommended requirements for these minerals in several countries. Next an extensive analysis is presented of various feeding trials described in the literature which were performed to derive the optimum phosphorus level of diets for pigs (see also Hoekstra, 1982). Then the influence of the Ca/P ratio of the diet on performance and health is discussed and finally the effect of dietary phosphorus level on locomotory disturbances and slaughter quality is considered.

5.2. DERIVATION OF PHOSPHORUS AND CALCIUM REQUIREMENTS OF PIGS, AND RECOMMENDATIONS IN SEVERAL COUNTRIES

In general, two methods are used to establish the phosphorus and calcium requirements of pigs. The first is the empirical approach; it uses the results of feeding trials with diets of various phosphorus and calcium contents. In interpreting these results, often not only growth rate, feed conversion ratio and feed intake were taken as criteria, but also bone ash content or bone breaking strength. The empirical approach is used in the USA, Denmark and Sweden.

The other method is the factorial approach which, for example, is used in the Federal Republic of Germany, the United Kingdom and France. In this method, the requirement for a mineral is estimated by the following equation:

requirement for a mineral =

$$\frac{\text{net requirement for maintenance + net requirement for growth or production}}{\text{availability of the mineral}}$$

The net requirement for maintenance is estimated to be between 10 and 30 mg phosphorus per kg live weight per day. The net requirement for growth is usually taken to be between 5.0 to 6.0 g phosphorus per kg growth. As we have seen in Chapters 4.3.2. and 4.4.3. these values are in agreement with our own calculations using data from the literature. In France and the Federal Republic of Germany, the true absorption of the mineral is taken for the availability of the mineral in the equation. In A.R.C. (1981) of the United Kingdom, availability is defined as:

$$\text{availability}(\%) = \frac{I - (F - F_o) - (U - U_o)}{I} \times 100$$

where I = intake of the mineral
F = total excretion of the mineral in faeces
F_o = obligatory loss of the mineral in faeces
U^o = total excretion of the mineral in urine
U_o = obligatory loss of the mineral in urine

In A.R.C. (1981), availabilities of Ca and P were derived and used for calculating the recommended quantities of Ca and P (Table 15).

Table 15. Requirements for Ca and P of growing pigs (A.R.C., 1981)

live weight (kg)	net requirement Ca (g/d)	P (g/d)	availability Ca (%)	P (%)	requirement Ca (g/d)	P (g/d)	intake (kg T/d)	in diet Ca (g/kgT)	P
5	3.4	2.7	85	80	4.0	3.4	0.37	10.8	9.2
25	6.3	4.6	60	75	10.5	6.1	1.04	10.1	5.9
45	7.7	5.2	50	70	15.4	7.4	1.78	8.6	4.2
90	8.8	5.8	45	65	19.5	8.9	2.78	7.0	3.2

In the United Kingdom, however, the empirical method was preferred. The factorial method was considered to have too many uncertainties, among which was a possible overestimation of the availability of phosphorus at higher live weights. Availabilities obtained by oral ^{32}P in an inorganic form were also applied to phosphorus from common feedstuffs. Moreover, the diets used for the A.R.C. calculations contained a large amount of inorganic phosphorus (fish meal, meat and bone meal, feed phosphate) and it was assumed that such diets were also fed to pigs of 45 kg and higher. In the Netherlands, in practice, this is not done; diets for pigs above 45 kg contain a lower amount of inorganic phosphorus and, as a result, a much lower availability of phosphorus is obtained. It has been shown in Chapter 2.8.3.2. that a barley-soybean meal diet without supplemented inorganic phosphate has a phosphorus concentration of about 4.0 g/kg T and an absorption percentage of phosphorus of about 34 per cent. The availability of such a diet will probably be 37 or 38 per cent. This value is much lower than the availability of 65 given by A.R.C. (1981).
For comparison of the phosphorus and calcium requirements of pigs used in several countries, the following sources of information were collected. Denmark: Andersen and Just (1979); Nielsen et al. (1979). Federal Republic of Germany: Oslage and Vemmer (1979). France: Guéguen and Perez (1981). Sweden: Ericksson et al. (1976). Switzerland: Pfirter et al. (1979) and the United States of America: N.R.C. (1979). The data given in A.R.C. (1981)

could not be used as such, due to the fact that only at 5, 25, 45 and 90 kg live weight were the relevant data given. The same was true of some of the other recommendations. Therefore, first for each country separately the recommendations concerning the daily allowance of phosphorus and calcium and the estimated intake of the diet at several live weights were plotted on a graph. The data points on these graphs for each country were connected by a line and the requirements at 5, 10, 20 up to 100 kg live weight obtained by interpolation. The calcium and phosphorus concentrations in the diet were expressed for a diet containing 12.55 MJ per kg air-dry diet. For obtaining a figure for the ME concentration of a diet for which this was not given, the following assumptions were made: 13.21 MJ DE = 12.55 MJ ME = 8.79 MJ NE_f = 1 EW and 700 g Gesamtnährstoff = 12.55 MJ ME. A summary of the calculations is given in Table 16; the mean is the average of the recommended values in the six countries (United Kingdom excluded) and the standard deviation gives some information on the variation among the values of the various countries.

Table 16. Daily allowances of P and Ca and P and Ca concentrations in diets according to recommended values in six countries (g/kg diet; 12.55 MJ ME/kg diet; mean and sd)

live weight (kg)	Ca (g/d)	P (g/d)	Ca (g/kg)	P (g/kg)
10	5.2 ± 1.3	3.9 ± 1.0	8.7 ± 1.5	6.3 ± 0.8
20	8.7 ± 1.7	6.3 ± 1.5	8.7 ± 1.6	6.2 ± 1.2
30	10.7 ± 2.0	8.1 ± 1.7	7.8 ± 1.4	5.9 ± 1.2
40	12.5 ± 2.2	9.3 ± 1.6	7.3 ± 1.3	5.4 ± 0.9
50	13.9 ± 2.3	10.3 ± 1.3	6.9 ± 1.2	5.0 ± 0.7
60	15.3 ± 2.6	11.2 ± 1.2	6.6 ± 1.2	4.8 ± 0.6
70	16.5 ± 2.6	12.0 ± 1.2	6.4 ± 1.2	4.7 ± 0.6
80	17.4 ± 2.7	12.8 ± 1.3	6.3 ± 1.2	4.6 ± 0.6
90	18.2 ± 2.9	13.3 ± 1.5	6.2 ± 1.3	4.5 ± 0.7
100	18.9 ± 3.2	13.8 ± 1.7	6.1 ± 1.3	4.5 ± 0.6

From Table 16 it can be seen that there are considerable differences in dietary allowances and recommended concentrations per 12.55 MJ ME.
In Table 17, a survey is given of the phosphorus and calcium requirements of pigs in different countries for three live weight classes. The table shows that the requirements for phosphorus are usually lowest in the USA and Germany.

Table 17. Recommended Ca and P requirements of pigs in different countries (g/kg diet; 12.55 MJ ME/kg diet)

live weight class	10 to 25 kg		25 to 50 kg		50 to 100 kg	
	Ca	P	Ca	P	Ca	P
Switzerland	10.0	7.0	7.5	6.0	6.5	5.0
Germany	8.5	6.5	7.5	4.8	6.0	4.0
France	9.9	7.0	9.2	6.5	8.5	5.0
Denmark	10.1	8.1	9.8	7.9	7.2	5.9
United Kingdom	9.8	7.8	8.4	6.3	7.3	5.8
USA	6.5	5.3	5.8	4.9	5.1	4.2
Sweden	-	-	8.6	6.2	7.0	5.3
mean±sd (excl.USA)	9.7±0.7	7.3±0.7	8.5±0.9	6.3±1.0	7.1±0.8	5.2±0.7
mean±sd (incl.USA)	9.1±1.4	7.0±1.0	8.1±1.3	6.1±1.0	6.8±1.1	5.0±0.7

One problem in evaluating the data is that it is not always clear whether the recommendations concern minimal or optimum requirements. Only the German data are stated to be minimal requirements.
The low values of the USA can partly be explained by the type of diet commonly used. A corn-soybean meal diet is usually used in the USA. For a 25 kg pig it contains, without supplemented inorganic phosphorus, about 3.6 g P/kg diet (2.3 g phytate phosphorus and 1.3 g non-phytate phosphorus). To meet the requirement for phosphorus, 1.4 g P/kg must be added from an inorganic source. N.R.C. (1979), states that at least 30 per cent of the phosphorus requirement should be provided by phosphorus from inorganic or animal product sources. Diets in the other countries have a higher concentration of intrinsic phosphorus, i.e. much organic phosphorus with low availability, being the reason why high requirements for total phosphorus in the diet are given. So, in fact, on a net basis, the differences between the requirements used in various countries are much smaller. It would be better to compare the requirements on the basis of available phosphorus, but this is only possible for France and Germany. In the United Kingdom, also the percentages of availability are also given, but these data do not correspond with those used for deriving their recommended requirements, which are based on the empirical method.
In discussing the N.R.C. phosphorus requirement for pigs, Cromwell (1980) assumes an availability of 12 per cent and 22 per cent in corn and soybean meal respectively, which means an availability of phosphorus in a corn soybean meal diet, without the addition of inorganic phosphate, of about 17 per cent. For feed phosphates he uses an availability of 98 per cent. Our calculations suggest an absorption percentage of phosphorus of 33 for a corn-soybean meal diet without supplementary inorganic phosphorus (see Chapter 2.8.2.2.) which means an availability of about 37. When the same availability of phosphorus from feed phosphates is assumed as by Cromwell (98 per cent), then a much higher concentration of available phosphorus per kg diet can be calculated. A summary of the recommendations of available phosphorus is given in Table 18. Even so, there are considerable differences, but the variation between the recommendations is less than for total phosphorus.

Table 18. Recommendations of available P for pigs (in g/kg diet; 12.55 MJ ME/kg diet)

	10 to 25 kg		25 to 50 kg		50 to 100 kg	
	P-availability (%)	avail-P (g/kg)	P-availability (%)	avail-P (g/kg)	P-availability (%)	avail-P (g/kg)
France	55	4.0	50	3.3	50	2.5
Germany	50	3.3	50	2.4	50	2.0
USA (Cromwell)	47	2.5	44	2.1	42	1.7
USA (own calculations)	60	3.2	57	2.7	56	2.3

5.3. OPTIMUM PHOSPHORUS LEVEL IN DIETS FOR GROWING PIGS AS DERIVED FROM FEEDING TRIALS

5.3.1. Introduction

Many feeding experiments have been performed in which the effect of the level of phosphorus in the diet on the performance of pigs was investigated. From the results, recommendations concerning the required phosphorus level of the diet were made. They vary widely from experiment to experiment. This might be due to differences between these experiments with regard to type of diet, level of feeding, initial weight, sex, etc. Therefore, regression analysis was used in an attempt to gain more insight into the factors which might have affected the relationships between the phosphorus level and performance; factors which might have been insufficiently considered by the authors of the experiments while deriving optimum phosphorus requirements. For this analysis, all relevant feeding experiments published from 1970 to 1982 were used. The year 1970 was chosen because experiments before then were usually done using pigs which had relatively low growth rates and high feed conversion ratios compared with those used now. In Chapters 2.3.4. and 4.4.3. it has been shown that a higher daily retention of protein, usually occurring at higher growth rates, can result in a higher requirement for phosphorus.
From each experiment the following data, if available, were collected:

- the author(s) and year of publication;
- number of animals per treatment and number of independent observations;
- the sex of the animals (barrows =1, gilts = 2, barrows and gilts = 3, boars = 4, boars and gilts = 5);
- the mean weight of the animals at the start of the experiment;
- the mean weight of the animals at the termination of the experiment;
- the level of feeding (ad libitum = 1 or restricted = 2);
- type of diet
  . corn + soybean meal or sorghum + soybean meal = 1;
  . barley + soybean meal or wheat + soybean meal = 2;
  . other diets with a maximum of three ingredients = 3;
  . diets with more than three ingredients = 4;
  . synthetic diets = 5;
- the energy content of the diet in MJ NE_f/kg diet, calculated from the amount of the several ingredients in the diet and their NE_f-value of each of the ingredients according to the Dutch Feeding Table;
- the phosphorus concentration in the diet, without its possible supplementation of phosphorus from an inorganic source, and the concentration of phytate phosphorus in that diet. If these data were not given in the publication they were calculated from those given in the Dutch Feeding Table (C.V.B., 1977) and by Simons et al. (1981). A summary of these data is given in Appendix 1;
- the Ca/P ratio of the diets (constant ratio = 1, variable ratio = 2 and calcium level is constant = 3);
- change to a lower phosphorus content during the feeding experiment (no change = 0, one time = 1, two times = 2, etc);
- growth rate, feed conversion ratio and feed intake of the first phosphorus level in the diet examined followed by growth rates, feed conversion ratios and feed intakes at the other phosphorus levels.
- the optimum phosphorus content in the diet which was proposed by the author(s). When the difference between two phosphorus concentrations in the diet was more than 0.10 per cent and the growth rate and feed conversion ratio were almost the same and the author(s) suggested an optimum range of phosphorus , then the mean of the two phosphorus levels was chosen, unless the author(s) came to a different conclusion. For differ-

ences less than 0.10 phosphorus this was not done and the highest level was chosen, because of the chance of getting systematically too low values.

A survey of all data collected from the feeding trials in the literature is given in Appendix 10, while Appendix 11 gives the number of observations specified according to initial weight, sex, type of diet and level of feeding.

5.3.2. Critical analysis of the optimum phosphorus level as given by the authors of the experiments

5.3.2.1. The value of the optimum phosphorus level derived by the authors of the experiments

In many of the experiments (43 per cent) the authors measured the performance of the pigs at only two phosphorus levels. This means that without other information it is not possible for either the authors or us to give an estimate of the optimum level. Very probably, the authors wanted to see whether a level of phosphorus in the diet which was somewhat higher or lower than the level recommended at that time affected the performance of the animals. The recommended optima by the authors are given in Appendix 10, column 14.

5.3.2.2. Optimum phosphorus levels based on growth rate

For the experiments in which it was possible (number of P levels ≥ 3), we estimated an optimal phosphorus level by regressing growth rate on P and P^2:

E (growth rate) = $c_o + c_1 P + c_2 P^2 + e$, with e normally distributed and

var (growth rate) = σ^2.

The estimated parameters $\hat{c}_1$ and $\hat{c}_2$ were used to estimate the optimum: $\hat{P}$ optimum = $-\hat{c}_1/2\hat{c}_2$. P optimum is a maximum if and only if $\hat{c}_2 < 0$. For a considerable number of these experiments (28 per cent) $\hat{c}_2$ was >0 and thus the optimum revealed a minimum. In the cases where the regression model gave a maximum, there was no clear relationship between the optimum calculated by us and the optimum given by the authors, as follows from Figure 8a.

5.3.2.3. Optimum phosphorus levels based on feed conversion ratio

The same procedure as described in 5.3.2.2. was applied to the feed conversion ratio. In 26 per cent of the experiments $\hat{c}_2$ was <0, thus the optimum was a maximum. The comparison of the estimates of the phosphorus levels with the minimal feed conversion ratio and the optimum by the authors is shown in Figure 8b.

The very weak relationships between the calculated optimum and the optimum given by the authors both in 5.3.2.2. and in 5.3.2.3. could, for example, be due to the inaccuracy of the estimates $-\hat{c}_1/2\hat{c}_2$. However, this concerns only half of all the experiments. Even so, these weak relationships and the fact that often only two levels of phosphorus were used, gives sufficient reason to doubt the reliability of the recommended optima. The authors might, however, have also taken other factors into account.

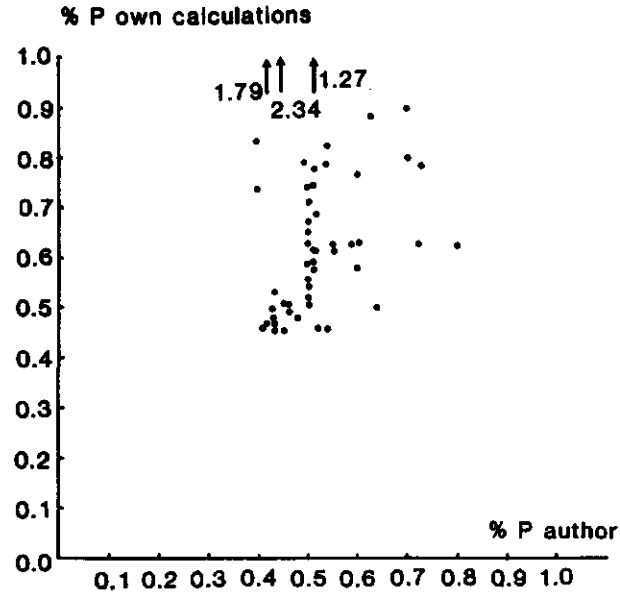

Figure 8a Estimated P levels at maximal growth rate in relation to the optimum given by the authors

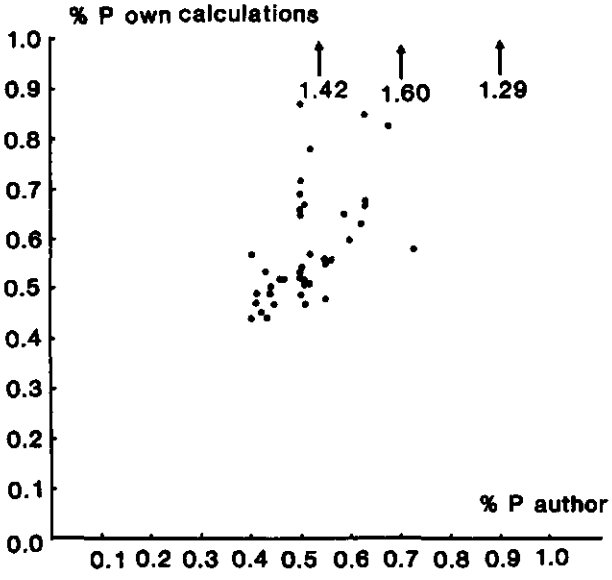

Figure 8b Estimated P levels at minimal feed conversion ratio in relation to the optimum given by the authors

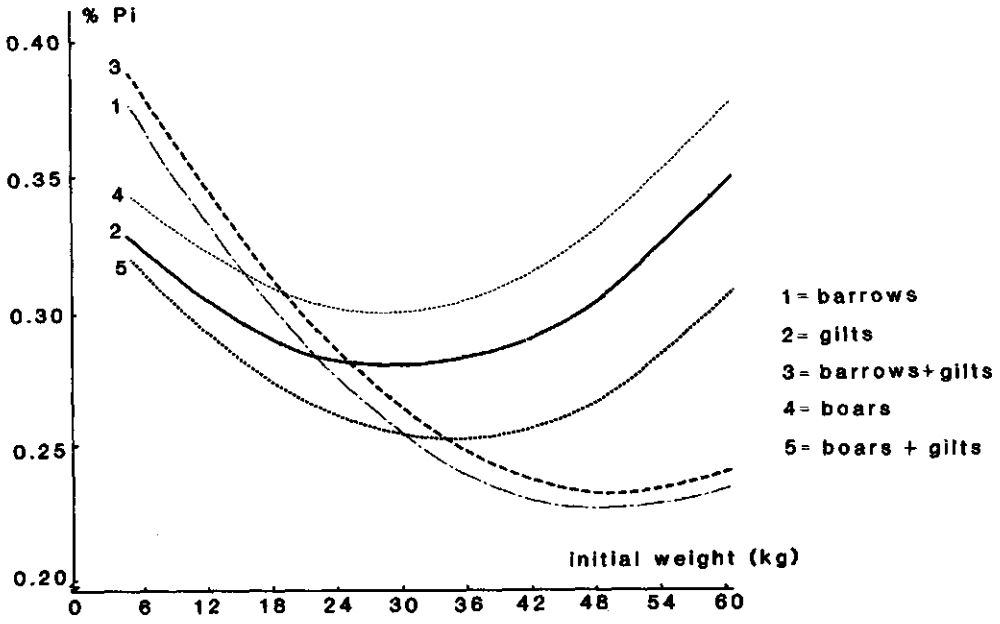

Figure 9 Pi optima, estimated on basis of the optima given by the authors for sexes 1 to 5, corn or sorghum-soybean meal diets and at ad libitum feeding

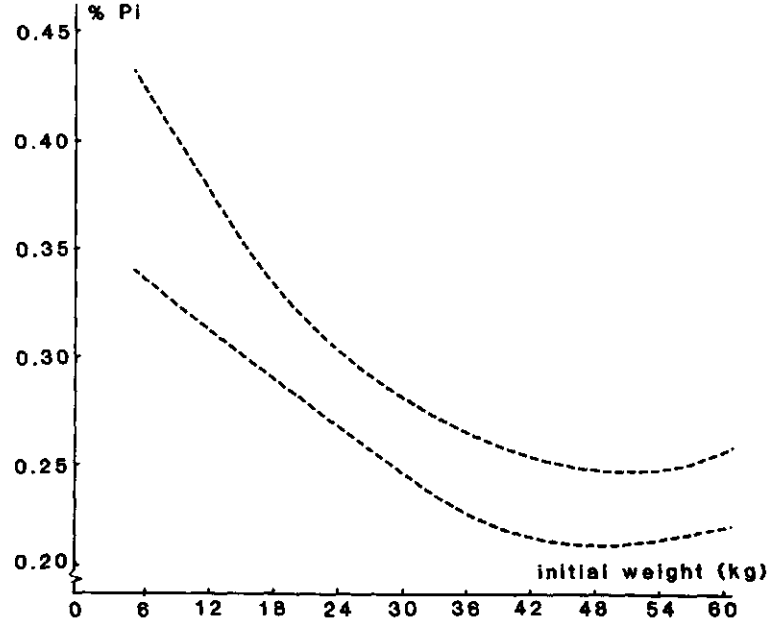

Figure 10 95% confidence interval for the mean Pi optimum for barrows and gilts receiving corn or sorghum-soybean meal diets at ad libitum feeding

5.3.3. Regression analyses

5.3.3.1. General

Using regression analysis, we investigated to what extent the factors Level of feeding (L), Sex (S), type of Diet (D) and the variables initial weight (B), B^2 and B^3 might have influenced the optimal phosphorus level (PO) as given by the authors.

As dependent variable we not only used PO but also some corrected values of PO i.e. POi, PO_c and POi_c:

1) the optimum total phosphorus content given by the authors: PO
2) the optimum inorganic phosphorus content: POi (=PO-phytate P)
3) PO, corrected for the NE_f content of the diet: PO_c (= POi x 8.79/NE_f; NE_f in MJ/kg diet)
4) POi, corrected for the NE_f content of the diet: POi_c (=POi x 8.79/NE_f; NE_f in MJ/kg diet)

On the basis of the assumptions, the most extensive model, with all independent variables (L, S, D, B, B^2 and B^3) and their interactions, was fitted using the method of least squares. The differences between the individual observations and the fitted values (i.e. the residuals) showed a strong relationship with the initial weight; the lower the initial weight, the greater the residuals.
Under several other assumptions for the variance of the residuals, the above mentioned model was fitted again. Plots of the weighted residuals against the initial weight showed that the variance of the deviations was approximately inversely proportional to $(\text{initial weight})^{1.5}$. In all the regression analyses which will be presented, the variance was corrected accordingly.
Calculations showed that for all four dependent variables only the interaction B x S was significant; $(B)^3$ was not significant. Sex was not significant, but because B x S was significant Sex was left in the model. When PO_c or POi_c were used instead of PO and POi respectively, the effect of Level of feeding reached a much higher level of significance.
Finally, for all four dependent variables, the following model was adopted in order to correct the optimum levels given by the authors for factors such as initial weight, sex, diet, etc.

$$E(\underline{P\ optimum}_{ijk}) = \text{constant} + b_i B + c_2 B^2 + Sex_i + Diet_j + L_k + \underline{e}, \text{ with } \underline{e}$$

normally distributed and $\text{var}(\underline{e}|B) = \sigma^2 B^{-1.5}$ in which E (P optimum$_{ijkB}$) is the expected value of the P optimum for sex_i, at $diet_j$, Level of feeding$_k$ and initial weight (B). The values of constant, c_1, c_2 and b_i are from the above mentioned final model. In Figure 9, the relationship is shown between POi and initial weight for all sexes at ad libitum feeding and diet 1 (corn or sorghum-soybean meal). In Figure 10, the 95 per cent confidence interval for the mean POi with barrows and gilts (sex = 3) receiving corn or sorghum-soybean meal diets at ad libitum feeding is given. In Figures 11 and 12, the same results are given for mixed feeds with more than three feedstuffs, diets which most resemble those used in the Netherlands. Confidence intervals for the less frequently observed diets and sexes and for the restricted feeding level (see Appendix 11) would of course be much more divergent.

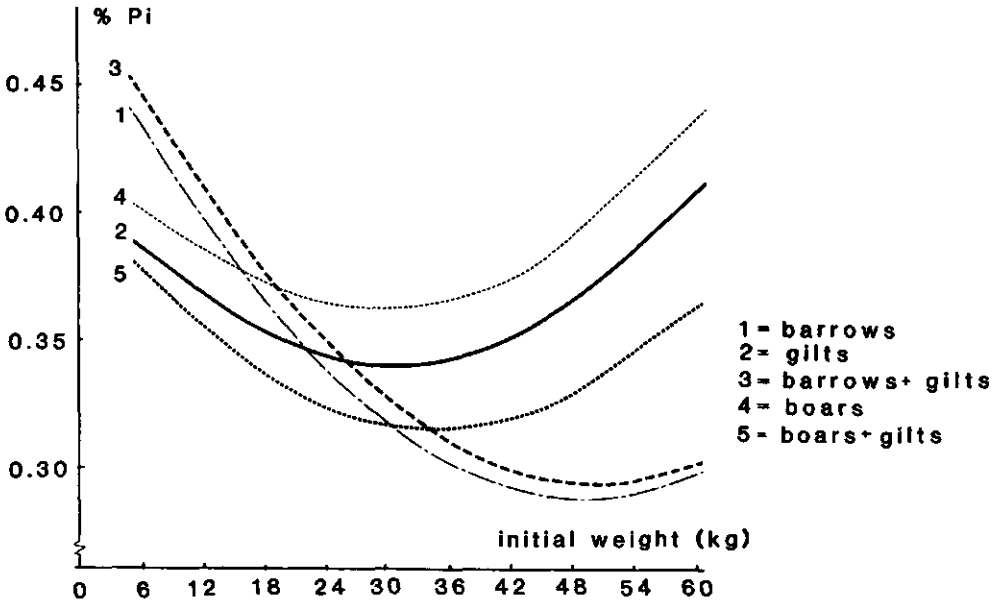

Figure 11 Estimated Pi optima for sexes 1 to 5 receiving diets with more than 3 feedstuffs at ad libitum feeding

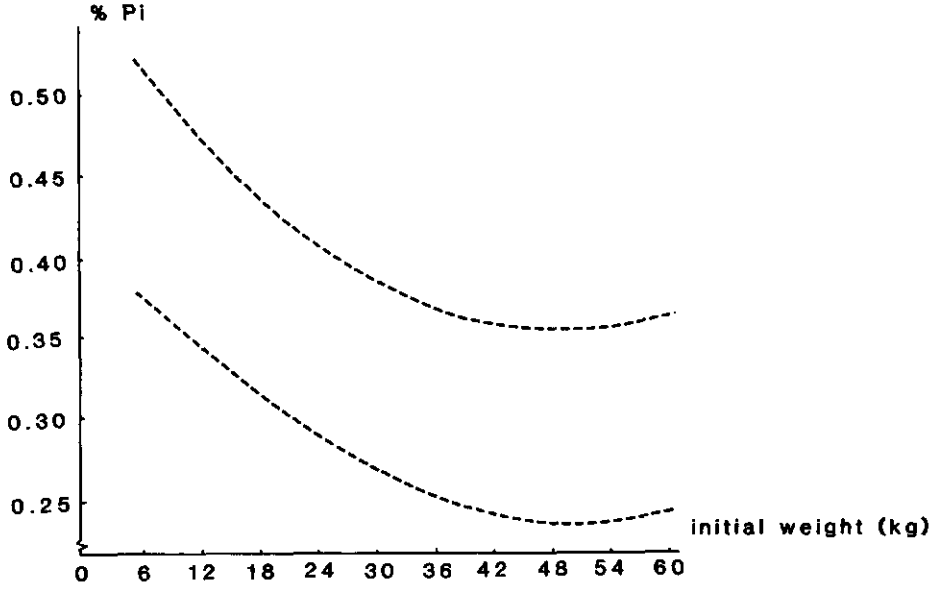

Figure 12 95% confidence interval for mean Pi optimum for barrows and gilts receiving diets with more than 3 feedstuffs at ad libitum feeding

5.3.3.2. Analysis of the observations of growth rate and feed conversion ratio

Because the P optima given by the authors are not clearly based on objective criteria, we submitted the observations concerning growth rate and feed conversion ratio to a direct analysis.

Analysis of growth rate

To obtain a more homogeneous variance, from each experiment only one observation of the growth rate at one P level was taken at random in the analysis. By means of regression analysis, it was investigated whether the growth rate depended on: initial weight, $(\text{initial weight})^2$, P, P^2, level of feeding, type of diet, sex, and whether there were any interactions between the independent variables. The analysis was only done for P = Pi, because this had also been done in 5.3.3.1. and in the Netherlands, Pi is usually used for formulating the diets on phosphorus content.

On the basis of plots of the residuals, it was decided to carry out the analyses under the assumption that the variance of the residual deviations was inversely proportional to the initial weight. For growth rate, the most extensive model with the independent variables (Pi, Pi^2, B, B^2, L, S, D) and several interactions (BxPi, B^2xPi, BxPi^2, PixL, PixD, PixS) was fitted. In contrast to the calculations in 5.3.3.1. no effect could be detected between growth rate and sex or type of diet. With only the significant effects in the most extensive model, and in the case of a significant interaction also the main effect, the following final model for growth rate was adopted:

$$E\,(\underline{\text{growth rate}}_{kBPi}) = c_o + c_1 Pi + c_2 Pi^2 + c_3 B + c_4 B^2 + c_5 B.Pi +$$

$$c_6 B^2.Pi + c_7 B.Pi^2 + c_8 B^2.Pi^2 + \text{Level of feeding}_k + \underline{e}, \text{ with } \underline{e} \text{ normally}$$

distributed and var $(\underline{e}|B) = \sigma^2 B^{-1}$, in which $E\,(\text{growth rate}_{kBPi})$ is the expected value of the growth rate at Level of feeding$_k$ (k = 1, 2), initial weight B and the inorganic phosphorus level Pi. Estimates of the regression coefficients are given in Appendix 12a. There is good agreement with the results given in section 5.3.3.1. The Pi optima can be estimated by:

$$POi = -\frac{(c_1 + c_5 B + c_6 B^2)}{2(c_2 + c_7 B + c_8 B^2)}$$ and this was always a maximum.

In Figure 13, the dotted line represents the estimates for the Pi optima and the unbroken lines give the 95 per cent confidence interval for these estimates from 35 to 60 kg initial weight (based on Fieller's theorem; see also Hoekstra, 1982).

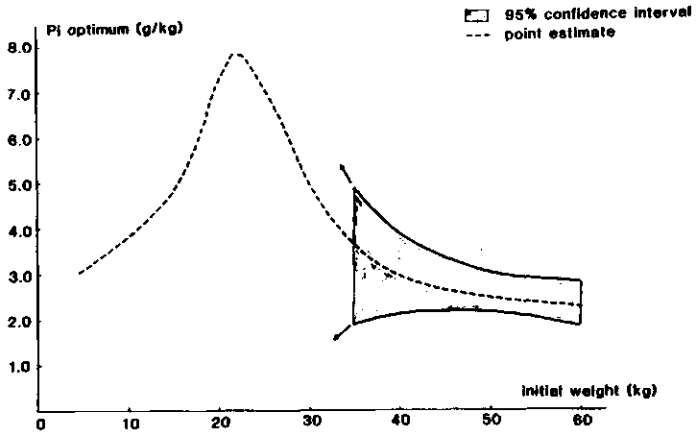

Figure 13 Pi level with maximum growth rate as a function of the initial weight

Analysis of feed conversion ratio

In the same way as for the observations of the growth rate, from each experiment one phosphorus level with the accessory observation for feed conversion ratio was used in the analysis. The regressions were again done under the assumption that the variance is inversely proportional to the initial weight. The results of the regression analysis finally led to the following model:

$$E\,(\underline{\text{feed conversion}}_{jBPi}) = c_o + c_1 Pi + c_2 Pi^2 + c_3 B + c_4 B.Pi + \text{type of diet}_j$$

$+ \underline{e}$, with $\underline{e}$ normally distributed, and var $(\underline{e}|B) = \sigma^2 B^{-1}$

Estimates of the regression coefficients are given in Appendix 12b. The Pi level, that gives the lowest feed conversion ratio is:

$$POi = -\frac{(c_1 + c_4 B)}{2\,c_2}$$

According to this model, the relationship between B (initial weight) and POi is linear. POi can be estimated by substituting the c_i's by the $\hat{c}_i$'s. The dotted line in Figure 14 gives these estimates. The unbroken lines give the 95 per cent confidence interval, which could be drawn over the whole traject of the relevant initial weights.

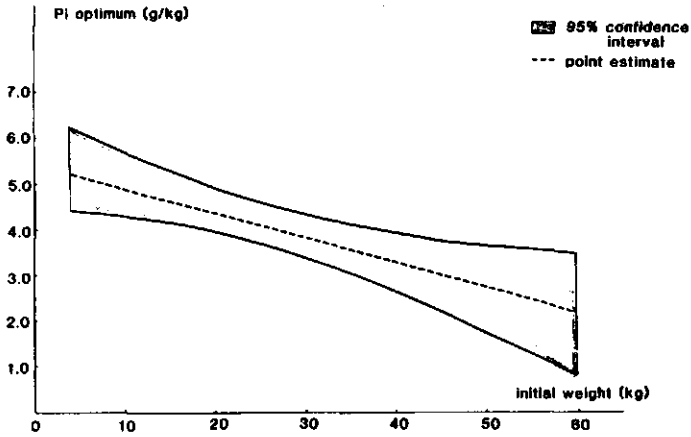

Figure 14 Pi level with minimal feed conversion rate as a function of the initial weight

5.3.3.3. Comparison of the methods

When the different methods for the estimation of the optimum phosphorus level, as described in the preceeding sections, are compared, it is evident that the initial weight is the variable which has the most effect. From the plots for the optimum Pi level derived from the point estimates for growth rate and for feed conversion ratio (Figures 13 and 14 resp.) it can be seen that there is good agreement above 35 kg. The plots derived from the regression analysis based on the author optimum (section 5.3.3.1), especially at initial live weights lower than 35 kg, give a lower optimum phosphorus level than the point estimates (section 5.3.3.2.). This difference in optimum Pi level can, to a large extent, be explained by the type of diet and sex, which were not significant when point estimates were used. It should be remarked that the confidence intervals are rather wide (± 0.05 per cent P) so that no significant differences can be shown between the different methods. Some preference must to be given to the regression method based on the optimum level given by the authors, because in many cases not only growth rate, feed conversion ratio and feed intake were the criteria used, but also bone ash content and bone breaking strength. It should be remarked that it is still debatable whether maximum bone mineralization is necessary or not for slaughter pigs. Still, the criticism that the authors often only used two levels of phosphorus still holds.

5.3.4. Sex and breed and the phosphorus and calcium requirements

It is not clear whether the phosphorus and calcium requirements of the sexes differ. Most of the feeding experiments were done with mixed sexes (barrows and gilts), but in some cases the results were given for the sexes separately. There does not seem to be any difference in the phosphorus and calcium requirements between barrows and gilts (Cromwell et al., 1970; Newman and Elliott, 1976).
Boars generally have a heavier skeleton at the same live weight than barrows and gilts, which might result in a higher requirement for phosphorus and calcium. Especially above 50 kg live weight, boars retain daily more protein than barrows and gilts. There is a close relationship between protein and phosphorus contents in the animal body. Together this might mean that above 50 kg the phosphorus requirement will be higher than in barrows and gilts. However, in several experiments no differences in the phospho-

rus requirement between boars and gilts could be detected (Kornegay et al., 1977[b]; Hansen and Grøndalen, 1979; Kornegay and Thomas, 1981). Only Bayley et al. (1975[b]) reported that 0.45 per cent phosphorus in the diet was sufficient for optimal growth rate of gilts, whereas boars needed between 0.45 and 0.60 per cent phosphorus, probably due to their higher growth rate. Our calculations showed that there are indications that the requirement for phosphorus of boars exceeds that of barrows above 30 kg live weight (see Figures 9 and 11).
In Chapter 4.2. breed differences in bone content, which might lead to differences in mineral requirements, have already been mentioned. No further information, however, is available at present.

5.4. EFFECT OF DIETARY CA/P RATIO ON PERFORMANCE AND HEALTH OF PIGS

Besides the level of phosphorus in the diet, in many experiments the Ca/P ratio was also varied. It is clear from most of these experiments, that Ca/P ratios in the diets of 1.0 and lower or 2.0 and higher result in a lower performance of the pigs than between 1.0 and 2.0 (Nielsen et al., 1971; Poppe et al., 1973; Stockland and Blaylock, 1973; Bayley et al., 1975[a]; Doige et al., 1975; Florescu et al., 1975; Hanssen, 1975; Rincon et al., 1976; Greer and Lewis, 1977; Pond et al., 1978[a,b]; Hansen and Grøndalen, 1979; Pfirter et al., 1979; Mahan, 1982; Koch and Mahan, 1985; Reinhart and Mahan, 1986). In some experiments, the Ca/P ratio in the diet was varied between 1.0 and 2.0. Chapple et al. (1979[a]) found that a Ca/P ratio of 1.18 was better than 1.44 and Van Kempen et al. (1976) observed that a Ca/P ratio of 1.3 resulted in a better performance than a Ca/P ratio of 1.9. Doige et al. (1975) concluded that a Ca/P ratio of 1.25 gave the best results. In their studies, Reinhart and Mahan (1986) came to the conclusion that at a low dietary phosphorus level, a Ca/P ratio above 1.3 resulted in reduced performance, whereas at high dietary phosphorus levels no detrimental effects were observed until the Ca/P ratio exceeded 2.0.
Extreme Ca/P ratios in the diet can lead to health problems in pigs. Libal et al. (1969) observed kidney disturbances when a diet with 0.65 per cent calcium and 1.95 per cent phosphorus was fed, so that these animals had to be slaughtered prematurely.
Also leg problems can be observed with extreme Ca/P ratios in the diet (Bayley and Thomson, 1969; Nielsen et al., 1971; Poppe et al., 1973; Pond et al., 1978[b]). According to Doige et al. (1975), extreme Ca/P ratios in the diet impair both performance and skeletal development. Such impairments are said to be minimal, provided that at low levels of either element the Ca/P ratio is 1.25.

5.5. EFFECT OF DIETARY PHOSPHORUS AND CALCIUM LEVELS ON LOCOMOTORY DISTURBANCES

It is clear that a higher concentration of phosphorus and calcium in a diet results in a higher concentration of these minerals in bones and in stronger bones as well. However, it is less clear whether a low intake of these minerals results in more locomotory disturbances; the often mentioned leg weakness.
In the early seventies in the Netherlands, many slaughter pigs had to be culled prematurely because of leg weakness, which led to great economic losses. In those days it was thought that the daily mineral supply might be responsible, so in many cases the concentrations of phosphorus and calcium in the diets were raised (Verdijk, 1969; Van der Kerk,1974). Other research workers, however, found no beneficial effect of higher mineral concentrations in the diet on the incidence of leg weakness (Walker et al., 1966; Dutie and Lancaster, 1964). In an extensive study on leg weakness in pigs, the "Studiecommissie" (1977) came to the conclusion that at a higher

level of feeding, leg weakness is observed more often than at a lower level of feeding, but it was doubtful whether a too low mineral concentration in the diet was responsible for this leg weakness. The higher incidence of leg weakness is often associated with selection of pigs towards the meaty type, and with housing conditions. The more rapid increase in live weight might not keep pace with development of the skeleton. Osteochondropathic changes are therefore greatest in joints where mechanical stress occurs. Other factors, such as animal or breed and possibly acid-base balance (Van der Wal et al., 1985) also play a part.
Extreme Ca/P ratios in the diet (below 0.5 or above 3.0) result in more locomotory disturbances (Nielsen et al., 1971; Poppe et al., 1973; Doige et al., 1975).
So far, no clear relationship has been shown between an increased supply of phosphorus and calcium and reduction in the incidence of leg weakness (Pointillart and Guéguen, 1978; Arthur et al., 1980; Calabotta et al., 1982[a]; Calabotta et al., 1982[b]; Kornegay et al., 1983; Brennan and Aherne, 1984; Mahan and Cera, 1985).

5.6. EFFECT OF DIETARY PHOSPHORUS LEVEL ON SLAUGHTER QUALITY

There is not much information about the effect of the phosphorus level in the diet on the slaughter quality of pigs, because in most of the publications it is not mentioned. Cromwell et al. (1970) observed in one experiment that 0.40 per cent phosphorus in the diet resulted in more backfat thickness and a lower ham + loin percentage than with higher phosphorus levels. However, no differences were found in backfat thickness, ham percentage or in ham-loin index by Stockland and Blaylock (1973) with various levels of calcium and phosphorus in the diet. This was also the case in the experiments described by van Kempen et al. (1976) who observed a significant higher killing-out percentage (quadratic effect) at 0.5 and 0.6 per cent phosphorus than at 0.4 and 0.7 per cent phosphorus, 77.3 and 76.6 respectively.

5.7. CONCLUSIONS

The requirements in several countries for total phosphorus of pigs expressed as g/kg diet vary enormously, partly due to differences in the availability of dietary phosphorus and to the criterion used: minimum or optimum requirement.
Extensive regression analyses of many feeding experiments showed that the authors' conclusions about the optimum phosphorus level in the diet can be criticized. It was also shown in these calculations that the optimum phosphorus level depends on factors such as initial weight, sex and possibly breed of the animals, type of diet and level of feeding and on the criteria used.
Most information concerning the optimum phosphorus level comes from studies with corn or sorghum plus soybean meal diets. The calculated inorganic phosphorus levels from the regression analyses based on the author's optimum for barrows and gilts agree well with the inorganic phosphorus levels in N.R.C (1979). This allows us to derive the optimum levels of inorganic phosphorus in corn or sorghum plus soybean meal diets at several live weights of barrows and gilts together from Figure 9. The estimations of the optimum phosphorus levels of other sexes than barrows and gilts together show that those for boars and gilts are somewhat higher above 30 kg live weight. However, due to the low number of observations above 30 kg it is difficult to indicate how large these differences are. The optimum phosphorus levels in diet 4, which most resembles the Dutch diets, can be derived from Figure 11; it is the result of only 14 experiments. From this Figure it can be concluded that for such diets the optimum levels of phosphorus

from 10 to 50 kg live weight of barrows and gilts together are at least 0.05 per cent of inorganic phosphorus higher than for corn or sorghum plus soybean meal diets. Differences of such a size can also be found in the recommended requirements in most Western European countries.

In order to compare the recommended phosphorus levels more efficiently, the available or apparently digestible phosphorus per unit of ME should be used instead of total phosphorus or inorganic phosphorus per kg diet.

From most feeding experiments it can be concluded that the Ca/P ratio in the diet should be close to 1.25. However, at higher phosphorus levels, when related to the phosphorus requirement, a higher Ca/P ratio does not induce detrimental effects so soon.

So far, no clear relationship has been shown between an increased supply of phosphorus and calcium and reduction in the incidence of leg weakness.

Experiments

(part two)

Figure 13. Overview of the trials (Chapter 6)

Trial number	described in Chapter	live weight (kg)	time of execution	purpose
VV326, VV327	7	35, 42	Nov-Dec 1973	length of adaptation and collection period
VV342, VV343	7	90, 90	March-April 1974	"
VV328 to VV330	7	76,83,86	May-June 1974	"
VV358 to VV360	7	38, 67 and 97	May-August 1974	live weight on Ca and P balance
VV367 to VV378	12	46, 70 and 98	July-October 1974	Ca and P concentration in diet on Ca, P, and N balance
VV395 to VV410	9	36, 55, 75 and 96	Jan-April 1975	lysine concentration in diet for barrows and boars
VV411 to VV422	13	41, 66 and 99	Jan-April 1975	Ca concentration and phytase actitivity on Ca and P balance
feeding exp.1 trial 1	16	25-111	Jan-May 1975	low Ca and P concentrations in diet on leg weakness and bone characteristics
VV430 to VV445	13	44, 70 and 99	July-Oct 1975	Ca concentration and phytase activity on Ca and P balance
feeding exp.1 trial 2	16	28-111	June-Nov 1975	low Ca and P concentrations in diet on leg weakness and bone characteristics
VV478 to VV495	15	36, 68 and 99	Dec 1975-April 1976	Cu concentration in diet and pelleting on Ca and P balance
feeding exp.1 trial 3	16	27-116	Dec 1975-April 1976	vitamin D and railway sleepers on leg weakness and bone characteristics
VV534 to VV548	14	39, 69 and 96	Aug-Dec 1976	P sources
VV566 to VV571	8	42, 68 and 95	Jan-May 1977	level of feeding; comparative slaughter technique
VV572 to VV583	11	40, 64 and 93	Jan-May 1977	crude fibre and lysine concentrations
VV 588	13, 16	66	April 1977	basal diet feeding exp. 3 trial 1
VV597 to VV599, VV603 to VV605	10	52, 67 and 84	June-Sept 1977	type of fat and Ca concentration in diet
VV606 to VV628, VV622	10	97, 109, 120, 73	Sept-Nov 1977	type of fat
VV614	13,16	90	Dec 1977	basal diet feeding exp. 3 trial 3
VV656 to VV671	9	36, 48, 77 and 98	Febr-May 1978	lysine concentration in diet for boars and gilts
VV672 to VV675	10	50-110	June-Aug 1978	type of fat and Ca concentration diet
VV688 to VV692	13	56,66, 74, 62 and 72	June-Aug 1980	digestibility of P in feedstuffs
VV680	13, 16	73	Sept 1979	basal diet feeding exp. 3 trial 5
LV06 to LV09	13	66 and 87	Aug-Oct 1979	type of diet (cereals vs by-products)
VV701 to LV708	8	28, 48, 74 and 98	Jan-April 1980	energy and protein intake; comparative slaughter technique
LV25 to LV28	8	33, 56, 81 and 103	March-April 1981	level of feeding
VV730 to VV736, VV738	13	43,56,62,72,91,101,114	April-Sept 1981	digestibility of P in feedstuffs
LV29 to LV32	8	43, 66, 94 and 112	Jan-April 1982	level of feeding
VV740, VV743	16	97, 96	Febr-March 1982	level of vitamin D in diet; digestibility and feeding trial
VV744, VV752	13	50, 87	March-June 1982	digestibility of P in feedstuffs
VV 749	13, 16	111	July 1982	basal diet feeding exp.3 trial 6
VV767 to VV770	13	66, 82, 106 and 112	Aug-Oct 1982	digestibility of P in feedstuffs
VV776 to VV780	13	44,53,63,76 and 80	Nov 1982-Jan 1983	digestibility of P in feedstuffs
VV784,VV789,VV790	13	74,117 and 84	Jan,April,Febr. 1983	digestibility of P in feedstuffs
VV800, VV802	13	106 and 68	Oct-Nov 1983	digestibility of P in feedstuffs
piglet trial	14	10 to 26	Sept-Dec 1984	P sources

6. EXPERIMENTAL METHODS

6.1. GENERAL

In this study, an experiment consists of several digestion and balance trials on the same groups of animals during their growth period from 25 kg to slaughter weight. All trials are registered at the I.V.V.O. institute with a VV or LV number. The difference between VV and LV trials is that in LV trials the energy balance (respiration trials) also was measured, which was not the case with the VV trials. One VV or LV trial consists of a digestibility or balance trial with a group of pigs (usually three or four) of about the same live weight at the same time. For example, VV 412 is the balance trial of (three) pigs at a live weight of about 66 kg performed in March 1975. In Figure 15, an outline is given of all the trials described in this thesis.

6.2. ANIMALS

Up to trial VV 622, the animals, good quality pigs, were purchased from commercial farms in the neighbourhood of the Institute. After VV 622 and in all LV trials, the animals were used from our experimental farm. At the beginning of the study, mostly barrows were taken, but later on boars were used more and more. In most trials, the animals were from the Dutch Yorkshire (GY) breed, in a few trials Dutch Landrace (DL) or crossbred GY x DL were used.

6.3. DIETS

The piglets used for the study received a commercial starter diet up to a live weight of about 25 kg, after which time they were given the experimental diet. Before composing the experimental diet, almost all the feedstuffs from which it was made were first analysed for calcium and phosphorus to ensure that the diet contained the desired concentration of these minerals. The experimental diets are described in detail in the relevant chapters and the analyses of the composite feedstuffs are given in Appendix 13. A standard premix and 0.25 per cent NaCl and, if desired, limestone ($CaCO_3$) and phosphorus from an inorganic source were added to the diet. The composition of the premix was not always the same because of the experimental design, or they were supplied by different manufacturers or the premixes from the same manufacturer varied somewhat in composition in the course of time. The composition of the different premixes used is given in Appendix 14. Per kg diet mostly 2 000 IU vitamin D_3 was added.
In nearly all the trials, the experimental diets were fed to the same group of animals from 25 kg to slaughter weight. Thus, the animals got the same diet throughout the whole experiment.
Usually, the level of feeding was according to the Dutch standards for energy (C.V.B., 1973), which is based on Net Energy for fattening pigs (NE_f) (C.V.B., 1977). This means that at 30 kg 12.30 MJ NE_f, at 50 kg 18.10 MJ NE_f, at 75 kg 23.02 MJ NE_f and at 100 kg 26.52 MJ NE_f was fed. There was a daily increase in the amount of feed given of 15 g up to 80 kg live weight and, subsequently, of 10 g, to keep pace with live weight change. To prevent feed refusals, 95 per cent of this standard was given when the animals were on metabolism crates. In some trials, other levels of feeding were used; these will be given in their description. Per kg diet, 2 to 2 1/2 l of water were added just before feeding time, so that the feed was not soaked. The animals were fed twice a day, at approximately 07.00 hr half the daily ration was given and at 16.00 hr the other half.

6.4. HOUSING

Except for trials VV 367 to VV 378, the animals were housed in a stall with individual feeding places and group housing. This stall was well-ventilated and could be heated, so that the animals were always within their thermo-neutral zone. A small amount of straw was used for bedding. In this room, the balance and digestion experiments were also done. In trials VV 367 to VV 378, the animals were group fed except when on metabolism crates. From VV 566 onwards and in all LV trials the animals were on metabolism crates from the first up to the last collection period just before slaughter.

6.5. WEIGHING THE ANIMALS

Up to VV 548, the animals were weighed once a week when not on metabolism crates, just before being put on metabolism crates and just after finishing the collection period. The growth rate during the balance period in these trials was taken as the increase in live weight during the preliminary and collection period together divided by the number of days. From VV 566 and in all LV trials the animals were weighed one or two days before and after the collection period and the daily growth rate was based on that time interval. Being on metabolism crates was suspected to increase gut contents so that the earlier weighing procedure might give a biased value of growth rate.

6.6. GENERAL DESIGN OF THE BALANCE EXPERIMENTS

Three or four animals per diet were usually used for the balance experiments. In most experiments, the mineral balances of each animal were determined three times, at live weights of approximately 35 to 45 kg, 60 to 70 kg and 90 to 100 kg. During the balance experiment, the animals were kept on galvanized metabolism crates, where separation of faeces and urine is possible. When the animals had not previously been on metabolism crates, the preliminary period was extended to at least ten days, otherwise it lasted seven days. In nearly all trials the collection period lasted ten days.

6.7. SAMPLING AND PREPARATION OF SAMPLES FOR ANALYSIS

6.7.1. Feed

The daily feed portions were weighed out separately for each animal and stored in plastic bags. All the daily rations of one trial were weighed out on the same day. Immediately before weighing every second or third bag, a spoonful of feed was put into a bottle with a tight fitting stopper to collect a composite sample. This sampling was done in triplicate. The samples were air-dried at 60 to 70°C; weight loss was measured and the samples ground using a sieve with 1 mm aperture after which they were used for further analysis. Feed refusals, which hardly occurred, were air-dried and weighed but not analysed because of the small amount.

6.7.2. Faeces

During the collection period, the faeces were quantitatively collected twice a day, preserved with formalin, 2 ml of which was added to the faeces each day, and stored in a collection vessel at 4°C. In trials up to VV 742, the collected faeces were weighed at the end of the trial, water equal to about one third of their weight was added and the total amount weighed again. The faeces were then thoroughly homogenized, and two random samples were taken. From trial VV 627 onwards, no formalin was used but the faeces

were stored at -20°C and homogenized in a mixer after thawing at the end of the collection period. Again, two random samples were taken.
The samples were taken to the laboratory, mixed again and sub-sampled for immediate analysis of dry matter and, if desired, of N. Another sub-sample of about 300 g was air-dried at 60-70°C, ground and used for further analysis. The above procedure was chosen to prevent loss of dry matter and N during air-drying.

6.7.3. Urine

The urine was collected in a bucket already containing 100 ml HCl (17 per cent) for preservation. On top of the bucket, a funnel with cottonwool was placed to prevent pollution with hair or faeces particles. Each day the produced urine was weighed and a constant proportion of the total amount (about 1.4 per cent) put into a bottle with a tight fitting stopper. This bottle was stored at 4°C. After trial VV 566, all the urine was stored at 4°C and at the end of the collection period a sample was taken for further analysis.

6.7.4. Water

A sample of the tap water was taken weekly and a composite sample of one month was analysed for calcium and magnesium; phosphorus was below detection level.

6.7.5. Radius

One day after slaughter, the forelimb was cut at the elbow joint and the radius desiccated and divested of muscle and connective tissue. Both proximal and distal epiphyses were removed, only the middle section was used (diaphyses) afterwards called "radius". Removal of both epiphyses was necessary, because in some bones mechanical measurements were also carried out, which can only be done on the diaphysis. Immediately after cleaning, fresh and underwater weight were determined and length and thickness of the midshaft of the radius on two sides were measured. After this, the radius was vacuum dried, extracted with diethylether or hexane, and vacuum-dried again to obtain its amount of fat-free dry matter. The bone was then crushed and ground in a small hammermill through a 0.5 mm sieve after which time it was ready for further chemical analysis.
For mechanical examination of the fresh radius within 24 hours after slaughter, bending tests were carried out by the Metaal Instituut T.N.O. (Metal Research Institute T.N.O.) in Apeldoorn (see also van Kempen et al., 1976). A load strain diagram was made by means of which the distortion strain (the point at which permanent distortion occurs) and the maximum strain (the load at which the bone breaks) were determined.

6.7.6. Tail vertebra

The fifth tail vertebra was roughly cleaned, after which it was boiled in water for some time, so that the adhering connective tissue and cartilage could be removed easily. After ether extraction and vacuum-drying, the whole vertebra was analysed for the concentration of ash, calcium, magnesium and phosphorus.

6.7.7. Carcass

After the animals had been killed, blood and emptied entrails were collected in a bucket, weighed and freeze dried. The carcass was weighed, carefully divided into two sides and the right half of each carcass deep

frozen and stored for further analysis. For preparing samples for analysis, the carcass was sawed frozen into pieces of 0.5 to 1 kg after which all pieces were chopped together in a cutter. After mixing, four or five samples were taken of 500 g each, put in a plastic bag and stored at -20°C. Before the samples of the carcass were analysed for ash, calcium, magnesium and phosphorus an amount of 200 g was taken, freeze dried, de-fatted and milled in a hamermill with a sieve diameter of 0.5 mm

6.8. ANALYSES AND ANALYTICAL METHODS

Apart from determination of dry matter, calcium, magnesium and phosphorus concentration in feed and faeces, sometimes the concentration of nitrogen, XL, XF, ash and energy were also determined for calculation of the NE_f content of the diet. In most diets, the concentration of phytate phosphorus was also determined. In urine specific gravity, the concentration of calcium, magnesium and phosphorus and sometimes also that of N and energy were determined. In the radius and in the tail vertebra, the concentration of calcium, magnesium and phosphorus were determined. In the tap water, only the concentrations of calcium and magnesium were determined.
The analytical methods for determining the concentration of dry matter, ash, XL, XF and energy in feed and faeces are described in NEN 3332, NEN 3329, NEN 3148, NEN 3327 and NEN-ISO 1928 respectively. In some trials, the concentration of XL was estimated by hexane extraction or by hexane after boiling with dilute hydrochloric acid (Berntrop method). The concentration of nitrogen in urine was estimated by the Kjeldahl method, that in feed and faeces by the Dumas method.
The concentrations of calcium and magnesium were determined by atomic absorption and that of phosphorus by spectrophotometry also after dry ashing. The concentration of phytate phosphorus was estimated by the method described by Oshima et al. (1964).

6.9. CALCULATIONS

Minerals are ingested from feed and drinking water, the sum is called intake. The excretion of minerals with faeces was corrected for the addition of water during sample preparation of the faeces. Concentrations in faeces and urine were corrected for added preservatives.
The following definitions and formulas were used:

absorption (g) = intake of mineral (g) - mineral (g) in faeces

$$\text{absorption \%} = \frac{\text{absorption (g) of mineral}}{\text{intake of mineral (g)}} \times 100$$

retention (g) = intake of mineral (g) - mineral (g) in faeces - mineral (g) in urine

$$\text{retention \%} = \frac{\text{retention (g) of mineral}}{\text{intake of mineral (g)}} \times 100$$

NE_f = 10.84 DXP + 36.11 DXL + 6.28 DXF + 12.68 DXX (equation 1)
(NE_f in kJ/kg diet; XP, XL, XF and XX in g per kg diet

NE_f (est.) = NE_f estimated from the values given for the separate feeds of the diet in the C.V.B. Feeding Table (1977)

NE_f (calc.) = NE_f calculated with equation 1 from chemical composition and digestibility coefficients determined in the VV of LV digestibility trial with that diet

The retention of the minerals during the whole experimental period was extrapolated from the results of the balance trials in four different ways:

1) the whole period in which the experimental diet was given was divided into about three or four equal sections, about 28 or 21 kg live weight, respectively. The total intake of a mineral during each section was multiplied by the retention percentage of that mineral in the balance trial of that section; finally, the results for the three or four sections were added;
2) the total feed intake of the experimental diet was multiplied by the mean retention percentage of the mineral, obtained by simply averaging the three or four retention percentages;
3) the number of days of each section was multiplied by the retention of the mineral of that section and the results for the three or four sections were added together;
4) the total number of days that the animals were used in the experiment were multiplied by the mean daily retention of the mineral.

The results of methods 3 and 4 were corrected for differences in feed intake during, before and after the balance trials, which means that the calculated retention was multiplied by the quotient:

$$\frac{\text{total realized intake of T in that section}}{\text{mean daily intake of T in balance trial x number of days in that section}}$$

The mineral retentions calculated according to the four methods did not differ more than 5 per cent. Therefore, only the mean of the four methods is presented and used in further calculations and discussions.
With regard to the calculations for the total retention of minerals it is assumed that the retention (per cent) will not be altered substantially if the mean feed intake during the balance period differs somewhat from that during the whole experiment. In most cases, the differences in feed intake were no more than 3 per cent.

6.10. STATISTICAL ANALYSIS

Most of the data collected were subjected to analysis of variance when orthogonal, or carried out by means of regression technique when inorthogonal. The dependent and independent variables in the regression analyses and other details of statistical analyses will be given in separate chapters. Analyses were done using the statistical package GENSTAT.

7. PRELIMINARY EXPERIMENTS

7.1. INTRODUCTION

In this chapter, the results of several preliminary experiments will be given. These experiments were performed to improve the technique of the mineral balance trial, to collect data on optimal duration of the preliminary period after a dietary change and on optimal duration of the collection period. Furthermore, the effect of changing to a diet with a low calcium and phosphorus concentration on mineral balances was examined. Finally, mineral balances were determined on animals under conditions not far removed from those in practice, i.e. when the same diet was fed from 23 kg to slaughter weight.

7.2. LENGTH OF PRELIMINARY PERIOD AND COLLECTION PERIOD

7.2.1. Experimental design (see also Table 19)

7.2.1.1. Trials VV 326 and VV 327

The barrows for these trials were bought from a pig farmer in the neighbourhood at about 30 kg live weight. They were fed the basal diet (without addition of extra calcium and phosphorus) 19 days before the first collection period of trial VV 326 was started. The pigs were put on metabolism crates 13 days before the start of the collection period. The respective experimental diets (diets 1 to 5) were offered five days before the collection period started (=start of preliminary period). The collection period of ten days was divided into two successive periods of five days. Faeces and urine from both periods were collected separately and analysed. After terminating VV 326, the animals stayed on the metabolism crates but were put onto other experimental diets, and eight days later the collection period was started again (VV 327). This was also divided into two periods of five days.

7.2.1.2. Trial VV 342

After trial VV 327 the animals were used for a digestion trial, and then a commercial diet was offered for 27 days. Diet 1 was then given to three animals for 19 days, after which time a collection period of two successive periods of five days was started. For this trial, the pigs were put on metabolism crates seven days before the start of the collection period.

7.2.1.3. Trial VV 343

After trial VV 327, the animals were used for a digestion trial, and then a commercial diet was offered for 46 days. The basal diet was then given to three animals for 21 days, after which time a collection period of two successive periods of five days was started. For this trial, the pigs were put on metabolism crates seven days before the start of the collection period.

7.2.1.4. Trials VV 328, VV 329 and VV 330

The animals used for these trials had already been fed diet 1 from 25 kg live weight onwards. After two months, two barrows were used for VV 328 and VV 329. A collection period of two successive periods of five days was performed. The animals in VV 328 were put on metabolism crates 12 days before the collection period started. After termination of VV 328, the animals stayed on the metabolism crates for 17 days, after which time a second collection period of two periods of five days was started (VV 329).

In this trial, each animal wore a harness attached to a plastic bag in which to collect the faeces.
VV 330 was done using two females which had been fed diet 1 for 78 days before the two collection periods, each of five days, was started. A technique was developed to collect the faeces and urine separately. This resulted in a piece of equipment consisting of a box covered with smallmesh wire-netting which was placed at a slope of approximately 45 degrees behind the animal. These females had already been on the metabolism crates for 19 days before the collection period was started.

7.2.2. Diets

In these experiments, the diets were derived from a basal diet composed of the following feedstuffs (g/kg):

		Some estimated characteristics of this diet are:		
maize	300	DXP	146	g/kg
barley	250	NE_f	9.04	MJ/kg
milo	150	lysine	8.2	g/kg
soybean meal	200	calcium	2.0	g/kg
oat husk meal	50	phosphorus	3.9	g/kg
grass meal	50			

The basal ration was supplied with the usual vitamins and minerals (see Appendix 14) with the exception of calcium and phosphorus. Calcium and phosphorus were then added to the basal diet to get the following experimental diets:

diet 1: basal diet plus $CaCO_3$ to get 0.64 per cent calcium and 0.45 per cent phosphorus in the dry matter; no supplementary phosphorus was used;
diet 2: basal diet plus dicalcium phosphate and $CaCO_3$ to get 0.86 per cent calcium and 0.60 per cent phosphorus in the dry matter;
diet 3: basal diet plus dicalcium phosphate and $CaCO_3$ to get 1.04 per cent calcium and 0.73 per cent phosphorus in the dry matter;
diet 4: basal diet plus Hostaphos and $CaCO_3$ to get the same concentration of calcium and phosphorus as in diet 2;
diet 5: basal diet plus Hostaphos and $CaCO_3$ to get the same calcium and phosphorus concentration as in diet 3.

Hostaphos consisted of 39 per cent disodium phosphate $Na_2HPO_4.2H_2O$, 33 per cent dicalcium phosphate ($CaHPO_4$) and 28 per cent dimagnesium phosphate ($MgHPO_4.3H_2O$).

The diets for trials VV 342, VV 343 and VV 328 to 330 came from another batch of feedstuffs than the ones used in trials VV 326 and VV 327. The amount of feed offered was 25 per cent below the Dutch standards for energy, with a daily increase of 10 g of feed.

7.2.3. Results and discussion

7.2.3.1. Effect of dietary change in calcium and phosphorus concentration on the absorption of these minerals

In this section the results will be given of trials in which the effect of a dietary change in mineral concentration on the absorption was studied in order to obtain some information on the desired length of the preliminary period. Because the animals had already received the diets (except for the calcium and phosphorus concentration in them) for 19 days or more, one can assume that they had already become adapted to the organic matter. Moreover, the animals had been on the metabolism crates for seven days or more, which is also regarded to be long enough. Furthermore, because of the difference of only five days, no effect of age or live weight on a change in digestibility or absorption percentage can be expected.
Because of the short length of the five day collection periods, it was feared that irregular excretion of faecal dry matter might conceal the actual absorption percentage of calcium and phosphorus. It was, therefore, decided to compare the calcium and phosphorus concentration in the faecal dry matter between the two consecutive five day collection periods. The results are given in Table 19. It is assumed that an animal has not become adapted to the mineral supply if the difference in mineral concentration in the faeces is more than 5 per cent. The results from VV 326 and VV 327 indicate that in about half the cases the animals had not become sufficiently adapted to the new diet. The results of animal 78 show that when the collection period started with diet 5 (VV 327) the animal had already become adapted (diets 3 and 5 had the same calcium and phosphorus concentration). This was also the case with animal 79 on diets 4 and 2.
The results from VV 342 and VV 328, and VV 329 and VV 330 indicate that the animals had already become adapted when the preliminary period had lasted 27 days or more. The results from VV 343 show that when the diet is changed to one with very low calcium and phosphorus concentrations, not all animals had become adapted to the diet after 21 days. Two animals in this trial, in contrast to what was expected, had an even higher concentration of minerals in the faecal dry matter in the second five day collection period. This might indicate that the rate of adaptation is also animal-dependent. Furthermore, the length of adaptation also seems to be dependent on the size of the difference in mineral concentration of the diet.
From the results given in Table 19 it can be concluded that an adaptation period of 14 days is too short if there is a substantial change in the mineral concentration of a diet, and that in most cases 21 days seems to be sufficient. This means that experiments using a latin square design with a short preliminary period are not suitable for mineral balance studies, as done by Vipperman et al. (1974). Partridge (1983) also concluded from his experiments with young pigs that the use of a change-over design with a relatively short adaptation period is not appropriate, due to carry-over effects and possibly age effects. Furthermore, Schenkel and Müller (1984) observed in pigs of 24 kg live weight that a sudden change from a diet with a high concentration of calcium and phosphorus (11.6 and 7.3 g/kg T resp.) to one with a low concentration of these minerals (1.2 and 5.3 g/kg T resp.) even resulted in a negative calcium retention during the first seven days after the change. In experiments on rats, Schaafsma (1981) also came to the conclusion that the adaptive response to diets low in calcium was not yet complete after one week.

Table 19. Effect of dietary change on the Ca and P concentration in the faecal dry matter (CP = collection period; PP = pre period

trial VV	animal no.	body weight during CP (kg)	diet* before PP	diet	days on crate prior to (CP)	length of PP (days)	CP I (5 days) d_T (%)	in faecal T Ca (%)	P (%)	CP II (5 days) d_T (%)	in faecal T Ca (%)	P (%)
326	75	34	19 d diet b	1	13	5	76.1	1.70	1.37	78.7	1.73	1.44
"	76	37	"	1	13	5	77.5	1.76	1.36	78.8	1.81	1.47
"	77	35	"	2	13	5	79.5	2.22	1.70	78.8	2.51	1.83
"	78	36	"	3	13	5	77.5	2.71	1.92	78.5	3.03	2.06
"	79	33	"	4	13	5	76.9	2.24	1.57	76.2	2.34	1.64
"	80	36	"	5	13	5	77.0	2.79	1.76	76.7	2.73	1.88
327	75	41	15 d diet 1	3	28	8	77.5	2.75	1.85	78.5	3.04	1.95
"	76	44	"	4	28	8	74.3	2.13	1.47	79.9	2.17	1.46
"	77	42	15 d diet 2	1	28	8	78.1	1.71	1.48	81.0	1.80	1.52
"	78	43	15 d diet 3	5	28	8	74.5	2.86	1.99	77.3	2.84	1.98
"	79	40	15 d diet 4	2	28	8	75.2	2.46	1.66	78.0	2.38	1.57
"	80	42	15 d diet 5	1	28	8	76.7	1.81	1.41	77.9	1.68	1.30
342	76	88	27 d diet c	1	7	19	77.7	1.42	1.18	78.4	1.39	1.15
"	78	92	"	1	7	19	78.8	1.38	1.06	75.3	1.41	1.12
"	80	91	"	1	7	19	76.1	1.41	1.13	77.3	1.42	1.10
343	75	93	46 d diet c	b	7	21	77.7	0.62	1.10	78.4	0.61	1.13
"	77	88	"	b	7	21	79.9	0.68	1.29	79.0	0.75	1.35
"	79	92	"	b	7	21	81.3	0.66	1.19	78.0	0.75	1.40
328	2	76	from 25 kg diet 1	1	12	61	75.8	1.34	1.14	77.7	1.22	1.12
"	7	76	"	1	12	61	75.9	1.46	1.16	80.2	1.40	1.15
329	2	87	"	1	29	17	78.3	1.32	1.19	76.5	1.33	1.16
"	7	85	"	1	29	17	77.8	1.54	1.26	79.4	1.59	1.20
330	1	87	"	1	19	78	76.0	1.86	1.31	77.7	1.87	1.34
"	6	86	"	1	19	78	81.3	1.59	1.23	83.0	1.64	1.28

* diets	b(asal)	1	2	3	4	5	c(ommercial)
Ca(g/kg T)	2.3	6.4	8.6	10.6	8.6	10.2	9.8
P (g/kg T)	4.5	4.5	6.0	7.2	6.0	7.4	6.6

7.2.3.2. The duration of the collection period

In this part, the results of a collection period of five days will be compared with the results of a collection period of ten days.
As shown in the previous part, because not all the animals had become adapted to the diets in the first collection period, the absorption and retention percentages for calcium and phosphorus of the two periods of five days could not be used for comparison. Therefore the absorption and retention percentages were corrected by assuming that the calcium and phosphorus concentration in the dry matter of the faeces in the two periods of five days was equal to the average of the two concentrations in the first and second collection period for the same animal. In this calculation, the results from VV 330 were not used because the two animals had an extremely high digestibility of the dry matter.
To compare the accuracy of the two successive collection periods of five days with that of one collection period of ten days, the variances of the digestibility of the dry matter and the absorption and retention percentages for calcium and phosphorus within the diets and trials were calculated. In this calculation s^2_{CPI}, s^2_{CPII} and s^2_{CP} are the variances for the first and second collection period of five days and of the collection period of ten days, respectively. After that, the s^2 values of all diets were added together according to the following formula:

$$\text{total } s^2_{CP} = \sum_{i}^{1} \frac{s^2_1(n-1) + s^2_2(n_2-1) + \ldots\ldots s^2_i(n_i-1)}{(n_1-1) + (n_2-1) + \ldots\ldots (n_i-1)}, \text{ in which}$$

$s^2_i = s^2$ of diet i and n_i = number of observations for diet i.

The main results of these calculations are given in Table 20.

Table 20. Comparison of the variance of two successive collection periods of five days with one collection period of ten days for corrected values (n=22)

	5 days s^2_{CPI}	5 days s^2_{CPII}	10 days s^2_{CP}	$\frac{2\, s^2_{CP}}{s^2_{CPI}+s^2_{CPII}} \times 100$
d_T (%)	2.0	2.0	0.8	43
absorption % of Ca	12.8	15.9	7.8	54
absorption % of P	11.2	21.4	8.1	50
retention % of Ca	9.1	17.0	6.2	47
retention % of P	9.7	15.6	4.5	35

The results given in Table 20 show that elongation of the collection period from five to ten days, in most cases s^2 for ten days, is about 50 per cent of the s^2 of five days and for the retention percentage of phosphorus even 35 per cent; theoretically one would expect 50 per cent.
In a further calculation s^2 for the uncorrected values was also calculated for those experiments in which the animals had already adapted to the diet. This was done for VV 342, VV 343, VV 328, VV 329 and for VV 326/327 for diet 1 with animals 75 and 77 and for diet 4 with animals 76 and 79. These results are given in Table 21.

Table 21. Comparison of the variance of two successive collection periods of five days with one collection period of ten days for uncorrected values (n=14)

	5 days s^2_{CPI}	5 days s^2_{CPII}	10 days s^2_{CP}	$\frac{2s^2_{CP}}{s^2_{CPI}+s^2_{CPII}} \times 100$
d_T(%)	1.6	2.8	0.8	36
absorption % of Ca	11.1	29.6	8.6	43
absorption % of P	5.4	42.5	9.7	40
retention % of Ca	8.4	33.6	8.5	41
retention % of P	11.2	35.0	5.8	25

The results of the uncorrected values in Table 21 indicate an even greater advantage of a collection period of ten days than for the corrected values. For the retention percentage of phosphorus s^2 of a collection period of ten days is 25 per cent of the mean s^2 of the first and second collection period of five days. It must be remarked that the results of the first and second collection period of five days are dependent on each other because they are linked. This is also one reason why the percentage is lower than 50 per cent. It must be concluded that a collection period of ten days is preferable to two collection periods of five days separated by a few days without collection; it is clear that in a short collection period, variances are increased due to too great an influence of variation in daily faeces excretion.
To complete these experiments, the results of the calcium and phosphorus balances of VV 342, VV 343 and VV 328 to VV 330 are given in Appendix 15. The results of VV 326 and VV 327 are not given because the animals had not become adapted to the diets in most cases.

7.3. THE COURSE OF THE ABSORPTION AND RETENTION OF CALCIUM AND PHOSPHORUS DURING THE GROWTH PERIOD (TRIALS VV 358 TO VV 360)

7.3.1. Materials and methods

The experiment was done using three barrows of the Dutch Yorkshire breed. The diet was composed of the following feedstuffs (g/kg):

barley	100
maize	405
milo	100
wheat middlings	170
soybean meal	105
whey powder low in lactose	25
fish meal	20
alfalfa meal	50
minerals and vitamins	25

Some estimated values of this diet are:	
XP (g/kg)	160
XL (g/kg)	32
XF (g/kg)	47
NE_f (MJ/kg)	9.08

The diet was prepared in three batches, so that during each balance period slightly different rations were fed to the animals. From a body weight of 22 kg onwards, the animals received the experimental diet and at about 38, 67 and 97 kg live weight the calcium and phosphorus and nitrogen balances were determined. The animals were fed 10 per cent below the Dutch standards for energy.

7.3.2. Results and discussion

The experiment proceeded without any difficulties. Some data of the performance are given in Table 22.

Table 22. Performance of the animals

	animal number 98	99	100
initial weight (kg)	23.5	22.0	25.0
growth rate (g/d)	662	636	671
feed conversion ratio*	2.88	3.01	2.87
feed intake (kg/d)	1.91	1.92	1.93
days in experiment	114	121	114

* corrected to a common NE_f concentration of the feed of 8.79 MJ/kg

The results of some chemical analyses of the diet are given in Table 23.

Table 23. Analysed chemical composition of the diets in trials VV 358 to VV 360

live weight	batch 1 20-50 kg	batch 2 50-80 kg	batch 3 80-100 kg
T (g/kg)	878	873	854
O (g/kg T)	939	933	929
XP "	182	181	178
lysine "	7.7	8.4	7.9
Ca "	9.7	11.5	12.6
P "	8.4	9.1	9.4

The results of the chemical analyses (Table 23) and the digestibility of the dry matter (Appendix 15) indicate that the three batches are different in composition, which could be caused by differences in chemical composition of the feedstuffs used because they were not reserved for the whole experiment.
The results of the calcium and phosphorus balance and, in order to complete the measurements, those of the N balance, are given in Appendix 15.
The analyses of variance showed significant effects of the live weight of the animal on the calcium, phosphorus and nitrogen retention per day ($p < 0.01$). No effect of live weight on the absorption percentages of calcium and phosphorus was found, but there was a tendency towards lower absorption percentages at 67 and 97 kg than at 38 kg live weight. The interpretation of the effect of live weight on the absorption and retention percentages of calcium and phosphorus is difficult, because the calcium and phosphorus concentrations in the three batches were not identical.
From the results, it can be calculated that during the experimental period 725 g calcium and 463 g phosphorus were retained which is 9.41 and 6.06 g, respectively per kg live weight gain.
We may conclude from this experiment, that because of changes in mineral utilization during the growth period, it is necessary to measure the calcium and phosphorus retention at several live weights. Also, it is better to use the same diet for the whole growth period in order to explain changes in mineral utilization during the growth period. Therefore, the whole diet must be prepared as one batch, or the ingredients for the diet must be reserved.

7.4. CONCLUSIONS

Research in this chapter has shown that due to carry-over effects for phosphorus and calcium balance studies, much attention should be paid to an adequate length of an adaptation period. When there is only a small change in dietary concentration of these minerals, a period of 14 days will suffice. However, if there is a substantial change in that concentration (e.g. twice the concentration), then the adaptation period should be at least 21 days.

A collection period of ten days is preferable to one of five days because the variance in absorption and retention percentages during a period of ten days is about half that of five days. This is also true for the digestibility of the dry matter.

Up to slaughter weight, the absorption and retention of phosphorus and calcium change with time, so that it is necessary to measure the phosphorus and calcium retention at several live weights. It is better to use the same diet then for the whole period to avoid a long adaptation period (carry-over effects), and to explain changes in mineral utilization in the growth period.

8. EFFECT OF THE LEVEL OF FEEDING AND ENERGY SUPPLY ON ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM

8.1. INTRODUCTION

In this chapter, the effect of the level of feeding and of the energy supply on absorption and retention of phosphorus is studied in order to find out whether or not the concentration of phosphorus in the diet at a higher level of feeding or energy supply should be raised. Furthermore, the accuracy of the balance experiments was checked and the course of phosphorus retention in the whole body studied.
For this study four experiments were set up. In the first three experiments, the phosphorus and calcium concentration of the diet was kept constant, whereas two feeding levels were applied, differing by 25 to 29 per cent. In the fourth experiment the energy supply was varied, (levels of 100, 110 and 125 per cent) but the daily intake of the minerals was kept constant. More details on this experiment and the concomitant feeding trial are given by Lenis and Metz (1983; experiment 3). The experiments were done with gilts or boars.
In addition to the balance measurements in experiments 1 and 4, the comparative slaughter technique was also applied to check the accuracy of the balance measurements. Furthermore, in the first experiment animals were slaughtered at various live weights to supply information on the course of phosphorus and calcium retention in the whole body from 25 to 110 kg. As experiments 2 and 3 are almost identical their results are reported together.
Literature on the effect of level of feeding and energy level has been reviewed in Chapter 2.2., while the course of the retention of phosphorus and calcium has been reviewed in Chapters 4.3.2. and 4.4.3.

8.2. EFFECT OF LEVEL OF FEEDING: FIRST EXPERIMENT (TRIALS VV 566 to VV 571)

8.2.1. Materials and Methods

Twenty-nine crossbred female piglets (Dutch Landrace x Dutch Yorkshire; full and half sibs) were group-housed but fed individually. At the start of the experiment, three piglets were slaughtered as zero time controls. The other animals were divided into 13 pairs of full sibs of about the same live weight. Within each pair, one animal was fed somewhat above the Dutch standards for energy: daily feed supply (energy content of 8.96 MJ NE_f/ kg feed) was 1.375 kg at 25 kg, 2.270 kg at 50 kg, 2.730 kg at 75 kg and 3.110 kg at 100 kg live weight. The other animal in each pair consumed 80 per cent of this quantity of feed daily; so independent of its own weight. The same diet was used for both treatments. The diet, composed of commercial pig feed ingredients (see Table 24) was rich in protein, in order to prevent the protein supply limiting the growth rate of the pigs on the low feeding level. Also, the calcium and phosphorus concentration in the diet were sufficient for a high growth rate. When the animals on the high feeding level reached live weights of about 30, 50, 70, 90 and 110 kg, two pairs of pigs were slaughtered. Three pairs were used for energy, N, Ca and P balance trials at live weights of 42, 68 and 94 kg. At about 100 kg live weight these pigs were also slaughtered. At slaughter, the blood was collected and weighed. The entrails collected, emptied and weighed. Each carcass was weighed and carefully divided into two sides. Blood, entrails and the right half of each carcass were deep frozen and stored for further analysis.
The right halves of the carcasses were dissected according to the EC reference dissection method, which is a complete tissue separation as developed by the *Bundesanstalt für Fleischforschung* at Kulmbach (Federal Republic of

Germany). Total bones except for the radius which was dissected separately, total muscles, total fatty tissues and total offal (mainly skin) from each carcass half were homogenized and chemically analysed. The same was also done for entrails and blood together after freeze-drying.
Metz et al. (1980) described the results of this experiment as far as protein or fat retention is concerned. Here, only the results with regard to the minerals and nitrogen will be given. The results of the mineral and N balance were subjected to analysis of variance.

Table 24. Feedstuff composition (g/kg), analysed chemical composition and feeding value of the diet

maize	360	T (g/kg)	858
barley	50	O (g/kg T)	943
maize gluten feed	130	XP "	210
wheat middlings	100	XL "	26
soybean meal solv. extr.	220	XF "	79
tapioca	60	Ca "	7.1
grass meal	20	P "	5.8
cane molasses	30	Mg "	2.3
$CaCO_3$	9.1	DXP "	165
dicalcium phosphate	5.2	NE_f (calc.;MJ/kg T)	9.71
minerals + vitamins (maize)	15.7		

8.2.2. Results

8.2.2.1. General

Due to a fire at the Institute, the analytical results of the samples of the bones of three animals were destroyed, so the results are incomplete. The performance of the animals is given in Table 25.

Table 25. Performance of the animals

	group fed animals all		balance animals > 100 days in exp.			
feeding level	high	low	high	low	high	low
number of animals	10	10	3	3	2	3
growth rate (g/d)	698	575	716	627	706	580
feed conversion ratio*	2.52	2.48	3.02	2.76	3.08	2.78
feed intake (kg/d)	1.86	1.51	2.28	1.83	2.21	1.83

*corrected to a common energy concentration of 8.79 MJ NE_f/kg

8.2.2.2. Balance experiment

During the balance trials, animal 21 on the high feeding level had considerable feed refusals at 71 and 99 kg and its pair-mate 14 on the low feeding level at 88 kg. Therefore, the results of the balances of these animals were discarded. Detailed results of the balance experiments are given in Appendix 16, while a summary of the analysis of variance is given in Table 26.

Table 26. Summarized results of the first experiment (df= 4)

	high level	low level	sed	sign. level
d_T (%)	80.0	81.2	0.6	ns
d_N (%)	79.1	81.4	1.7	ns
absorption % of Ca	36.8	41.9	1.8	*
absorption % of P	35.3	38.4	2.2	ns
retention % of Ca	35.4	40.0	1.3	*
retention % of P	30.4	33.5	1.6	ns
retention of Ca (g/d)	5.34	4.85	0.32	ns
retention of P (g/d)	3.65	3.23	0.26	ns
retention of N (g/d)	21.1	18.2	1.2	ns

8.2.2.3. Slaughter experiment

The results of the amount of dry matter, N, fat, ash, calcium and phosphorus present in the slaughtered animals are given in Appendix 17. In most cases, the concentrations of the minerals in the ash, in the fat-free dry matter as well as the Ca/N and P/N ratios did not differ significantly for the high and low levels of feeding (see Tables 27, 28 and 29). Only the concentration of calcium in the ash of the entrails and the concentration of phosphorus in the ash of fatty tissues was significantly higher at the low level of feeding. Also, the concentration of phosphorus in the fat-free dry matter of the entrails was higher at the low level of feeding. The concentration of ash in the fat-free dry matter of the fatty tissues at the high level of feeding was significantly higher than at the low level of feeding.
The Ca/N ratio in the entrails was significantly higher at the low level of feeding, while there was a tendency for the P/N ratio in the bones to be higher at the higher level of feeding. A small increase was noticed in the ash concentration in the fat-free dry matter of the bones and radii with increasing age of the animals. This was also the case with regard to the concentration of calcium and phosphorus in the ash of the radius, the Ca/N ratio and the P/N ratio in the bones.
The relative amounts of ash, calcium and phosphorus in the separate fractions are given in Table 30. There were hardly any differences between the high and low levels of feeding.

8.2.3. Discussion

8.2.3.1. Balance experiment

The absorption percentages of calcium and phosphorus were higher at the low level of feeding in the first balance period, slightly higher in the second period and almost the same in the third period (Appendix 16). Thus, in this diet the absorption could be adapted to the mineral requirement of the animal. The same tendency as for the absorption percentage is true for the retention percentage, except for the third period in which the retention percentage at the high level of feeding was somewhat higher. The retention of the minerals per day was higher at the higher level of feeding and the differences became greater with age. It is somewhat surprising that the Ca/P ratio of the retention at ± 42 kg live weight is about 1.3 whereas it might be expected to be about 1.6 (see Chapters 4.3.2. and 4.4.3.).

Table 27. Calcium and phosphorus concentration in ash (g/kg) of different fractions of all animals (mean and rsd; H = high feeding level, L = low feeding level; all = all animals)

	calcium					phosphorus				
	H	L	rsd	sign.	all	H	L	rsd	sign.	all
bones	369.0	368.6	3.6	ns	368.7	178.8	178.3	1.0	ns	178.7
muscles	6.4	6.7	0.8	ns	6.6	149.1	148.3	17.6	ns	150.1
fatty tissues	25.5	23.6	6.3	ns	24.0	151.4	166.0	18.2	p=0.06	159.7
offal	33.5	34.8	12.9	ns	34.4	122.7	129.0	12.4	ns	125.2
entrails	16.3[a]	18.2[a]	2.0	*	16.7[a]	186.3	191.0	19.7	ns	186.3
radius	371.8	372.5	2.4	ns	372.1	181.0	179.2	3.4	ns	180.1
total animal	277.1	278.8	8.4	ns	277.8	172.6	172.0	2.7	ns	172.6

a) values increase with increasing age of the animal

Table 28. Calcium, phosphorus and ash concentration in fat free dry matter (g/kg) of different fractions (mean and rsd; H = high feeding level, L = low feeding level, all = all animals)

	ash					calcium					phosphorus				
	H	L	rsd	sign.	all	H	L	rsd	sign.	all	H	L	rsd	sign.	all
bones	536.4[a]	533.6[a]	6.1	ns	527.6[a]	197.0	196.6	2.8	ns	194.3	96.0	95.1	1.5	ns	94.3
muscles	59.6	60.5	5.6	ns	59.9	0.4	0.4	0.1	ns	0.4	8.8	8.9	0.5	ns	8.9
fatty tissues	59.2	45.6	14.9	*	53.2	1.5	1.1	0.6	ns	1.3	9.1	7.5	2.8	ns	8.5
offal	31.1	30.3	1.8	ns	31.4	1.0	1.0	0.3	ns	1.0	3.8	3.9	0.5	ns	3.9
entrails	67.8	67.4	5.8	ns	69.2	1.1	1.2	0.1	*	1.1	12.6	12.7	0.6	ns	12.8
radius	694.2[a]	692.1[a]	7.2	ns	690.7[a]	258.1	257.8	2.5	ns	257.0	125.7	124.0	3.0	ns	124.4
total animal	171.0	169.6	7.8	ns	169.3	46.7	47.5	2.8	ns	46.9	29.3	29.2	1.2	ns	29.2

a) values increase with increasing age of the animal

Table 29. Calcium to nitrogen and phosphorus to nitrogen ratios (g/kg) of different fractions (mean and rsd; H = high feeding level, L = low feeding level; all = all animals)

	calcium/nitrogen					phosphorus/nitrogen				
	H	L	rsd	sign.	all	H	L	rsd	sign.	all
bones[a)]	2720	2670	80	ns	2640	1320	1290	30	p=0.07	1280
muscles	2.6	2.7	0.5	ns	2.7	59.1	59.2	3.3	ns	59.5
fatty tissues	10.0	8.6	2.6	ns	9.1	58.7	59.9	6.4	ns	59.6
offal	6.4	6.5	2.2	ns	6.6	23.9	24.4	2.8	ns	24.6
entrails	7.3	8.1	0.6	**	7.6	83.5	86.2	5.0	ns	85.9
total animal	353	360	20	ns	355	220	222	8	ns	221

a) values increase with increasing age of the animal

Table 30. Relative amounts of ash, calcium and phosphorus in the different fractions (g/kg; mean and rsd; H = high feeding level, L = low feeding level; all = all animals).

	ash					calcium					phosphorus				
	H	L	rsd	sign.	all	H	L	rsd	sign.	all	H	L	rsd	sign.	all
bones	742	748	18	ns	745	988.4	988.8	1.7	ns	988.6	769	775	12	ns	771
muscles	167	167	18	ns	165	3.9	4.0	0.8	ns	4.0	146	143	11	ns	144
fatty tissues	35	32	4	p=0.06	33	3.3	2.8	0.6	p=0.07	2.9	31	31	4	ns	31
offal	20	18	1	*	19	2.4	2.3	0.2	ns	2.4	14	13	2	ns	14
entrails and blood	36	35	3	ns	38	2.0	2.1	0.2	ns	2.1	40	38	5	ns	40

8.2.3.2. Slaughter experiment

General

From the analyses it appears that within pairs there are no great differences in the amount of ash, calcium and phosphorus present in the animals. This means that at both levels of feeding, the mineral supply was sufficient for optimal (maximal ?) mineralization of the bones.

The concentration of calcium and phosphorus in the ash of the bones is very constant. The concentration of the minerals in the ash of the other fractions is not as constant as in the bones, but that may be due to random errors because of the low concentration of ash in the dry matter and the low concentration of calcium in the ash. The Ca/P ratio in the animals at slaughter was on average 1.61 and not significantly different between treatments. This ratio is in agreement with the values found in the literature.

It can be seen in Figure 16 that the concentration of ash in the fat-free dry matter of the bones increases considerably up to 50 days (60 kg live weight) after which there is a small increase. This is also found in the concentration of the minerals in the bones expressed per gram nitrogen in the bones, because the concentration increased as the animals became older. This might indicate that up to about 60 kg live weight, an intensive bone formation takes place. A declining concentration of ash in the fat-free dry matter of the offal in the older animal was observed, but no explanation for it can be given. The Ca and P concentrations in the different fractions, expressed per kg fat-free dry matter and per kg nitrogen, agree well with the values found in the literature.

From Table 30 it can be concluded that nearly all the calcium of the animal is found in the bones and that it is not necessary to analyse for calcium in the other fractions. Most of the phosphorus is found in bones, but rather high quantities are also found in the muscles. These values are in good agreement with those of Moinizadeh (1975).

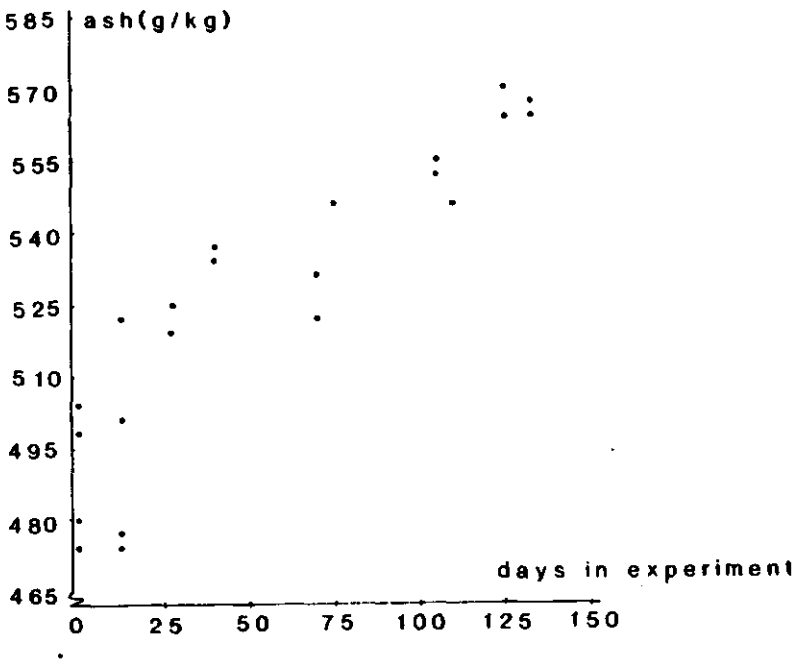

Figure 16 Relationship between ash concentration in the fat-free dry matter of bones and age of the animals

When the retention percentages of phosphorus and calcium of the balance animals at slaughter are compared with that of the group-housed animals which were slaughtered when 104 days or more in the experiment we get the following results (Table 31). This retention percentage of calcium and phosphorus was calculated as the increase of these minerals from the start of the experiment to slaughter, divided by the intake of these minerals in that period.

Table 31. Comparison of the retention percentage at slaughter for Ca and P between balance animals and the group-housed animals slaughtered after day 103 (mean and sd)

animal	calcium		phosphorus	
	balance	group-housed	balance	group-housed
n	2	3	2	3
high feeding level	39 ± 4	39 ± 2	30 ± 4	29 ± 2
low feeding level	42 ± 5	51 ± 3	33 ± 4	38 ± 3

Although the number of observations are low there is a good agreement at the high level of feeding, but at the low level the retention percentage of both minerals tended to be higher for the group-housed animals. The reason for the difference at the low level of feeding is not known.
The retention percentage of calcium and phosphorus of all group-housed animals was calculated. Using the paired-t statistic, it appeared that for those animals which had been in the experiment for 27 days or more, the retention percentages for both minerals were significantly ($p < 0.01$) higher (10 and 7 units, respectively) at the low level of feeding. This is more than the differences between the two levels of feeding for the balance animals.

The total amount of Ca and P present at a given body weight in the range of 25 to 110 kg.
The following model to predict the total amount of Ca and of P in the body at a given body weight for all data of Appendix 17 was used:

$$\ln \underline{y} = c_o + c_1.L + c_2 \ln x + c_3 \ln^2 x + c_4.L.\ln x + \underline{e},\ \underline{e} \text{ is normally distributed}$$

and var $(\underline{e}) = \sigma^2$,
in which ln y = ln calcium (g) or ln phosphorus (g), L = level of feeding, x = the independent variable (W = live weight (kg), EBW = empty body weight (kg), NW = weight of nitrogen (g), FFW = fat-free body weight (kg) and FFEBW = fat-free empty body weight (kg)). This model included the feeding level as an independent variable so that the significance of this factor could be tested. A model with a logarithmic expression for x was chosen because it was shown in the literature review that in this way the best fit could be obtained. The calculations showed a significant effect of level of feeding when W and EBW were used as independent variables, c_3 nor c_4 proved to be significant. In nearly all cases, R^2 was 0.98 or 0.99 (Table 32). We also used x instead of lnx as independent variable but calculations showed that the use of lnx gave slightly better results.
In Table 32 the results for W and EBW are given separately for the high and low levels because of a significant effect of the level of feeding, while for FFW, FFEBW and NW all observations were grouped together because no effect of the feeding level could be demonstrated. To complete this table, the equations for W and EBW of all observations are also given.

Table 32. Amount of Ca and P in the body as a function of different variables

equation no.	equation	n	R^2	rsd*	remarks
1	ln Ca = 1.855 + 1.045 ln W	11	0.99	0.055	high level
2	ln Ca = 2.046 + 1.020 ln W	12	0.97	0.094	low level
3	ln Ca = 2.074 + 1.005 ln W	26	0.98	0.085	all observations
4	ln P = 1.590 + 0.997 ln W	11	0.99	0.045	high level
5	ln P = 1.647 + 1.000 ln W	12	0.98	0.075	low level
6	ln P = 1.724 + 0.975 ln W	26	0.98	0.069	all observations
7	ln Ca = 2.279 + 0.976 ln EBW	11	0.99	0.057	high level
8	ln Ca = 2.271 + 0.996 ln EBW	12	0.97	0.089	low level
9	ln Ca = 2.290 + 0.983 ln EBW	26	0.98	0.080	all observations
10	ln P = 1.995 + 0.931 ln EBW	11	0.99	0.046	high level
11	ln P = 1.865 + 0.977 ln EBW	12	0.98	0.067	low level
12	ln P = 1.934 + 0.953 ln EBW	26	0.99	0.063	all observations
13	ln Ca = -1.315 + 1.038 ln NW	26	0.99	0.066	all observations
14	ln P = -1.558 + 1.006 ln NW	26	0.99	0.050	all observations
15	ln Ca = 1.756 + 1.136 ln FFW	26	0.98	0.086	all observations
16	ln P = 1.415 + 1.102 ln FFW	26	0.98	0.069	all observations
17	ln Ca = 1.972 + 1.126 ln FFEBW	26	0.98	0.073	all observations
18	ln P = 1.625 + 1.092 ln FFEBW	26	0.99	0.054	all observations

*) the variance of W is approximately equal to $\sigma^2.e^{2a}.W^2$ when the coefficient b (slope) is about 1; to calculate the rsd at a given W:

$$rsd_W = \sqrt{rsd \quad e^{2a}.W^2} \quad ; \quad a = \text{intercept}$$

It can be seen from Table 32 that the coefficients for ln W, ln EBW and ln NW are close to 1.00, which means that when the amount of calcium or phosphorus present is related to these independent variables there is hardly any increase or decrease from 25 to 100 kg. This is most pronounced when phosphorus is related to NW in the body. The results of the calculations indicate that the amount of calcium and phosphorus per unit of W and EBW is higher at the low level of feeding than at the high level of feeding (Table 32).

In Table 33 the retention of calcium and phosphorus is given per kg increase of W, EBW and FFEBW. The retention of calcium and phosphorus per kg increase of body weight is in good agreement with the results mentioned in the literature. The ratio of Ca/NW increased from 0.342 at 25 kg body weight to 0.360 at 100 kg, while that of P/NW remained almost constant (from 0.219 to 0.221).

Table 33. Estimated retention of calcium and phosphorus (g) per kg increase of W, EBW and FFEBW at the given weights for all observations together and for the high and low levels of feeding separately for W and EBW

ALL OBSERVATIONS

	Calcium			Phosphorus		
	W	EBW	FFEBW	W	EBW	FFEBW
kg						
25	8.12	9.18	12.15	5.04	5.67	7.47
50	8.15	9.07	13.26	4.95	5.49	7.97
75	8.16	9.01	13.96	4.90	5.38	8.27
100	8.17	8.97	14.48	4.86	5.31	8.49

HIGH AND LOW LEVELS OF FEEDING SEPARATELY

	Calcium				Phosphorus			
	W		EBW		W		EBW	
kg	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW
25	7.72	8.41	8.84	9.53	4.83	5.18	5.48	5.86
50	7.97	8.52	8.69	9.51	4.82	5.18	5.23	5.77
75	8.12	8.59	8.61	9.50	4.82	5.18	5.08	5.72
100	8.22	8.64	8.55	9.48	4.81	5.18	4.98	5.68

8.3. EFFECT OF LEVEL OF FEEDING: SECOND AND THIRD EXPERIMENT (TRIALS LV 25 TO LV 28 AND LV 29 TO LV 32)

8.3.1. Materials and Methods

In two experiments two different types of diets were compared (see Table 34). One diet (diets 1 and 3) was mainly composed of cereals, while the other (diets 2 and 4) was mainly composed of by-products. These types of diets were chosen because the main aim of these experiments was to study the effect on the utilization of ME of diets which differed substantially in carbohydrate fraction. The estimated NE_f of diets 1 and 2 was 9.2 MJ/kg, that of diets 3 and 4 was 9.3 and 9.5 MJ/kg, respectively. The supplementation of DCP and $CaCO_3$ to diets 1 and 2 was regulated so that these diets had the same concentration of inorganic phosphorus. This was not the case for diets 3 and 4.
In these experiments, boars were used in a modified latin square design which is given in the following scheme. H is high level of feeding; L is low level of feeding; the figure indicates the diet:

	Experiment 2				Experiment 3				
	period					period			
	1	2	3	4		1	2	3	4
pair 1	H_1	H_2	H_2	H_1	pair 5	H_4	H_3	H_3	H_4
pair 2	H_2	H_1	L_1	L_2	pair 6	H_3	H_4	L_4	L_3
pair 3	L_1	L_2	L_2	L_1	pair 7	L_3	L_4	H_4	H_3
pair 4	L_2	L_2	H_1	H_2	pair 8	L_4	L_3	L_3	L_4

For calculating purposes, the results of the couples that got H_1 in the four periods were grouped together and called trial LV 25, those of L_1 trial LV 26, those of H_2 trial LV 27 and for L_2 that was trial LV 28. The same was done for H_3, L_3, H_4 and L_4 and called trials LV 29, LV 30, LV 31 and LV 32 respectively.

Table 34. Composition of the diets (g/kg)

	diet 1	diet 2	diet 3	diet 4
experiment	2	2	3	3
barley	411.4	-	-	-
wheat	300	-	-	-
maize	-	-	620	-
cane molasses	30	30	20	20
soybean meal solv.extr.(Brasil)	70	70	-	-
soybean meal solv.extr.(XF>7 %)	-	-	270	-
animal fat	30	45	-	30
grass meal	60	-	-	-
potato protein dried	75	75	-	45
hominy feed USA	-	190	-	230
maize gluten feed	-	220	-	-
tapioca	-	136.5	-	-
citrus pulp	-	119	68	120
linseed expeller	-	95	-	-
wheat middlings	-	-	-	258
rice bran (<3 % husks)	-	-	-	127
groundnut expeller	-	-	-	150
minerals + vitamins: included	23.6	19.5	22.0	20.0
dicalcium phosphate	11.0	8.18	13.0	5.0
limestone	8.25	6.79	4.6	10.6

Up to ± 25 kg, the boars got a commercial pig starter after which they were put on the experimental diets. The animals were so divided among the treatments that litter mates were put on the same diet, but one at the high level of feeding and one at the low level. Four times during the growing period from 30 to 120 kg body weight mineral, N and energy balances were measured. The following feeding schedule was used (MJ NE_f/d):

	body weight (kg)			
	25	50	75	100
high feeding level	11.18	18.64	23.71	27.30
low feeding level	7.92	13.21	16.80	19.35

This schedule was chosen to get an average growth rate on the high and low levels of feeding of 900 and 600 g/d respectively and was based on the estimated NE_f content of the diet.
The results were averaged per pair and subsequently subjected to analysis of variance to examine the effect of period, pair, feed level, diet and the interaction feed level x diet. Detailed results of the energy and N balances are given by Van der Honing et al. (1984).

8.3.2. Results and discussion

8.3.2.1. Experiment 2

One animal had to be replaced after the first measuring period because of considerable feed refusals during the adaptation period for the next diet. On the high level of feeding there were, during the third and fourth periods, some feed refusals. The mean growth rate on the high level of feeding on diets 1 and 2 was 760 and 790 g/d respectively and on the low level of feeding 580 and 510 g/d respectively. The intended high growth rate of 900 g/d was not achieved because of these feed refusals.
The results of the chemical analysis and the feeding value of diets 1 and 2 are given in Table 35. The detailed results of the balance trials of LV 25 to LV 28 are given in Appendix 18, and are summarized in Table 36.

Table 35. Chemical analysis and feeding value of the diets

	diet 1 (cereal)	diet 2 (by-product)	diet 3 (cereal)	diet 4 (by-product)
T (g/kg)	862	887	861	886
O (g/kg T)	939	931	945	926
XP "	211	229	191	230
XL "	55	73	34	92
XF "	45	72	49	73
DXP "	178	175	162	190
NE_f (calc.; MJ/kg T)	10.72	10.03	10.96	10.65
Ca (g/kg T)	8.1	8.5	8.6	9.7
P "	6.4	6.5	6.6	8.8
phytate P (g/kg T)	2.8	3.0	2.6	5.7

Table 36. Summarized results of experiment 2 (df = 6)

	level of feeding				significance	
	high		low			
	diet 1 (cereal)	diet 2 (by-prod.)	diet 1 (cereal)	diet 2 (by-prod.)	diet	level
absorption % of Ca	39	37	46	41	*	*
absorption % of P	47	35	52	36	***	ns
retention % of Ca	37	35	45	38	*	*
retention % of P	36	33	40	33	**	ns
retention of Ca (g/d)	5.8	5.9	5.3	5.2	ns	ns
retention of P (g/d)	4.3	4.1	3.6	3.2	*	***
Ca/N retention (g/kg)	235	209	274	286	ns	ns
P/N retention (g/kg)	175	148	187	175	*	ns

No interactions were observed between diet and level of feeding. The differences in daily Ca retention as a result of the level of feeding was almost significant (p = 0.06). From Table 36 it can be concluded that the absorption and retention percentage of phosphorus was not significantly influenced by the level of feeding but the daily retention of phosphorus was significantly lower at the low level of feeding. When the retention of phosphorus is expressed per g N retained there is no significant difference.

Because the same amount of inorganic P was offered at the same level of feeding the results show that the absorption percentage of P was significantly higher when diet 1 was given. In practice, it is usually assumed that inorganic P, irrespective of its origin, is absorbed equally but the results between diets 1 and 2 show substantial differences. Two reasons for the differences can be given: differences in absorption percentage of phosphorus due to the origin of inorganic P but also differences in absorption percentage of phosphorus present as phytate P due to the fact that the cereal-based diet contained 30 per cent (phytase-rich) wheat.

8.3.2.2. Experiment 3

In this experiment there were hardly any problems. Only five animals on the high level of feeding had some feed refusals (< 50 g T/d). The results of the chemical analysis and the feeding value of diets 3 and 4 are given in Table 34. The detailed results of the balance trials are given in Appendix 19 and are summarized in Table 37. The mean growth rate on the high level of feeding on diets 3 and 4 was 930 and 905 g/d respectively and on the low level of feeding 590 and 636 g/d respectively.

Table 37. Summarized results of experiment 3 (df = 6)

	level of feeding				significance	
	high		low			
	diet 3 (cereal)	diet 4 (by-prod.)	diet 3 (cereal)	diet 4 (by-prod.)	diet	level
absorption % of Ca	43	34	48	37	***	ns
absorption % of P	38	31	43	33	***	ns
retention % of Ca	42	33	47	36	***	ns
retention % of P	35	26	39	28	***	ns
retention of Ca (g/d)	8.2	7.6	6.3	5.5	ns	***
retention of P (g/d)	5.2	5.3	3.9	3.8	ns	**
Ca/N retention (g/kg)	278	247	293	266	***	ns
P/N retention (g/kg)	179	177	183	184	ns	ns

There were no interactions between diet and level of feeding. The level of feeding had no significant effect on the absorption and retention percentages of calcium and phosphorus, but did have one on the retention of these minerals per day. The P/N ratio was close to 180 and was not affected by diet or level of feeding.

8.4. EFFECT OF ENERGY AND LYSINE SUPPLY AT THE SAME DAILY INTAKE OF PHOSPHORUS AND CALCIUM: FOURTH EXPERIMENT (TRIALS VV 693 TO VV 708)

8.4.1. Materials and methods

In this experiment four diets were used, the feedstuff composition of which is given in Table 38. The diets were made at one time from the same batch of feedstuffs. There were three levels of energy (C.V.B., 1974) and two levels of lysine in this experiment, a survey of which is given in Table 39a. The treatments must be seen in relation to the feeding scheme (Table 39b).

Table 38. Composition of the diets (g/kg)

	diet 1	diet 2	diet 3	diet 4
maize	501	385	282	535
maize gluten feed	-	67	150	-
barley	234	259	296	238
soybean meal solv. extr.	147	162	160	130
grass meal	25	27	30	24
potato protein dried	49	54	33	29
cane molasses	20	20	20	20
premix + NaCl	4.72	5.30	5.88	4.72
limestone	6.86	7.98	9.15	6.68
dicalcium phosphate	12.08	12.71	14.17	12.55

Table 39a. Survey of the treatments

treatment	diet	energy level	mean allowance of lysine (g/d)
1	1	C.V.B. + 10%	18.5 + 20%
2	2	C.V.B.	18.5 + 20%
3	3	C.V.B. - 15%	18.5
4	4	C.V.B. + 10%	18.5

Table 39b. Feeding scheme (kg/d)

diet	live weight (kg) 25	50	75	100
1	1.30	2.18	2.74	3.25
2	1.18	1.98	2.48	2.93
3	1.05	1.76	2.20	2.55
4	1.30	2.18	2.74	3.25

In all treatments, the calcium and phosphorus concentration in the diets were chosen so that the daily intake of these minerals was the same.
The animals used in this experiment were crossbred boars (GY (GYxDL)) which weighed about 14 kg upon arrival at the Institute. A commercial pig starter was fed for one week after arrival, after which the experimental diets were supplied. At ± 16 kg live weight, three animals were slaughtered and used as zero time controls. Each diet was fed to four boars twice a day. During the growing period with animals on diets 3 and 4, the absorption and retention of nitrogen, calcium and phosphorus were measured four times. At about 105 kg, all animals were slaughtered, the half carcass taken and the entrails and blood collected for further analysis. This was done to check the accuracy of the balance measurements. Also, the radii of these animals were dissected to compare the amount of calcium and phosphorus in them with the total amount of calcium and phosphorus in the whole body. The results were analysed by analysis of variance.

8.4.2. Results and discussion

8.4.2.1. Balance experiment

There were no problems during the experiment except for some feed refusals in the third and fourth balance periods on diet 4. This resulted in a lower calcium and phosphorus intake than on diet 3. The performance of the animals is given in Table 40.

Table 40. Performance of the animals

	diet**			
	1	2	3	4
initial weight (kg)	18	19	19	19
growth rate (g/d)	936	903	795	917
feed conversion ratio*	2.36	2.27	2.23	2.46
feed intake (kg/d)	2.11	2.02	1.79	2.14
days in experiment	93	95	107	96

* corrected to a common NE_f value of 8.79 MJ/kg.
** see Table 39.

Table 40 shows that the growth rate is very high while the feed conversion ratio is favourable on all diets.
The results of the chemical analyses and feeding value of the diets are given in Table 41. The more detailed results of the balance trials are given in Appendix 20, while a summary of the analysis of variance is given in Table 42.

Table 41. Determined chemical composition and feeding value of the diets

	diet*			
	1	2	3	4
T (g/kg)	867	866	866	868
O (g/kg T)	947	941	932	945
XP "	207	226	222	183
XL "	32	30	30	32
XF "	32	39	44	35
lysine "	10.7	12.0	11.3	8.9
NE_f (calc.; MJ/kg T)	10.62	10.27	10.02	10.61
Ca_f (g/kg T)	7.6	8.6	9.9	7.6
P "	6.7	7.2	8.0	6.6
phytate P (g/kg T)	2.5	2.7	2.9	2.5

* see Table 39.

Table 42. Summarized results of balance experiment 4 (df= 6)

energy supply/d	diet 3 C.V.B.-15%	diet 4 C.V.B.+10%	sed	significance
d_T (%)	81.8	83.5	0.4	***
absorption % of Ca	45.4	46.8	1.0	ns
absorption % of P	43.8	42.4	0.5	*
retention % of Ca	41.3	41.7	1.9	ns
retention % of P	36.0	33.6	0.8	*
retention of Ca (g/d)	6.80	6.26	0.32	ns
retention of P (g/d)	4.62	4.28	0.14	ns
retention of N (g/d)	25.3	26.0	1.4	ns
Ca/N retention (g/kg)	268	238	22	ns
P/N retention (g/kg)	185	164	10	ns

From Table 42 and Appendix 20 it can be seen that the absorption and retention percentages of calcium on both diets are almost the same but those of phosphorus are just significantly different. As in the first three periods the intake of phosphorus was about equal for the two diets, this means that the retention of phosphorus per day was also the same. In the fourth period, the intake of diet 4 was lower than planned due to some feed refusals. Thus, the intake of calcium and phosphorus from diet 4 was not equal to that of diet 3. This has probably resulted in a lower retention of these minerals on diet 4.
There was no significant decline in the absorption percentages of calcium and phosphorus during the four balance trials; the retention percentages of calcium and phosphorus were significantly lower at 100 kg live weight when compared with the other live weights ($p < 0.005$). The Ca/N and P/N ratios of the retention tended to be higher at the lower energy level.
From the balance experiment, the following retention of calcium and phosphorus in the pigs during the whole experiment was calculated (Table 43).

Table 43. Amount of Ca and P retained during the experiment according to the balance experiment

	diet 3		diet 4	
energy supply/d	C.V.B.-15%		C.V.B.+10%	
animal no.	Ca	P	Ca	P
1	775	497	559	384
2	640	456	545	392
3	670	472	575	394
4	710	493	618	415
mean	699	480	574	396

It can be seen from Table 43 that the total retention of calcium and phosphorus during the whole experiment is much lower on diet 4 than on diet 3.

8.4.2.2. Slaughter experiment

Whole body

In the slaughter experiment, the three zero time control animals were totally analysed, including gut-fill. In the other animals, the blood and entrails were, with respect to the minerals, only analysed for phosphorus. To estimate the total amount of calcium in the pig it was assumed that 99.8 per cent of the calcium is found in the carcass (Table 30). The results of the analyses of the pigs are given in Appendix 21. Because of great differences in ash concentration in control animal C3, the results of the minerals in that animal were omitted. Moreover one animal on diet 2 had to be taken out of the experiment because of considerable feed refusals.

The concentration of calcium, magnesium and phosphorus in the ash of the whole body was fairly constant, as was the Ca/P ratio. There was only a small effect of the diet on the concentration of phosphorus in the ash of the whole body. This can be seen in Table 44. The P/N ratio in the bodies (on average 180 g/kg) was significantly lower than the values in the literature and in the first experiment described in this chapter (210 and 221 resp.) Some possible reasons for this may be suggested. On one hand boars with a very lean type of growth might have a lower P/N ratio of retention than pigs with a moderate lean type of growth. This can also be derived theoretically from the values given in Table 29 in which it was shown that the P/N ratio in muscles was 59 g/kg compared with that in bones 1 280 g/kg. On the other hand one may argue that the dietary phosphorus concentration was insufficient and so leading to a decreased P/N ratio of retention. However, this is not so probable and certainly not for the animals which received diet 3 (8.0 g P/kg T). Our conclusion is that the former reason is most likely.

Table 44. Concentration of Ca, Mg and P in ash of the whole body (g/kg), Ca/P ratio (g/g), Ca/N and P/N ratio (g/kg) of retention

diet[a]	n	Ca	Mg	P	Ca/P	Ca/N	P/N
1	4	274.2	9.99	176.2	1.56	282	181
2	3	272.8	10.21	173.4	1.57	268	171
3	4	283.4	9.86	175.0	1.62	309	191
4	4	274.1	9.79	177.4	1.55	272	176
	rsd	7.1	0.33	1.6	0.36	21	10
significance	diet	ns	ns	*	ns	ns	ns

a) see Table 45

The retention of calcium and phosphorus can be calculated by subtracting the amounts of these minerals present at the start of the experiment from the amount at slaughter (Table 45).

Table 45. Retention of Ca and P during experiment 4 (g)

	diet 1		diet 2		diet 3		diet 4	
energy supply/d	C.V.B.+10%		C.V.B.		C.V.B.-15%		C.V.B.+10%	
mean lysine intake (g/d)	22.2		22.2		18.5		18.5	
animal no.	Ca	P	Ca	P	Ca	P	Ca	P
1	540	363	554	356	765	464	566	366
2	649	411	532	356	646	397	557	380
3	622	411	648	409	671	439	551	359
4	616	405	-	-	745	463	602	404
mean	607	397	578	374	707	441	569	377
sd	47	23	62	31	57	31	23	20

From Table 45 it can be seen that there is a wide variation in the amount of calcium and phosphorus retention between animals and diets. This variation is partly due to the number of days the animals were in the experiment. The average retention of calcium per day on diets 1 to 4 was 6.51, 6.06, 6.58 and 5.98 and for phosphorus 4.26, 3.92, 4.11 and 3.96 g/d respectively.

The radius

The main results of the analysis in the radii are given in Table 46. Further discussion on the relationship between the amount of ash, calcium and phosphorus in the radius and their amount in the whole body has been given in Chapter 17.5.2.2.

Table 46. Analyses in the radii (g/kg)

diet[a]	ash in fat-free T	Ca in ash	P in ash	Mg in ash	fat-free T (g)
1	629	361	177	6.7	27.60
2	652	359	177	7.0	27.22
3	649	360	176	6.8	30.58
4	645	361	177	6.5	26.41
rsd	9	4	2	0.2	2.45
sign. diet	*	ns	ns	ns	ns

a) see Table 45

8.5. GENERAL DISCUSSION ON THE FOUR EXPERIMENTS AND CONCLUSIONS

8.5.1. Level of feeding or energy supply and the desired P level in the diet

The cause of the lower absorption percentage of phosphorus at the higher level of feeding is not clear. Two possibilities may be suggested. The first is that the animals are not able to absorb the quantity of phosphorus needed for optimal tissue growth, which might be caused by a higher passage rate of the digesta. According to the work of Whittemore et al. (1972) and Sauer et al. (1982) this is improbable. Another reason might be that in relation to the animal's requirement, relatively more phosphorus is offered than required. In this case, the absorption of phosphorus is less efficient because of a feed-back mechanism. In this respect, one should also consider the tissue that is synthesized due to the higher level of feeding or energy supply. This is summarized for the four experiments in Table 47.

Table 47. Effect of level of feeding or energy supply on daily retention of protein and fat

Experiment	diet	at low level protein (g/d)	fat (g/d)	increase at higher level amount of diet or energy	protein (g/d)	fat (g/d)
1	1	86	147	25	7	56
2	1	123	56	28	21	113
2	2	120	37	25	45	91
3	3	132	57	33	53	136
3	4	128	59	33	61	137
4	1 and 2	150	163	10	2	28
4	4 and 3	143	109	25	-1	83

It can be seen from Table 47 that in experiments 1 and 4 there was hardly any increase in daily protein retention, but a marked increase in fat retention due to the higher level of feeding or energy supply. In experiments 2 and 3 the daily protein retention increased on average by 45 g (36 per cent), but the daily fat retention increased much more: on average 119 g (229 per cent) at the higher level of feeding. As fat tissue hardly contains any phosphorus, a higher daily fat retention needs no higher concentration of phosphorus in the diet unless the higher weights are to be borne by heavier bones. However, on this last aspect little is known. Table 32 showed that when the amount of phosphorus was related to FFW or FFEBW, there were no differences in the low and high levels of feeding, which confirms the view that for additional fat retention a higher phosphorus concentration is not necessary. On the contrary, a lower level of phosphorus in the diet might be possible at a higher level of feeding, provided that fat is predominantly synthesized additionaly. This can be concluded from the results of the first three experiments, as there is a clear tendency towards a lower absorption percentage of phosphorus at the higher level of feeding. The difference averaged 3 and 4 percentage units respectively. The retention percentage was on average 2 and 4 percentage units lower at the higher level of feeding. In the fourth experiment, on diets 3 and 4, the same amount of protein per day was retained but the retention of fat was 80 g/d higher on diet 4. Nevertheless, the absorption percentage of phosphorus was not higher when the energy supply was increased by 25 per cent. The retention percentage of phosphorus was even lower on diet 4, but when diets 1 and 2 in this experiment were compared, the retention percentage of phosphorus on diet 1 tended to be higher at the higher energy supply. The lower retention percentage of phosphorus at the

higher level of feeding is confirmed by data in the literature (Stoy, 1983; Fandrejewski and Rymarz, 1986).
In the first three experiments, there was a clear tendency towards a higher retention of calcium and phosphorus per day, which can be explained by the higher growth rate and higher intake of these minerals per day (Moinizadeh, 1975; Chidume, 1977; Stoy, 1983; Fandrejewski and Rymarz, 1986). It can be seen from the results of the slaughter investigation (first experiment), that despite a clear tendency towards a higher retention per day at the high level of feeding, the retention per kg live weight gain is lower than at the lower level of feeding (Table 33).
When the retention of calcium and phosphorus is related to the amount of FFEBW or to the amount of N present in the body, no significant differences were observed between the high and lower levels of feeding in the slaughter experiment, or in the balance experiments when related to N retention. The slaughter experiment described by Fandrejewski and Rymarz (1986) showed no effect of the level of feeding on the concentration of calcium or phosphorus per kg EBW, dry FFEBW or NW.
When the amount of added inorganic phosphorus is considered, it looks as though the differences of absorption and retention percentages, as a result of the level of feeding, are greater when more inorganic phosphorus is added; in other words, the higher the surplus of available phosphorus (Table 48). This suggests a regulation of calcium and phosphorus at the intestinal level as mentioned by Vemmer (1982) and also for phosphorus at the renal level.

Table 48. Effect of level of feeding and Pi added on mean difference in absorption and retention percentage of Ca and P (Low-High)

Trials	absorption % Ca	absorption % P	retention % Ca	retention % P	added Pi (g/kg)
VV 566 to VV 571	3	2	3	2	1.0
LV 25, LV 26	7	5	8	4	2.2
LV 27, LV 28	4	1	3	0	1.4
LV 29, LV 30	5	5	5	4	2.6
LV 31, LV 32	3	2	3	2	1.0

Although the results of Whittemore et al. (1972) and Sauer et al. (1982) can be criticized because of experimental design (see literature review) it can be concluded, when our results are also taken into account, that there are no great differences in absorption percentage of calcium and phosphorus at different levels of feeding. The same is true for the retention percentage of these minerals. The retention of phosphorus when related to N retention is almost the same at the two levels of feeding tested. It might be concluded that it is not necessary to raise the concentration of calcium and phosphorus in the diet when higher amounts of feed are offered and these result mainly in increased fat retention.

8.5.2. Accuracy of the balance experiments

In the first and fourth experiments a comparison can be made between the retention of calcium and phosphorus obtained by the balance technique and the retention of these minerals by the comparative slaughter technique. This comprised a total of 14 animals.
The calculation of the total retention of calcium and phosphorus during the whole experimental period by means of the balance technique has already been described in Chapter 6.9. The retention of these minerals by the

comparative slaughter technique is calculated as follows: the amount of the minerals in the animal at slaughter minus the amount of the minerals at the start of the experiment. The amount at the start was estimated by assuming that the amount per kg live weight of the zero time control animals that were slaughtered, was the same.
The results of the comparison are given in Table 49 and are expressed as the amount of calcium and phosphorus retained during the experiment and as a percentage of the intake of these minerals.

Table 49. Retention (g) and retention percentage of Ca and P according to the balance (B) and comparative slaughter technique (S)

trials VV	in diet (g/kgT) Ca	P	animal no.	retention (g) Ca B	Ca S	P B	P S	retention % Ca B	Ca S	P B	P S
566-568	7.1	5.8	10	572	612	385	359	35	36	29	27
"	"	"	21	553	562	384	346	33	33	28	26
"	"	"	30	607	670	423	411	39	42	33	32
569-571	"	"	6	556	532	371	331	41	38	33	30
"	"	"	14	515	504	332	321	37	36	29	29
"	"	"	28	503	588	354	362	39	45	34	35
701-704	9.9	8.0	Bl 1	775	765	497	464	46	45	36	34
"	"	"	Bl 2	640	646	456	397	39	39	35	30
"	"	"	Bl 3	670	671	472	439	41	41	36	34
"	"	"	Bl 4	710	745	493	463	43	45	37	35
705-708	7.5	6.6	Ye 1	559	566	384	366	43	43	34	32
"	"	"	Ye 2	545	557	392	380	40	40	33	32
"	"	"	Ye 3	575	551	394	359	42	39	32	30
"	"	"	Ye 4	618	602	415	404	46	44	35	34
mean			-	600	612	411	386	40.3	40.4	33.1	31.4
mean difference ± sd			-	12 ± 33		25 ± 17		0.1 ± 2.4		1.7 ± 1.4	

It can be seen from Table 49 that there is very good agreement between the two methods. For calcium the results are almost identical. With regard to phosphorus the balance method gives on average 1.7 percentage units (6 per cent relatively) higher retention ($p < 0.01$, paired-t statistic) than the comparative slaughter technique. We have no good explanation for this difference, but some aspects can be mentioned. Differences in estimated total intake of feed according to the balance measurements compared to the realized intake could be a cause despite a correction for these differences. The realized feed intake was on average 2.8 per cent lower, predominantly caused by the animals in trials VV 566 to VV 571. However, the data in Table 49 do not support this possibility as being a cause. Perhaps the urinary phosphorus measurements could be a cause of discrepancy between the two techniques, since its urine concentration is generally very variable from one day to another, and from one animal to another (Pointillart, 1986). Taking into account that the Ca/P ratio in retention should be approximately 1.6 and the good agreement of the two methods for calcium, one can assume that the balance method gives a slight overestimation concerning the retention of phosphorus.
Nielsen (1972) found that the results obtained by the balance technique were on average 15 and 39 per cent respectively higher for calcium and phosphorus than by the comparative slaughter technique, and Hendriks (1981) found even greater differences. These authors could not explain the considerable differences between the two methods. One reason might be that

the concentration of calcium and phosphorus in the diets far exceeded requirement, so that errors can be made more easily, especially when the diet for the whole experiment is not from the same batch of feedstuffs. Another reason might be that it is not so easy to obtain representative samples, especially with regard to minerals, from a ground carcass. These samples should be de-fatted before the concentration of the minerals is determined.
It can also be seen from Table 49 that the differences in retention of the minerals between the balance and slaughter technique in trials VV 701 to VV 708 are smaller than in VV 566 to VV 571. This might be due to the fact that in VV 701 to VV 708 the mineral balances were measured four times, while they were only done three times in trials VV 566 to VV 571.
We can conclude from our results that the balance technique applied gives an accurate measurement of the retention of calcium and phosphorus from 20 to 110 kg live weight.

8.5.3. The amount of phosphorus in the pig at a given body weight

The calculation in experiment 1 showed that the use of the allometric function $y = ax^b$ (in which a = constant, b = slope or growth coefficient and x = weight of the animal) gave a slightly better estimated amount of phosphorus in the body than when using a polynomial function such as $y = a + bx + cx^2$. This was also found in the literature review (see Chapter 4.4.3.). The additional quadratic independent variable in the allometric model was not significant, either in the literature or in experiment 1, except for a slight but still significant effect ($p = 0.05$) of EBW for the amount of phosphorus in experiment 1.
The growth coefficients of phosphorus when related to W, EBW or NW in the literature review are close and not significantly different from 1.00. Also, in experiment 1 this is true for W en NW but for EBW it was significantly lower than 1.00. When the growth coefficient is close to 1.00 it means that the growth of phosphorus is isometrically to the weight. Thus the increase in phosphorus retention per kg weight gain is the same at e.g. 20 and 100 kg. Estimations from the literature indicated that it amounted to 5.1 g P/kg weight gain and from our own experiment 5.0 to 4.9 g P/kg weight gain could be calculated. There seems to be a slight tendency towards a decrease in phosphorus retention per kg weight gain from 20 to 100 kg live weight in our own experiment (trials VV 566 to VV 571) or when the model $y = a + bx + cx^2$ is applied to the data from the literature.
From the foregoing it can be concluded, that the amount of phosphorus in the body at a given body weight can be estimated rather accurately. However, this may only be true for average conditions concerning feeding level, growth rate and supply of phosphorus and calcium. From the calculations in the literature, data of trials with a low feeding level (< 2.5xM) were excluded, when the phosphorus and calcium concentrations in the diet was inadequate (< 5.0 g/kg) or when the Ca/P ratio in the diet was lower than 1.0 or higher than 2.0. The results given in Table 32 (equations 4 and 5) and Table 33 show that at the higher level of feeding a lower amount of phosphorus per kg live weight gain is retained. Also, the results of experiment 4 (Appendix 21) show that at the same daily phosphorus supply a lower supply of energy results in a lower growth rate, but in a higher amount of phosphorus per kg live weight gain. This was also found by Moinizadeh (1975) and Fandrejewski and Rymarz (1986).
Because not much data is available in the literature on the effect of phosphorus and calcium concentrations on the amount of phosphorus in the body (except for those of Günther et al. (1967/68) and Mudd et al. (1969[b]) with young pigs), we tried to obtain more insight in this matter from our experiments. In section 8.5.2. it was shown that, when the results of the balance technique were compared with those of the comparative slaughter

technique, on the basis of our balance experiments, reliable estimates could be given of the amount of phosphorus retained in the body. The following procedure was followed. To estimate the amount of phosphorus in the body at slaughter weight, first the amount at the start of the experiment was estimated. This was done using equation no. 6 from Table 32 (ln P = 1.724 + 1.000 ln W). The amount of phosphorus retained during the experiment was estimated as described in Chapter 6.9.
The amount of phosphorus in the body at the start of the experiment was added to the amount of phosphorus retained, so that the amount of phosphorus in the body at slaughter was known. This amount was proportionally corrected for slight deviations from 110 kg live weight to make comparisons simpler. The calculations were done for the relevant experiments from trials VV 358 to VV 708. The results are given in Table 50 together with data on mineral concentrations in the diets and performance of the animals. According to equation no. 6 from Table 32 the total amount of phosphorus in the body at 110 kg live weight is 548 g.
The last column in Table 50 shows that there is a wide variation in the amount of phosphorus at 110 kg body weight. In the first experiment in this table (trials VV 358 to VV 360), the diet contained an extremely high concentration of calcium and phosphorus which resulted in very high amounts of phosphorus in the body at 110 kg. Also, in trials VV 420 to VV 422 a considerable amount of phosphorus was found, probably due to the high concentration of calcium and digestible phosphorus, the high feed intake and a rather low growth rate.
At extremely low calcium concentrations in the diets (< 2.1 g/kg T), the amount of phosphorus at 110 kg live weight is much lower than the expected amount of 550 g and varied from 350 to 450 g (trials VV 376 to VV 378, VV 411 to VV 413, VV 431 to VV 433, VV 434 to VV 436 and VV 437 to VV 439). In diets with calcium concentrations above 4.0 g/kg T but with a limited phosphorus supply (digestible P = 1.6 g/kg T) the amount of phosphorus was close to 500 g (VV 367 to VV 369, VV 373 to VV 375 and VV 534 to VV 536).
Diets with calcium and digestible phosphorus concentrations above 4.0 and 1.6 g/kg T respectively resulted in values between 480 and 587 g phosphorus at 110 kg body weight (values above 600 g not included). The mean and sd of the amount of phosphorus at 110 kg for these diets was 544 $\pm$ 30, a value close to the expected value of 550 g. Nevertheless, with these diets there is still a wide variation. It is striking that the standard deviation at 110 kg is of the same order as can be calculated from the literature review at that body weight.
It might be concluded that the amount of phosphorus in the body at 110 kg live weight can fairly accurately be estimated, provided that the phosphorus and calcium supplies are sufficient and that the daily allowance of feed and the growth rate approach mean values found in practice.

Table 50. Estimated amount of P in the body at 110 kg live weight

trials VV	g/kg T Ca	P	Pi added	P^a dig.	n	initial weight (kg)	final weight (kg)	mean intake (kg/d)	growth rate (g/d)	days in exp.	amount of P in body (g) at 110 kg
358-360	11.3	9.0	4.0	*	3	24	100	1.92	655	116	646
367-369	6.0	4.0	0	1.6	9	27	108	2.07	637	128	495
370-372	6.0	5.6	1.6	1.6	9	26	111	2.01	661	128	563
373-375	4.1	4.1	0	1.6	3	26	110	2.09	648	129	519
376-378	2.1	4.1	0	1.6	3	26	110	2.11	668	125	442
411-413	2.1	3.7	0	1.2	3	27	111	2.06	741	114	351
417-419	4.0	6.7	0	2.5	3	23	107	2.18	611	137	542
420-422	6.4	6.7	0	2.4	3	24	106	2.19	636	129	634
431-433	1.9	3.8	0	1.4	3	26	111	2.10	699	122	363
434-436	1.5	6.3	0	3.2	3	26	114	2.09	668	131	445
437-439	1.6	5.3	1.5	1.4	3	32	111	2.11	716	111	374
440-442	2.5	6.4	0	3.1	3	28	114	2.12	708	122	539
443-445	3.7	6.3	0	3.0	3	29	115	2.14	734	117	529
478-486, 490-492	7.7	6.3	1.4	1.9	12	25	110	2.18	666	128	583
487-489, 493-495	6.1	4.8	0	1.9	4	24	106	2.18	625	134	587
534-536	5.0	3.9	0	1.6	4	27	103	2.13	708	108	488
537-545	7.3	5.6	1.6	1.6	9	29	103	2.17	701	106	543
566-568	7.1	5.8	1.0	*	11	25	110	2.28	716	119	532[b]
569-571	7.1	5.8	1.0	*	12	25	110	1.83	627	136	571[c]
572-574	8.6	6.5	2.3	*	3	28	101	1.90	745	98	539
575-577	8.6	6.7	2.0	*	3	27	99	1.89	703	103	528[d]
578-580	8.4	6.6	2.3	*	3	25	102	1.88	698	110	545
581-583	8.6	6.8	2.0	*	3	25	97	1.81	634	114	528[d]
656-659	6.5	5.7	1.8	*	4	25	103	2.32	852	92	550
660-663	7.7	6.1	1.8	*	4	24	103	2.30	861	92	557
664-667	7.0	5.9	1.8	*	4	24	103	2.29	861	92	558
668-671	7.4	6.1	1.8	*	4	24	105	2.30	922	88	578
693-696	7.6	6.7	2.4	*	4	18	105	2.11	936	93	504[e]
697-700	8.6	7.2	2.5	*	4	19	105	2.02	903	95	487[e]
701-704	9.9	8.0	2.8	*	4	19	104	1.79	795	107	559[e]
705-708	7.6	6.6	2.5	*	4	19	107	2.14	917	96	483[e]

a) digestible P of diet without addition of Pi;* = not measured;
b) based on equation no. 4 from Table 32 (ln P = 1.590 + 0.997 ln W);
c) based on equation no. 5 from Table 32 (ln P = 1.647 + 1.000 ln W);
d) corrected for differences in gut-fill;
e) based on values in slaughter exp. (see Appendix 21).

8.6. CONCLUSIONS

It has been shown in the experiments presented in this chapter, that at the higher levels of feeding the absorption and retention percentage of phosphorus was slightly lower than at the lower levels of feeding. As at the higher levels of feeding the additional supply of feed or energy mainly resulted in fat retention, it was concluded that when higher amounts of feeds are offered and these result mainly in increased fat retention, it is not necessary to raise the concentration of phosphorus in the diet; somewhat lower levels of phosphorus might be possible.

Comparison of the results from balance experiments with those obtained by the comparative slaughter technique, showed that an accurate measurement of the retention of phosphorus from 20 to 110 kg live weight can be given. Those from the balance experiments were on average six per cent higher than those of the comparative slaughter technique. For calcium, the difference was only two per cent.

Estimation of the total amount of phosphorus in the body at 110 kg live weight, can be done fairly accurately provided that the phosphorus and calcium supplies are sufficient and that the daily allowance of feed and growth rate approach mean values found in practice. On average, 5.1 to 5.0 g phosphorus is retained per kg live weight gain; the higher value at a lower live weight. These results are in good agreement with those of others.

9. EFFECT OF DIETARY PROTEIN/LYSINE LEVEL ON THE ABSORPTION AND RETENTION OF PHOSPHORUS, CALCIUM AND NITROGEN IN BARROWS, BOARS AND GILTS

9.1. INTRODUCTION

In this chapter, the effect of the protein (amino acids) level on absorption and retention of phosphorus is described in order to find out whether or not the concentration of phosphorus in the diet at a higher protein supply should be raised. Furthermore, a comparison is made in the utilization of phosphorus and calcium between the different sexes and the P/N ratio in the bodies of pigs is discussed. As already outlined in the literature review (Chapter 2.3.), the effect on mineral utilization may depend upon the effect of the additional protein on growth rate.
The experiments described in this chapter were primarily set up for studies on protein requirements of growing pigs. For these studies, N balances were measured, but also phosphorus and calcium balances. Two experiments are described in this chapter.
In the first experiment, the effect of two levels of lysine in the diet on the N, phosphorus and calcium retention in barrows and two other levels of lysine in boars were investigated. The objective in the second experiment was to study the effect of four levels of protein (lysine) on the N and mineral retention in boars and gilts. More details on this study and the performance of animals in a concomitant feeding trial are given by Lenis and Metz (1983; experiment 1).

9.2. FIRST EXPERIMENT: EFFECT OF THE LYSINE CONCENTRATION IN THE DIET ON THE PHOSPHORUS, CALCIUM AND NITROGEN RETENTION IN BARROWS AND BOARS (TRIALS VV 395 TO VV 410)

9.2.1. Materials and methods

In the first experiment, four diets were used of which diets A and C were fed to barrows and diets B and D to boars. Each diet was fed to two crossbred animals of "Nieuw Dalland" boars x Dutch Landrace sows. The composition of the diets is given in Table 51 which shows that a higher protein concentration in the diet was achieved by exchanging barley for soybean meal.

Table 51. Composition of the diets (g/kg)

trials VV	395 to 398	399 to 402	403 to 406	407 to 410
diet	A	B	C	D
maize	396	397	396	396
barley	154	134	84	64
maize gluten feed	128	129	129	129
wheat middlings	99	99	99	99
soybean meal	104	122	173	193
tapioca	70	70	70	70
grass meal	20	20	20	20
minerals and vitamins	29	29	29	29
(included 15.4g$CaCO_3$)				
(" 8.3g DCP)				
NE_f (calc.;MJ/kg)	9.05	9.05	8.96	8.96
XP^f (g/kg)	146	153	168	174
lysine (g/kg)	6.1	6.4	7.6	8.1

At a live weight of ± 25 kg, the diets were individually fed to the animals until slaughter, at ± 103 kg. At ± 35, ± 55, ± 75 and ± 95 kg live weight the appropriate balances (length of adaptation period and collection period seven days) were determined while the animals were on metabolism crates. During that time the animals were fed 90 per cent of the C.V.B. scheme (1974); in the pens, they were fed according to the C.V.B. scheme.
The first analyses showed that the diets were not very homogeneous, probably due to mistakes in mixing. Therefore, after the balance trials at ±35 kg the remainder of the diets were mixed again. These were fed for ten days before the next collection period started.
The results, for barrows and boars separately, were subjected to analysis of variance. This analysis was performed for all four periods together and also for the last three periods, because the diet for period one was not the same as for the other three periods.

9.2.2. Results

The results of growth rate, feed conversion ratio and feed intake are given in Table 52 and must be regarded as indicative because there are only two animals per diet.

Table 52. Performance of the pigs receiving the four diets

diet	A	B	C	D
lysine (g/kg T)	6.5	6.9	8.0	8.4
initial weight (kg)	26	24	24	25
growth rate (g/d)	625	621	597	599
feed conversion ratio	3.25	3.11	3.37	3.37
feed intake (kg/d)	2.03	1.93	2.07	2.02
days in exp.	126	126	126	126

The results of the chemical analyses of the diets are given in Table 53 and those of the balance trials in Appendix 22. A summary of the analysis of variance is given in Table 54.

Table 53. Chemical analysis of the diets

diet	A	B	C	D
T (g/kg)	865	861	861	863
O (g/kg T)	940	940	940	932
XP "	169	174	193	194
XL "	28	27	28	28
XF "	68	67	70	67
lysine "	6.5	6.9	8.0	8.4
Ca "	10.1	9.6	9.1	11.5
P "	6.6	6.4	6.3	7.0

Table 54. Summarized results of the first experiment on effect of dietary lysine concentrations

	barrows								boars							
	all periods				periods 2 to 4				all periods				periods 2 to 4			
	diet A	diet C	sed	sign.	diet A	diet C	sed	sign.	diet B	diet D	sed	sign.	diet B	diet D	sed	sign.
lysine (g/kg T diet)	6.5	8.0			6.5	8.0			6,9	8.4			6,9	8,4		
d_T (%)	79.0	78.7	0.3	ns	79.0	78.8	0.1	ns	78.9	76.3	0.6	*	78.6	76.8	0.9	ns
absorption % of Ca	30.9	33.6	1.1	ns	27.3	31.2	3.1	ns	36.8	30.3	3.3	ns	32.2	29.6	3.4	ns
absorption % of P	32.6	36.3	0.7	*	30.2	35.3	0.6	*	33.8	32.4	2.2	ns	31.9	32.0	3.4	ns
retention % of Ca	28.4	30.7	1.9	ns	25.7	28.9	3.3	ns	34.4	27.9	2.6	ns	30.5	27.7	3.2	ns
retention % of P	30.5	32.5	0.4	*	27.4	30.5	1.5	ns	32.5	31.2	2.9	ns	30.2	30.4	4.4	ns
retention of Ca (g/d)	4.96	4.94	0.20	ns	4.76	5.42	0.44	ns	5.64	5.53	0.37	ns	5.46	5.60	0.57	ns
retention of P (g/d)	3.47	3.54	0.10	ns	3.48	3.80	0.06	*	3.56	3.83	0.40	ns	3.68	4.06	0.58	ns
retention of N (g/d)	17.5	16.2	1.8	ns	19.0	16.5	2.0	ns	18.9	20.1	1.1	ns	21.0	21.8	1.5	ns

9.2.3. Discussion

One may wonder why the results of the mineral balances at a live weight of 36 kg are presented, because of the differences between the mineral concentration of the diets at this and the other live weights.
The first reason is the possibility of carry-over effects. As can be seen in Appendix 22, the calcium and phosphorus concentrations of diets A, B and D were higher during the balance at 36 than at 55 kg live weight and higher This led to a lower calcium and phosphorus retention per day at 55 kg when compared to 36 kg live weight. For diet C, where the mineral concentration was somewhat lower at 36 kg, more calcium and phosphorus were retained at 55 kg as might be expected. This stressed the need for a long adaptation period if the concentration of calcium and phosphorus is considerably changed. Further discussion on length of adaptation period has been given in Chapter 7.2.2.
The second reason is a possible difference in mineral retention between barrows and boars. Although the diets for barrows and boars were not identical, there were no great differences between diets A and B and between diets C and D (Table 53). No significant differences are found in calcium and phosphorus retention between barrows and boars up to 75 kg live weight. In the last period at 95 kg, the calcium and phosphorus and also the N retention was higher in boars due to less excretion of calcium and phosphorus in the urine. This might indicate that differences in mineral retention between barrows and boars will usually appear after 75 kg live weight. This can probably be explained by the higher N retention and growth rate of the boars (see also section 9.4.3.).
The third reason is that, in practice, such differences in mineral concentration from one batch to the other are also likely to occur. This experiment shows the consequences of this.
Finally, it was expected that due to a higher lysine supply a higher growth rate would occur and thus a higher mineral retention. However, Table 52 shows that the growth rate was the same and the feed conversion ratio hardly differed, so that on the basis of these data no great differences are to be expected. In the barrows, the N retention tended to be somewhat lower at the higher lysine level but no difference in calcium and phosphorus retention was found. In the boars, the N retention tended to be higher and so was the calcium and phosphorus retention at the higher lysine level in the diet, but this might also be due to the somewhat higher mineral concentration in the diet at the higher lysine level.

9.3. SECOND EXPERIMENT: EFFECT OF DIETARY LYSINE LEVEL ON THE ABSORPTION AND RETENTION OF PHOSPHORUS, CALCIUM AND NITROGEN IN BOARS AND GILTS (TRIALS VV 656 TO VV 671)

9.3.1. Materials and methods

The boars and gilts for this experiment came from the Experimental Farm at Raalte and arrived at the Institute with a live weight of about 18 kg. All animals were crossbred pigs (GY x DL). Fourteen days after arrival, at about 24 kg live weight, the animals were divided according to sex and litter to the treatments. Two boars and two gilts were used for each treatment.
Up to ± 24 kg, a commercial pig starter was offered after which time the experimental diets were given. The feedstuff composition and chemical composition of the diets are given in Tables 55 and 56. Casein was used to supply the four levels of protein/lysine because of its high concentration of protein, so that a small amount of maize and barley in the diet had to be exchanged for casein.

Table 55. Feedstuff composition of the diets (g/kg)

diet	1	2	3	4
maize	435	429	422.5	415
barley	240	234	226.2	220
maize gluten feed	120	120	120	120
soybean meal solv. extr.	110	110	110	110
grass meal	50	50	50	50
cane molasses	20	20	20	20
casein	-	12	26	40
premix (incl.NaCl, choline chloride)	7.5	7.5	7.5	7.5
limestone	8.8	8.8	8.8	8.8
dicalcium phosphate	8.8	8.8	8.8	8.8

The animals were given the same diet during the experiment until slaughter. We aimed at feeding the animals somewhat above the Dutch standards for energy, and it was assumed that the diets contained 9.12 MJ NE_f/kg diet. The following amounts of net energy were offered to the pigs:

	live weight (kg)					
	25	40	55	70	85	100
MJ NE_f/d	11.68	16.34	20.47	23.81	26.36	28.64

At about 35, 50, 75 and 90 kg live weight, the mineral and N balances were determined. Moreover, at 75 kg the measurements for a digestion trial were made in order to calculate the NE_f content of the different diets. When not in the collection period the animals were weighed weekly.
The results of the balance experiments were subjected to analysis of variance according to the following model:

$$y_{ijkl} = \mu + sex_i + lysine_j + weight_k + litter_l + sex \,.\, lysine + weight.sex + lysine.weight + weight.sex.lysine + \underline{e},$$ with $\underline{e}$ normally distributed and

$$var\ (\underline{e}) = \sigma^2$$

Table 56. Determined chemical composition and feeding value of the diets

diet	1	2	3	4
T (g/kg)	855	857	858	861
O (g/kg T)	941	943	949	947
XP "	180	184	192	199
XL "	30	33	31	31
XF "	54	48	44	44
XX "	677	679	682	673
DXP "	137	142	152	156
NE_f (calc.; MJ/kg T)	10.11	10.18	10.37	10.15
lysine (g/kg T)	**7.7**	**8.6**	**9.7**	**10.8**
Ca "	6.5	7.7	7.0	7.4
P "	5.7	6.1	5.9	6.1
phytate P "	2.8	2.6	2.6	2.5

9.3.2. Results

This experiment ran smoothly; only one animal in trial VV 663 had 1 009 g feed refusal, and one animal in trial VV 667 had 308 g refusal during the collection period of ten days. One animal in trial VV 670 had a negative mineral balance so that these results were not used for further calculations. The performance of the animals during the experiment is given in Table 57.

Table 57. Performance of the animals.

	diet					
	1	2	3	4	sows	boars
lysine (g/kg T)	7.7	8.6	9.7	10.8		
initial weight (kg)	25	24	24	24	25	23
growth rate (g/d)	852	861	861	922	850	897
feed intake (kg/d)	2.32	2.30	2.29	2.30	2.34	2.26
feed conversion ratio	2.73	2.68	2.67	2.51	2.76	2.53
days in experiment	92	92	92	88	90	92
backfat thickness (mm)	27	26	29	25	28	25

The detailed results of the calcium, phosphorus and N balances are given in Appendix 23, while a summary of the results is given in Table 58.
Analysis of variance showed a small linear increase in phosphorus absorption and retention percentages when the lysine concentration was higher ($p < 0.05$). There was also a significant linear increase in phosphorus retention ($p < 0.005$), calcium retention ($p < 0.025$) and N retention ($p < 0.005$) when the lysine concentration increased.
Boars had a significantly higher absorption and retention percentage for phosphorus than gilts ($p < 0.05$). The retention percentage for calcium and the daily retentions of calcium and phosphorus also were significantly higher in boars. There was hardly any decrease in the absorption and retention percentages for calcium and phosphorus when the animals were heavier, but the urinary excretion of phosphorus increased significantly.
The Ca/N and P/N ratios of the retention were affected by the diets ($p < 0.05$) and were, on average, 261 and 168 respectively. The P/N ratio of the retention was higher in boars than in gilts ($p < 0.05$).

9.3.3. Discussion

In contrast to the feeding experiment, the animals in the balance trials showed no great differences in growth rate and feed conversion ratio between the different lysine levels. The great growth response observed in the feeding trial, as a result of the lysine concentration in the diet, was not observed in the balance animals, and might have resulted in greater differences in the absorption and retention of the minerals then.
In the balance experiment, no decrease was found in absorption and retention percentages for calcium and phosphorus at a higher live weight, which we usually found in other experiments. This might be due to the very high growth rate of the animals in this experiment. Despite small differences in growth rate, there was a higher retention of calcium, phosphorus and nitrogen per day when the lysine concentration was higher. When the retention of calcium and phosphorus is related to kg live weight gain, the following results can be calculated (Table 59).

Table 58. Summarized results of the second experiment on effect of dietary lysine concentrations

	diet					sex			significance		
	1	2	3	4	sed	gilts	boars	sed	diet (df=6)	sex (df=2)	period (df=6)
lysine (g/kg T)	7.7	8.6	9.7	10.8							
d_T(%)	82.4	82.1	83.1	82.2	1.2	82.0	82.9	0.4	ns	ns	***(lin)
absorption % of Ca	51	49	49	53	1.9	49	52	1.0	*(quad)	ns	ns
absorption % of P	41	41	42	43	1.0	41	43	0.4	*(lin)	*	ns
retention % of Ca	49	46	47	49	1.6	45	50	1.2	ns	*	ns
retention % of P	37	36	37	40	1.2	36	39	0.7	*(lin+quad)	*	ns
retention of Ca (g/d)	6.7	7.3	7.0	7.8	0.3	6.8	7.6	0.2	*(lin)	*	**(lin+quad)
retention of P (g/d)	4.4	4.5	4.5	5.1	0.1	4.4	4.9	0.1	**(lin)	*	**(lin+quad)
retention of N (g/d)	24.7	26.7	28.7	29.6	1.1	27.0	27.8	0.3	**(lin)	*	***(lin+quad)
Ca in urine (g/d)	0.3	0.5	0.3	0.6	0.1	0.5	0.4	0.1	ns	ns	ns
P in urine (g/d)	0.5	0.6	0.6	0.5	0.1	0.6	0.5	0.1	*(quad)	ns	***(lin)
Ca/N retention (g/kg)	272	275	240	258	9	253	270	5	*(lin)	ns	*(lin)
P/N retention (g/kg)	179	169	157	169	5	163	174	2	*(lin+quad)	*	ns

Table 59. Retention of calcium and phosphorus in g/kg live weight gain

	diet 1	2	3	4	sows	boars	rsd	significance diet	sex
lysine (g/kgT)	7.7	8.6	9.7	10.8					
Ca	7.53	8.18	7.64	8.10	7.86	7.87	0.43	ns	ns
P	4.96	5.03	4.98	5.28	5.06	5.06	0.25	ns	ns

From this table it can be concluded that, with regard to calcium, no significant differences between diets was found, but there is a tendency for more calcium to be retained when the calcium concentration in the diet is higher. Due to the differences in calcium concentration in the diets, no conclusions can be drawn concerning the effect of dietary lysine on calcium retention. For phosphorus, hardly any differences in retention per kg live weight gain are found, except for the diet with the highest lysine level. From Table 59 it can also be concluded that there are no differences in retention per kg live weight gain between sows and boars. The higher absorption and retention percentages in boars can be explained by the higher growth rate. When the results of one sow on diet 4 are omitted because of a very high retention per kg live weight gain, the retention per kg live weight gain is 0.13 g calcium and 0.09 g phosphorus higher in boars.

9.4. GENERAL DISCUSSION

9.4.1. Dietary protein level and its effect on absorption and retention of phosphorus and calcium

With regard to the effect of dietary protein/lysine concentration on the absorption and retention of phosphorus and calcium, not only the two experiments described in this chapter can be regarded but also those of trials VV 572 to VV 583 (see Chapter 11) and trials VV 693 to VV 708 (see Chapter 8.4.). However, it is difficult to compare these experiments because of several differences in experimental design. To give some idea, Table 60 gives an overview of the main characteristics and results of the relevant experiments. This table shows that different breeds and sexes were used as well as calcium, phosphorus and lysine concentrations in the diets. Lysine is taken because it is the first limiting amino acid in normal Dutch diets. The mean daily intake of energy (EW) differed greatly from one experiment to the other, as did the daily intake of lysine, which was substantially higher in the last two experiments of this table. The initial weight, and the duration of the experiments were about the same. As a result of differences in daily energy and lysine intake, the growth rate differed greatly, from 610 g/d to 880 g/d. Both the mean retentions of calcium and phosphorus as well as those of N also increased in the last two experiments.
To evaluate the experiments mentioned in Table 60, the differences between them should be taken into account. Therefore, it is only logical to compare the results within each experiment.

Table 60. Main characateristics of experiments with different dietary protein/lysine concentrations.

Trials VV	breed	sex	number of animals	number of balance trials/animal	weight(kg)at start	weight(kg)at end	in diet(g/kg)T Ca	P	lys	mean intake per day during experiment EW	Ca(g)	P(g)	lys(g)	dig.lys(g)	growth rate (g/d)	mean retention (g/d) Ca	P	N	Ca in urine (g/d)
395to398	Nieuw Dalland	barrow	2	4	26	105	10.1	6.6	6.5	2.09	17.7	11.6	11.4		625	5.0	3.5	17.5	0.42
399to402	DL*	boar	2	4	24	102	9.6	6.4	6.9	1.99	16.0	10.6	11.5	-	621	5.6	3.6	18.9	0.37
403to406	"	barrow	2	4	24	102	9.1	6.3	8.0	2.11	16.2	11.2	14.3	-	597	4.9	3.5	16.2	0.44
407to410	"	boar	2	4	25	100	11.5	7.0	8.4	2.06	20.0	12.2	14.6	-	599	5.5	3.8	20.1	0.46
572to574	GY*DL	boar	3	3	28	100	8.6	6.5	9.0	1.87	13.6	10.3	14.3	11.1	745	5.8	3.6	24.2	0.16
575to577	"	"	3	3	27	99	8.6	6.7	9.9	1.80	14.0	10.9	16.1	10.4	703	5.4	3.2	20.5	0.10
578to580	"	"	3	3	25	101	8.4	6.6	7.7	1.84	13.4	10.5	12.2	9.2	698	5.8	3.6	20.8	0.20
581to583	"	"	3	3	25	97	8.6	6.8	8.5	1.76	13.4	10.6	13.3	8.4	634	5.0	3.1	19.9	.0.13
656to659	GY*DL	boar+gilt	4	4	25	103	6.5	5.7	7.7	2.28	12.9	11.3	15.3	-	852	6.7	4.4	24.7	0.34
660to663	"	"	4	4	24	103	7.7	6.1	8.6	2.28	15.2	12.0	17.0	-	861	7.3	4.5	26.7	0.55
664to667	"	"	4	4	24	103	7.0	5.9	9.7	2.32	13.8	11.6	19.1	-	861	6.9	4.5	28.7	0.31
668to671	"	"	4	4	24	105	7.4	6.1	10.8	2.29	14.6	12.1	21.4	-	922	7.8	5.1	29.7	0.65
693to696	GY*(GY*DL)	boar	4	4	18	105	7.6	6.7	10.7	2.21	13.9	12.3	19.6	-	936	6.5[a]	4.3[a]	24.1[a]	-
697to700	"	"	3	4	19	105	8.6	7.2	12.0	2.04	15.0	12.6	21.2	-	903	6.1[a]	3.9[a]	23.8[a]	-
701to704	"	"	4	4	19	104	9.9	8.0	11.3	1.77	15.3	12.4	17.5	-	795	6.6[a]	4.1[a]	22.8[a]	0.60
705to708	"	"	4	4	19	107	7.6	6.6	8.9	2.24	14.1	12.3	17.3	-	917	6.0[a]	4.0[a]	23.3[a]	0.73

a: based on slaughter technique

Trials VV 395 to VV 410
In trials VV 395 to VV 410, there were only two animals per treatment and one should bear in mind that because the diets had not been mixed well enough they had to be mixed again after the first balance trial at 36 kg live weight. Due to a higher protein/lysine concentration in the diet, there was a small positive tendency towards higher calcium, phosphorus and nitrogen retentions in the barrows and boars.

Trials VV 572 to VV 583
In trials VV 572 to VV 583, diets with a normal and a high concentration of crude fibre were used. Therefore, trials VV 572 to VV 574 can only be compared with trials VV 578 to VV 580 and trials VV 575 to VV 577 with trials VV 581 to VV 583. The higher dietary protein/lysine level in trials VV 572 to VV 574 resulted in the same calcium and phosphorus retention per day, but there was a tendency for the higher lysine level in trials VV 575 to VV 577 to produce a somewhat higher daily retention of calcium and phosphorus.

Trials VV 656 to VV 671
In trials VV 656 to VV 671 due to an increased protein/lysine concentration in the diet, a positive linear effect was found on the absorption and retention percentages of phosphorus and on the daily retention of phosphorus and nitrogen. Due to the small variation in the dietary calcium concentrations, no clear conclusions could be drawn as to the effect of lysine on calcium retention. However, because of the close relationship between calcium and phosphorus retention, a positive effect might also be expected.

Trials VV 693 to VV 708
With regard to the effect of the dietary lysine concentration, only the results of trials VV 693 to VV 697 can be compared with those of trials VV 705 to VV 708. The results of the comparative slaughter technique showed that the higher lysine concentration resulted in a higher daily retention of calcium, phosphorus and nitrogen.

The results of the above mentioned experiments show that, due to a higher protein (lysine) concentration in the diet, there is a tendency towards a higher daily retention of calcium, phosphorus and nitrogen. This effect seems to be more obvious at higher growth rates and has a positive relationship with the retention of nitrogen. The positive relationship between the retentions of nitrogen and phosphorus was also observed by Müller and Kirchgessner (1974) and Livingstone et al. (1962) (section 9.4.2.). Furthermore, in feeding experiments where a higher protein level in the diet resulted in a higher growth rate, a beneficial effect of additional phosphorus supplementation could be demonstrated on bone ash content and inorganic phosphate content in blood serum (Reinhart et al., 1976; Fammatre et al., 1977; Schiefelbein, 1979).
Now we will try to quantify the effect of protein/lysine in terms of the retained amount of phosphorus per kg live weight gain. From the results in Chapter 8.4. (diets 1 and 4) it can be calculated that at the same daily supply of energy and phosphorus, but with 20 per cent more lysine, the retention of phosphorus was 0.28 g/kg weight gain more at the higher supply of lysine. In section 9.3. it was concluded that boars retained possibly 0.09 g phosphorus per kg live weight gain more than sows, and furthermore it was shown in the same experiment that on the highest level of lysine (10.8 g/kg T) the retention of phosphorus per kg live weight gain was 0.25 g higher than on the diet with 2.2 g lysine/kg T less (8.6 g/kg T) but with the same phosphorus concentration (6.1 g/kg T). Also in Chapter 8.2. it was shown that at a lower level of feeding, the weight gain was more lean than at the higher level of feeding and it was calculated that per kg live

weight gain, 0.36 g more phosphorus was retained than at the higher level of feeding. However, in this last mentioned experiment the daily supply of phosphorus was not the same, so that the higher figure is not only the result of a difference in protein retention per kg weight gain. A theoretical approach can also be made concerning a higher phosphorus retention due to a more lean weight gain. For example, an animal has a 150 g higher weight gain/kg increase of weight than another animal due to higher protein retention (more lean). If this higher weight gain only consists of protein and water + ash (23 : 77) (Metz et al., 1982) then it contains 35 g of protein. In Chapter 8.2. we have seen (Table 28) that dry fat-free muscle contains 8.9 g P/kg, so that in this example, the retention of phosphorus will be 0.3 g higher.
From the higher retentions of phosphorus per kg live weight gain due to the higher supply of protein/lysine or the higher retention of protein (boars vs gilts) it can be concluded that on average 0.2 to 0.3 g more phosphorus per kg live weight gain may be retained.
In the literature review (Chapter 2.3.2.), it was shown that in experiments on rats, urinary excretion of calcium increased due to higher concentrations of protein in the diet. Whether this is also true for pigs is not known. In order to get some insight, an additional column is given in Table 60 concerning the mean daily amount of calcium excreted in the urine. From this column, it can be seen that the daily excretion of calcium in the urine is low (0.1 to 0.7 g), which can be expected for diets with a favourable Ca/P ratio. (Chapter 2.6.2.). A higher concentration of protein and/or lysine in the diets did not result in significant differences of calcium excretion in the urine. This might be explained by the small amounts excreted in the urine but also by differences in calcium concentration between the diets (e.g. trials VV 656 to VV 671). In trials VV 572 to VV 583, where the dietary calcium concentrations were the same, no indication of a higher amount of calcium excreted in the urine is found. Differences with the results found in the literature on rats and humans, might be due to doubling the protein levels in these diets, which were then far above the protein requirement; in our experiments, the protein contents were raised only up to two percentage units.
It can be concluded that when a higher protein level in the diet results in a higher growth rate or nitrogen retention, the concentration of phosphorus in the diet should be raised. The present experiments on pigs give no evidence of a higher amount of calcium excreted in the urine.

9.4.2. Relationship between the retention of nitrogen and phosphorus

It was shown in the literature review (Chapter 4.4.3.), that using data up to early 1982, there was a close relationship between the amounts of phosphorus and nitrogen in the body ($\ln P(g) = -1.387 + 0.978 \ln NW\ (g)$) in slaughter experiments. From this relationship, it was calculated that the P/N ratio in the animal varied from 214 g/kg at 20 kg body weight to 206 at 100 kg. These figures are close to those found in more recent experiments (Rymarz et al., 1982; Stoy, 1983; Fandrejewski and Rymarz, 1986). Our slaughter experiments (Chapter 8) showed that the P/N ratio was, on average, 220 g/kg in trials VV 566 to VV 571, while in trials VV 693 to VV 708, with fast growing boars, the mean ratio was 180; much lower than the foregoing values.
To get more insight into the P/N ratio of the retention, we did additional calculations with the results of our balance experiments, in which both the phosphorus and nitrogen retention had been measured. By means of regression analysis, we wanted to know whether variation in the P/N ratio could be explained by the concentration of phosphorus and nitrogen in the diet and the level of energy intake (expressed as MJ NE_f/W). In the model, the data were first corrected for experiment and sex. For these calculations,

the data of the balance experiments were divided into four live weight groups: up to 50 kg, from 50 to 70 kg, from 70 to 90 kg and 90 kg and more. This was done because there might be an effect of live weight, due to a decrease in the requirements for phosphorus and nitrogen at higher live weights. For the live weight groups mentioned, in total 98, 59, 56 and 89 observations were available.
The mean P/N ratios of the four live weight groups were 176, 181, 170 and 209 respectively. The much higher ratio for the highest weight group is surprising. We have no clear explanation for it.
The P/N ratio of the retention found in balance experiments is usually lower than in slaughter experiments. This can largely be explained by errors in measuring the nitrogen balance due to losses of ammonia. In general, the overestimation of nitrogen retention in balance experiments is 10 to 15 per cent (Just et al., 1982). In balance experiments VV 693 to VV 708, the overestimation of the nitrogen balance was, on average, eight per cent. When the P/N ratio of the retentions measured in balance experiments is corrected for nitrogen losses, then this ratio comes close to 210, the mean value calculated from slaughter experiments.
In the lowest weight group, regression analyses showed (Table 61) significant effects of the phosphorus and nitrogen concentrations in the diet and of the level of energy intake on the P/N ratio. In the live weight groups from 50 to 70 and from 70 to 90 kg, only the nitrogen concentration in the diet was significant, although there was a slight tendency towards an effect of phosphorus concentration in the diet and level of energy intake on the P/N ratio. Above 90 kg, no significant effects of the factors mentioned on the P/N ratio could be demonstrated. The significant effect of the phosphorus concentration on the P/N ratio below 50 kg is, amongst other things, caused by one experiment (trials VV 367 to VV 372) in which the phosphorus level in one half of the diets was below the requirement. At higher live weights, this effect was not so strong because the requirement for phosphorus decreased at higher live weights and the requirement for it was almost met. It can be seen in Table 61, that a higher nitrogen concentration in the diet decreases the P/N ratio, which might mean that the increase in nitrogen retention is more than that of phosphorus. In the group below 50 kg, more phosphorus in the diet resulted in a higher P/N ratio. Furthermore, in this group a higher level of energy intake resulted in a lower P/N ratio which is in agreement with the results in Chapter 8.

Table 61. Effect on the P/N ratio of retention by several factors

	live weight group (kg)							
	<50		50-70		70-90		>90	
factor	estimate	sign.	estimate	sign.	estimate	sign.	estimate	sign.
P diet (% in T)	291	***	-	ns	-	ns	-	ns
N diet (% in T)	-93	***	-35	*	-38	*	-	ns
energy intake (MJ $NE_f/W^{0.75}$)	-67	**	-	ns	-	ns	-	ns
sex -barrow	0	ns	0	ns	0	ns	0	ns
-gilt	-13	ns	-14	ns	-15	ns	-22	ns
-boar	-10	ns	-4	ns	-	-	-23	ns

Although not significant, there were tendencies for the P/N ratio in barrows to be higher than in gilts and boars. This can probably be explained by the higher retention of nitrogen in gilts and boars when compared with barrows. This is in accordance with the observation in the slaughter experiment of trials VV 693 to VV 708, in which the P/N ratio was 180 with fast growing boars (see further section 9.4.3.).

Table 62. Main characteristics of experiments with different sexes

Trials VV	in diet (g/kg T)		number of observations per sex	mean retention (g/d)								
				barrow			gilt			boar		
	Ca	P		Ca	P	N	Ca	P	N	Ca	P	N
367 to 369	6.0	4.0	9	3.6	2.7	19.1	3.9	2.8	21.6	3.4	2.7	23.0
370 to 372	6.0	5.6	9	4.8	3.3	20.4	5.2	3.5	22.8	5.3	3.6	23.6
395 to 402	9.8	6.5	8	5.0	3.5	17.5	-	-	-	5.6	3.6	18.9
396 to 398, 400 to 402	9.2	6.3	6	4.8	3.5	19.0	-	-	-	5.5	3.7	21.0
403 to 410	10.3	6.6	8	4.9	3.5	16.2	-	-	-	5.5	3.8	20.1
404 to 406, 408 to 410	9.8	6.5	6	5.4	3.8	16.5	-	-	-	5.6	4.1	21.8
656 to 659	6.5	5.7	8	-	-	-	6.5	4.2	24.1	7.0	4.6	25.3
660 to 663	7.7	6.1	8	-	-	-	6.8	4.2	25.6	7.8	4.8	27.7
664 to 667	7.0	5.9	8	-	-	-	6.6	4.3	28.8	7.4	4.7	28.6
668 to 671	7.4	6.1	8	-	-	-	7.5	4.8	29.4	8.2	5.3	29.8

It may be concluded that the P/N ratio in the bodies of pigs may vary slightly and may be affected by the nitrogen and phosphorus concentrations of the diet, level of energy intake and,possibly, by the sex of the animal. No answer can be given to the question at what P/N ratio of the retention will the performance of the animal be decreased, but it can certainly be lower than 210.

9.4.3. Effect of sex on absorption and retention of phosphorus and calcium

In section 9.4.1. it was shown that there was a tendency towards a higher daily retention of calcium and phosphorus due to a higher protein/lysine concentration in the diet. In most cases a higher nitrogen retention was also observed.
From most experiments in which the protein or amino acid requirements of growing pigs are studied, it is concluded that this requirement is higher in boars than in gilts and barrows (e.g. Lenis and Metz, 1983). This higher requirement results in a higher daily nitrogen retention. Therefore, it is necessary to know if boars also retain more calcium and phosphorus per day than barrows and gilts.
In three experiments, the effects of sex on the absorption and retention of calcium and phosphorus was studied. These experiments were trials VV 367 to VV 372 (for details see Chapter 12), trials VV 395 to VV 410 and trials VV 656 to VV 671, the main characteristics of which are given in Table 62.
In trials VV 367 to VV 372 and VV 656 to VV 671, the effect of sex was studied within the same diet. In trials VV 395 to VV 410, the boars and barrows did not receive identical diets, so that comparison of sex in these trials does not have the same weight as in the other trials.
From Table 62 it can be seen that in trials VV 367 to VV 369, with a dietary phosphorus concentration below requirement, no differences in retention of calcium and phosphorus were found between the sexes. In trials VV 370 to VV 372, however, there was a tendency towards a higher calcium and phosphorus retention in boars. It can also be seen in Table 62 that gilts tended to retain more calcium, phosphorus and nitrogen per day than barrows.
In trials VV 395 to VV 410 there was also a tendency towards a higher daily retention of calcium, phosphorus and nitrogen in boars when compared with barrows.
In trials VV 656 to VV 671, for each diet, there was a strong tendency towards a higher daily retention of calcium, phosphorus and nitrogen in boars compared with gilts. The differences approached the level of significance ($p < 0.10$).

In a further analysis, we tried to discover in which live weight range the main differences in retention of calcium and phosphorus appear, because it is known from several investigations (e.g. Wiesemüller, 1983) that boars retain more nitrogen in the second part of the growing period than barrows and gilts. Therefore, differences in daily retention of calcium, phosphorus and nitrogen between the sexes at various live weights were calculated.
Because there were differences in daily intake of calcium, phosphorus and nitrogen between the sexes in trials VV 367 to VV 372, due to small differences in dry matter intake, the daily retentions were corrected to the same daily intake of calcium, phosphorus and nitrogen. Trials VV 367 to VV 372 were not taken together because the dietary phosphorus concentration in trials VV 367 to VV 369 was below the requirement. Therefore, these results may not be applicable for practical situations. In trials VV 395 to VV 410, the values obtained at 36 kg live weight were not taken into account because of reasons mentioned earlier.

The results of the calculations are given in Table 63. When boars and gilts are compared it can be seen in this table, that except for trials VV 367 to VV 369, in trials VV 370 to VV 372 and in trials VV 395 to VV 410 there is a tendency towards more positive differences in calcium, phosphorus and nitrogen retention at the higher live weights, while in trials VV 656 to VV 671 this becomes very clear. The same can be seen when boars are compared with barrows or when gilts and barrows are compared. The calculations concerning the P/N ratio in the retention (Table 61) showed that this ratio was higher for barrows than for boars and gilts. As barrows have a lower nitrogen but a higher fat retention at the same daily supply of feed than boars and gilts, this means that barrows have more phosphorus available per kg growth. In the literature (Chapter 5.3.4.), little information is available on possible differences in the phosphorus requirement between sexes. No differences are suggested in phosphorus requirement between barrows and gilts. Also, in most experiments no differences could be demonstrated between boars and gilts. Our calculations of data in the literature showed that there was a tendency for the phosphorus requirement of boars to be higher than that of barrows above 30 kg live weight (Figures 9 and 11). However, the number of observations for this comparison was small.

Table 63. Difference in daily retention (g) of Ca, P and N at various live weights (kg)

trials VV	live weight (kg)	boar - gilt			boar - barrow			gilt - barrow		
		Ca	P	N	Ca	P	N	Ca	P	N
367	47	-0.3	0.0	-0.2	0.0	0.1	1.9	0.3	0.0	2.1
368	70	-0.4	0.1	2.2	-0.4	0.0	2.8	0.0	-0.1	0.6
369	99	-0.9	-0.4	2.4	-0.7	-0.2	5.9	0.2	0.2	3.6
370	46	-0.4	-0.3	-0.3	-0.5	-0.3	-0.1	-0.1	0.0	0.2
371	71	0.3	0.4	0.1	0.7	0.7	3.0	0.4	0.3	3.0
372	99	0.3	0.1	2.1	0.9	0.2	5.3	0.6	0.1	3.2
395-410	55	-	-	-	-0.2	-0.1	2.0	-	-	-
"	75	-	-	-	-0.1	-0.3	2.5	-	-	-
"	96	-	-	-	0.8	1.2	6.3	-	-	-
656-671	36	0.5	0.2	0.2	-	-	-	-	-	-
"	48	0.5	0.3	1.8	-	-	-	-	-	-
"	77	0.8	0.6	-1.1	-	-	-	-	-	-
"	98	1.2	0.8	2.5	-	-	-	-	-	-

Our observations led to the conclusion that the higher retention of calcium, phosphorus or nitrogen per day in boars is mainly due to a higher retention in the second part of the growing period. So, the requirement of calcium and phosphorus for boars, when compared with barrows and gilts, will mainly be higher after 60 kg live weight.

9.5. CONCLUSIONS

When a higher protein level in the diet results in a higher growth rate or nitrogen retention, there is also a tendency towards a higher retention of phosphorus per day. For animals with a leaner type of daily gain the results of our experiments indicate that per kg live weight gain the retention of phosphorus may be 0.2 to 0.3 g higher. If the supply of phosphorus is minimal then the concentration of phosphorus in the diet should be raised. Contrary to results in the literature, no effect of a higher dietary protein level on calcium excretion in the urine was detected.

Comparison of boars, barrows and gilts showed that above 60 kg live weight, boars retain more phosphorus per day than barrows and gilts. This effect is mainly due to the higher nitrogen retention and growth rate of boars in that period. Therefore, the phosphorus requirement of boars above 60 kg live weight will be somewhat higher than of barrows and gilts.

It was shown that the P/N ratio in the bodies of pigs is not constant but may be affected by several factors such as the concentrations of phosphorus and protein in the diet, the level of energy intake and possibly the sex of the animal.

10. EFFECT OF DIETARY FAT AND CALCIUM LEVEL ON ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM

10.1. INTRODUCTION

To study the effect of dietary fat on the absorption and retention of phosphorus two experiments were set up. In both experiments, the effect of several sorts of fat were tested, while additionally two concentrations of dietary calcium were used because of its possible effect on soap formation. Pure tallow was used in both experiments because of its rather high concentration of long chain saturated fatty acids, which might readily react in the intestinal tract with calcium and magnesium. Soybean oil and coconut fat were used, because of the high concentration of unsaturated long chain fatty acids and short chain saturated fatty acids respectively, which do not react readily with calcium and magnesium. Because of the quite different fatty acid composition of industrial fats, when compared to renderer's fat, the effect of industrial fats on the absorption and retention of phosphorus and calcium was also studied. Renderer's fat originates from cadavers of cattle, swine and poultry, while industrial fats are mainly by-products of refining fats and oils for human consumption.
The extra amount of $CaCO_3$ was used to discover whether more soap formation would occur, and thereby a lower digestibility of the fat. In this chapter, the results of the digestibility of the fats will not be given but will be published elsewhere.
The relevant literature on fat has been reviewed in Chapter 2.4.

10.2. MATERIALS AND METHODS

10.2.1. General design of the experiments

10.2.1.1. First experiment (trials VV 597 to VV 599, VV 603 to VV 608 and VV 622)

In the first experiment different diets were subsequently fed to pigs from 40 to 120 kg live weight. The basal diet in VV 597 to VV 599 had a moderate calcium concentration, while that of VV 603 to VV 608 and VV 622 was identical to VV 597 to VV 599 except for a higher calcium concentration. The trials VV 597 to VV 599 and VV 603 to VV 605 were done at the same time with two groups of three barrows. The pigs in VV 597 to VV 599 were also used for trials VV 606 to VV 608. For trial VV 622 other animals were used.

10.2.1.2. Second experiment (trials VV 672 to VV 675)

In the second experiment, the diets were fed to four barrows from 50 to 120 kg live weight in a latin square design. In this experiment the pre-period lasted at least seven days but in most cases it was ten.

10.2.2. Diets

The basal diets used in the first and second experiment are given in Table 64, while in this table some characteristics of these diets are also given. In the first experiment, 1 000 g of the basal diet was diluted with 60 g fat or oil and 0.12 g vitamin E (50 per cent), while for the diet with the higher dietary calcium concentration, 5.56 g more $CaCO_3$ was added to raise the Ca/P ratio in the diet from 1.1 to 1.5.
In the second experiment, 1 000 g of the basal diet was diluted with 75 g fat and 0.13 g vitamin E (50 per cent), and for the diet with the higher calcium concentration 9.8 g extra $CaCO_3$ was added to raise the Ca/P ratio in the diet from 1.4 to 2.0.

Table 64. Composition of the basal diets (g/kg) and the results of some chemical analyses and feeding value

	basal diet	
	Exp. 1	Exp. 2
maize	356.3	-
wheat	70	-
barley	50	450
tapioca	120	-
soybean meal ext.	220	140
wheat middlings	80	-
grass meal	60	-
cane molasses	20	-
maize starch	-	237.5
skimmed milk powder	-	150
$CaCO_3$	5.6	8.0
DCP	7.8	7.5
premix and other additions	10.3	7.0

	basal diet	
	Exp. 1	Exp. 2
T (g/kg)	868	867
O (g/kg T)	938	941
XP "	188	183
XL " (hexane)	27	13
XF "	79	32
DXP "	147	156
NE_f (calc.;MJ/kgT)	9.55	10.29

In the following scheme the different diets will be given:

First experiment
VV 597: basal diet
VV 598: basal diet + soybean oil + vitamin E
VV 599: basal diet + tallow + vitamin E
VV 603: basal diet + $CaCO_3$
VV 604: basal diet + $CaCO_3$ + soybean oil + vitamin E
VV 605: basal diet + $CaCO_3$ + tallow + vitamin E
VV 606: basal diet + $CaCO_3$ + industrial fat 1 + vitamin E
VV 607: basal diet + $CaCO_3$ + industrial fat 2 + vitamin E
VV 608: basal diet + $CaCO_3$ + industrial fat 3 + vitamin E
VV 622: basal diet + $CaCO_3$ + industrial fat 4 + vitamin E

Second experiment
VV 572: diet A = basal diet
VV 573: diet B = basal diet + tallow + vitamin E
VV 574: diet C = basal diet + tallow + vitamin E + $CaCO_3$
VV 575: diet D = basal diet + coconut fat + vitamin E

To give an idea of the different types of fats or oil some characteristics are given in Table 65. The added fats in the first experiment were analysed for fatty acid composition, those of the second experiment were not. The animals were fed 80 per cent of the Dutch standards for energy (C.V.B., 1974), which means that a lower amount of diet was fed if it contained extra fat.
The effect of the calcium level in the diets of the first experiment was within the source of fat analysed by the t statistic for two means, while the results of the second experiment were analysed by analysis of variance.

Table 65. Some characteristics of the fats used

	pattern of main fatty acids					free fat acids (%
	<C14	C16:0	C18:0	C18:1	C18:2	
VV 598 and VV 604 soybean oil	-	10	4	21	56	nil
VV 599 and VV 605 tallow	3	26	20	40	5	nil
VV 606 industrial fat 1	2	44	5	38	10	87
VV 607 industrial fat 2	58	13	5	16	5	78
VV 608 industrial fat 3	2	46	8	42	-	3
VV 622 industrial fat 4	4	28	62	2	-	17
VV 672 to VV 675						
diet B and C tallow	3	26	20	40	5	nil
diet D coconut fat	65	9	2	7	2	nil

10.3. RESULTS

10.3.1. First experiment

During the first experiment the results concerning one animal in trial VV 605 were omitted because it had a raised temperature during the collection period. The results of this animal, however, were hardly different from those of the other two animals in VV 605. In trial VV 597, one animal had a 500 gram feed refusal in the middle of the collection period. The reason for this is not known. There were no other difficulties during this experiment and the growth rate of the animals was satisfactory. The results of the mineral balances are given in Appendix 24. When trials VV 597 to VV 599 are compared with trials VV 603 to VV 605, it can be seen that except for the basal diets the absorption percentages of calcium and phosphorus are higher; those with tallow were significantly higher in VV 599. The absorption percentage of calcium in trials VV 608 and VV 622 seems to be depressed by the added fat.

10.3.2. Second experiment

The second experiment was performed without difficulties and the animals had a reasonable growth rate. From analysis of diet D in the fourth period it appeared that the calcium and magnesium concentration in the diet was higher than expected (0.89 per cent calcium and 0.19 per cent magnesium). The reason for this is not clear. Therefore, the results of the calcium balance of this animal were omitted for further calculations. The results of the balances are given in Appendix 24.
Analysis of variance showed a significant ($p < 0.05$) higher absorption percentage for calcium and phosphorus and a higher retention percentage for phosphorus in diets B and D when compared to diet A. The retention percentage for calcium in diet A was significantly lower than in diet B. The retention of phosphorus did not differ significantly and only the retention of calcium in diet A was significantly higher ($p < 0.025$) than in diet D.
The higher calcium concentration in diet C resulted in a significantly lower absorption percentage for phosphorus, a lower retention percentage for calcium but a higher daily calcium retention when compared to diets B and D ($p < 0.025$).

10.4. DISCUSSION

10.4.1. General

When fat is added to a diet it means that when the animals are fed the same amount of energy a day, lower amounts of minerals are supplied. A lower supply of these minerals a day means that, because the mineral requirement of the animal is supposed to be the same, they will try to compensate for the lower supply. This can lead to a higher absorption and retention percentage of the minerals when fat supplemented diets are given. This should be kept in mind when the effect of fat on the balance of calcium and phosphorus is discussed. Furthermore, one should be aware of the fact that when the diets are fed to the same animals as they grow older, the absorption and retention percentages for the minerals can also decline.

10.4.2. Effect of dietary fat on the phosphorus balance

Addition of fat to the diet resulted in a higher absorption and retention percentage for phosphorus, because of the diminished daily supply of this mineral. On the whole, no great effect of the various fats on absorption and retention of phosphorus was noticed. This agrees well with the results mentioned in the literature review (Chapter 2.4.).
In trial VV 622, in contrast to the effect on calcium balances the absorption and retention percentage of phosphorus was not lower, which might be due to soap formation as a result of the high concentration of saturated long fatty acids and, as will be discussed in Chapter 12, that a lower Ca/P ratio in the diet stimulates the absorption of phosphorus.

10.4.3. Effect of dietary fat on the calcium balance

The results of the two experiments show that in most cases addition of fat to a diet leads to a higher absorption and retention percentage of calcium. This is obviously caused by the lower supply of calcium a day. This confirms the results of Gundel and Kemenes (1980). In diets with a high concentration of saturated long chained fatty acids (trials VV 608 and VV 622), the absorption percentage of calcium is depressed. The effect of tallow in the diet on calcium absorption is variable. In two cases the absorption and retention percentage of calcium was not affected and in one case it was lower. Newman et al. (1967) found that the addition of 10 per cent tallow resulted in the same absorption percentage of calcium despite a lower calcium intake, which means that the absorption in their experiments was actually depressed. However, they were working with diets containing 0.2 per cent and 0.8 per cent calcium and 0.45 per cent phosphorus and the results of the two calcium levels were not given separately. There was an interaction between the percentage of calcium retained and the fat level, which hampers a good interpretation of their results.
In diets containing fats with many short chained fatty acids (trials VV 607 and VV 675), the absorption and retention percentage of calcium is not much different from diets supplied with fats containing about 50 per cent C16:0 + C18:0. In rats, however, greater effects of the fatty acid composition on calcium absorption are observed (e.g. Calverley and Kennedy, 1949; Tadayyon and Lutwak, 1969).
In the Netherlands, it is usually renderer's fat that is added to the diets. The fatty acid composition of such fat is often as follows: 2 per cent <C14, 25 per cent C16:0, 15 per cent C18:0, 41 per cent C18:1 and 9 per cent C18:2 but depends on sources of fat used: from cattle, pigs or poultry. This resembles tallow, but has more C18:2, so it may be expected that the absorption of calcium will hardly be influenced. To show what the influence is of calcium bound by formation of soaps, the following calcula-

tion can be made. It is assumed that the pig gets 2 kg diet containing 6 per cent fat and, by means of soap formation, the digestibility of the fat is depressed by 20 units. One gram equivalent fat is 270 gram. This means that 120 x 0.20/270 = 0.089 gram equivalent calcium can be bound and in the diet this means 0.09 per cent calcium. A practical diet for growing pigs contains about 0.8 or 0.9 per cent calcium so that the binding of calcium to fatty acids in this example is nearly 10 per cent of the total amount of calcium in the diet. In a normal diet, the digestibility of renderer's fat is about 90 per cent, so that the effect on calcium binding by fatty acids is obviously small. When, however, industrial fats with a very high concentration of long saturated fatty acids are added to a diet (4 to 6 per cent) and when the calcium concentration in the diet is 0.6 to 0.7 per cent, one can expect problems concerning calcium feeding. This can be seen from the results of trial VV 622 where a very low digestibility of the fat (50 per cent) was found. A depression of the digestibility of the fat from 80 to 50 per cent means that on average, 0.11 gram equivalent calcium could be bound per kg diet, which is 2.2 gram calcium.

10.4.4. Effect of dietary calcium concentration on the calcium and phosphorus balance

In the two experiments, the higher calcium concentration in the diet resulted in a lower absorption and retention percentage of calcium and a higher calcium retention per day. Also, the absorption percentage for phosphorus was depressed and, with the exception of trial VV 597, in which a relatively large amount of phosphorus was excreted in the urine, also the retention percentage and retention of phosphorus. The relationship of the calcium concentration in the diet with the phosphorus utilization is given in Table 66. This is discussed further in Chapter 12.

Table 66. Relationship between dietary calcium (% in T) to absorption and retention of P

trials	weight (kg)	equation
VV 597 and VV 603	52	absorption % of P = 0.5 Ca % diet + 37.1
"	"	retention % of P = 21.0 " + 17.4
VV 598 and VV 604	67	absorption % of P = -30.5 " + 64.9
"	"	retention % of P = -9.0 " + 45.7
VV 599 and VV 605	84	absorption % of P = -43.8 " + 72.3
"	"	retention % of P = -25.2 " + 51.8
VV 673 and VV 674	90	absorption % of P = -12.2 " + 51.5
"	"	retention % of P = 7.5 " + 26.0

10.5. CONCLUSIONS

The two experiments show that when fat is added to the diet no great effect on the absorption and retention of phosphorus is noticed if the fat has a fatty acid composition, as in renderer's fat. The same holds true for calcium. When fats are used with a high concentration of long chain saturated fatty acids, calcium retention can become suboptimal at high inclusion levels of fat, because insoluble calcium soaps are formed.

11. EFFECT OF DIETARY CRUDE FIBRE LEVEL ON ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM

11.1. INTRODUCTION

In this chapter, an experiment is described in which the effect of an increased concentration of crude fibre on the absorption and retention of phosphorus and calcium was studied. In fact, this experiment was set up for a study in which the nitrogen retention and the digestibility of amino acids of diets differing in crude fibre and digestible lysine content were determined. In addition, phosphorus and calcium absorption and retention were also measured. This research was done with boars and the diets had two concentrations of digestible lysine. The source of crude fibre was mainly from grass meal.
Literature on the effect of crude fibre on phosphorus absorption and retention has been reviewed in Chapter 2.5.

11.2. MATERIALS AND METHODS (TRIALS VV 572 TO VV 583)

Four different diets were used in this experiment (see Table 67). Diets A and B had the same calculated concentration of digestible lysine (6.7 g/kg) but differed in some ingredients, crude protein and crude fibre concentration. Diets C and D had also the same, although lower, calculated digestible lysine concentration (5.3 g/kg) but also differed in some ingredients, crude protein and crude fibre concentration. It was tried to get the same concentrations of calcium and of phosphorus in the four diets by adjusting the supplementary amounts of limestone and dicalcium phosphate. The diets were mixed in one process for the whole experiment from the same batches of ingredients, and pelleted.

Table 67. Composition of the diets

	diet			
	A	B	C	D
maize	426.6	147.6	426.2	154.7
barley	140.0	-	160.0	-
maize gluten feed	162.5	102.5	210.0	162.5
grass meal	20.0	200.0	20.0	200.0
coconut expeller	-	200.0	-	200.0
soybean meal	197.5	175.0	130.0	107.5
wheat bran	-	80.0	-	80.0
cane molasses	30.0	30.0	30.0	30.0
soybean oil	-	50.0	-	50.0
minerals + vitamins	4.2	4.2	4.2	4.2
limestone	7.8	0.8	8.1	1.1
dicalcium phosphate	11.4	9.9	11.5	10.0
NE_f(est.; MJ/kg)[1)]	9.08	9.08	9.08	9.08
XP (g/kg)[1)]	175	195	159	180
DXP (g/kg)[1)]	148	147	132	132
lysine (g/kg)[1)]	7.7	8.6	6.2	7.1
digestible lysine (g/kg)	6.7	6.7	5.3	5.3
XF (g/kg)[1)]	49	121	48	121

1) calculated from Dutch Feeding Table.

From ± 22 kg live weight, the animals, boars of the GY x (GYxDL) breed, three per diet, were given their respective diets until slaughter at ± 100 kg. The balances of N, calcium and phosphorus were measured at ± 40, ± 64 and ± 93 kg live weight. During the balance trial at ± 64 kg, the digestibility of all proximate components was determined to calculate the NE_f content. The results were statistically analysed by analysis of variance.

11.3. RESULTS

The performance of the animals during the experiment is given in Table 68. The lower average feed intake on diet D was due to feed refusals at the start of the experiment.

Table 68. Performance of the animals

	diet**			
	A	B	C	D
initial weight (kg)	28	27	25	25
growth rate (g/d)	745	703	698	634
feed conversion ratio*	2.52	2.56	2.64	2.80
feed intake (kg/d)	1.90	1.89	1.88	1.81
backfat thickness (mm)	25	24	25	24
days in experiment	98	103	110	114

* corrected to a NE_f concentration of 8.79 MJ/kg.
** see Table 69

The chemical analyses of the diets are given in Table 69, the results of the balance experiments in Appendix 25 and a summary of the results of the analysis of variance in Table 70. The results of the calcium and phosphorus balance at 64 kg for diet B showed a lower retention than expected, which could partially have been caused by the low digestibility of the dry matter, which was higher in the other periods. Unfortunately, no additional analyses on the cell wall fractions in the diets could be done due to a fire in the laboratory which destroyed all the samples.

Table 69. Chemical analyses of the diets and feeding value

	diet			
	A	B	C	D
T (g/kg)	835	860	846	863
O (g/kg T)	946	926	943	928
XP "	206	220	200	211
XF "	59	139	62	133
lysine "	9.0	9.9	7.7	8.5
Ca "	8.6	8.6	8.4	8.6
Mg "	1.9	2.7	2.0	2.7
P "	6.5	6.7	6.6	6.8
phytate P "	2.8	2.9	3.0	3.0
DXP "	169	158	163	152
digestible lysine (g/kg T)	7.0	6.4	5.8	5.4
NE_f (calc.; MJ/kg T)	10.38	9.72	10.15	9.93

Table 70. Summarized results of the balance experiments (df = 8)

	diet					significance	
	A	B	C	D	sed	XF	dig. lysine
XF (g/kg T)	59	139	62	133			
dig.lysine (g/kg T)	7.0	6.4	5.8	5.4			
d_T (%)	83.3	72.3	81.0	71.8	0.6	***	*
d_N (%)	82.0	71.7	81.5	72.2	1.0	***	ns
absorption % of Ca	41.3	37.2	42.6	35.0	1.1	***	ns
absorption % of P	39.8	35.4	41.3	37.2	1.0	***	ns
retention % of Ca	40.2	36.5	41.2	34.1	1.4	***	ns
retenton % of P	33.4	28.3	32.5	27.0	1.0	***	ns
retention of Ca (g/d)	5.85	5.44	5.83	5.05	0.21	*	ns
retention of P "	3.61	3.21	3.58	3.09	0.12	**	ns
retention of N "	24.2	20.5	20.8	19.9	0.5	***	***
P in urine (g/d)	0.73	0.84	1.00	1.19	0.09	ns	**

11.4. DISCUSSION

The diets used had a slightly different nutritive value than was intended. The digestion experiment at 64 kg showed a lower NE_f value for diet B than for the other diets (Table 69). Also, the digestible lysine concentration in diet B was lower than in diet A, while that in diet D was lower than in diet C. Some of the differences may be due to analytical error which, especially for lysine, is rather high. Some may have been true, resulting in differences in growth rate which might have influenced the results of the mineral balances.

The inorganic phosphorus concentration, which is assumed to be the difference between the concentrations of total and phytate phosphorus, was almost the same in all four diets. This was achieved by the addition of 0.03 per cent more phosphorus from dicalcium phosphate to diets A and C than to diets B and D.

The analyses of variance indicated a significant effect of the crude fibre concentration on the absorption and retention of calcium and phosphorus. No effect of the digestible lysine concentration or an interaction of digestible lysine x crude fibre concentration was found on the calcium and phosphorus absorption and retention except for the urinary excretion of phosphorus. At the lower digestible lysine concentrations, on average 0.3 g more phosphorus per day was excreted in the urine ($p < 0.01$), which can probably partly be explained by the lower protein retention.

There was a significant negative influence of the higher crude fibre concentration in the diet on the absorption percentage of calcium and phosphorus; on average the absorption percentage was 6 and 5 units lower respectively. In accordance with this, lower retention percentages for calcium and phosphorus were also found and, in both cases, were on average 5 units lower at the higher crude fibre concentration in the diet. There was also a significant negative effect of XF on the daily retention of calcium and phosphorus. On average, 0.6 g calcium and 0.4 g phosphorus less were retained per day at the higher crude fibre level.

There were differences in growth rate of the animals between the diets, so this might have influenced mineral retention. In order to eliminate the effect of differences in growth rate, the retention of calcium and phosphorus was also calculated per kg live weight gain. The results of these calculations are given in Table 71. It can be seen that the retention of calcium and phosphorus per kg live weight gain on the diets with a higher crude fibre concentration are also lower. When corrected for the live weight gain, the calcium and phoshorus retention for the crude fibre-rich diets

are on average, respectively 5 and 7 percent lower than in the normal diets. However, when corrected for differences in gut-fill due to the higher crude fibre concentration in the diet, which is at slaughter weight approximately 0.5 kg per percentage crude fibre in the diet (Jongbloed and Hoekstra, 1985), then there are hardly any differences in retention of calcium and phosphorus per kg weight gain.
From the work described by Partridge (1978[b]) it can be concluded that 90 instead of 30 g wood cellulose (Solca Floc) per kg diet depressed the absorption percentage of phosphorus from 81 to 74. This effect was explained by the higher rate of passage, or by the greater volume of the digesta. It is doubtful, however, whether the volume of the digesta is increased, because Solca Floc is regarded as being amorphous and will therefore hardly swell. Also, in a recent experiment described by Partridge et al. (1986), using straw meal treated with concentrated hydrochlorid acid and steam, the absorption of phosphorus was reduced. Oat hulls in a diet (10 per cent) also reduced the absorption and retention of phosphorus in experiments done by Moser (1980) and Moser et al. (1982), whereas Drochner (1984) also observed negative effects of fibrous components on phosphorus absorption.

Table 71. Retention of calcium and phosphorus during the whole experimental period, as such and per kg live weight gain (mean and sd)

	XF (g/kgT)	n	total retention calcium (g)	total retention phosphorus (g)	retention per kg live weight gain calcium (g/kg)	retention per kg live weight gain phosphorus (g/kg)
diet A	59	3	551 ± 41	341 ± 24	7.55 ± 0.60	4.68 ± 0.36
diet B	139	3	538 ± 25	317 ± 9	7.45 ± 0.07	4.40 ± 0.08
				7.89 ± 0.07[a]	4.66 ± 0.09[a]	
diet C	62	3	614 ± 76	376 ± 50	8.01 ± 0.73	4.91 ± 0.49
diet D	133	3	528 ± 41	325 ± 18	7.34 ± 0.37	4.51 ± 0.04
				7.71 ± 0.39[a]	4.74 ± 0.06[a]	

a) when corrected for differences in gut-fill

Den Hartog et al. (1985) found no effect of the inclusion of either 5 per cent cellulose, 5 per cent pectin or 5 per cent straw meal in a control diet on the absorption of phosphorus. The results of their experiment might have been disturbed by the high mineral levels in the control diet, so that there was ample possibility to compensate for a possible negative effect of carbohydrate sources used. Furthermore, it is found by Bagheri and Guéguen (1985) that the effect of pectin on the absorption of minerals depends on its degree of methoxylation; high-methoxylated pectin had little effect, but low-methoxylated pectin drastically diminished the absorption of phosphorus.
The effect of crude fibre in the present experiment is a combination of the effects of hemicellulose, cellulose and pectin, so it is difficult to compare the results with those in the literature. Moreover, the physico-chemical properties within the same carbohydrate source are not the same. On the basis of the hemicellulose and cellulose concentration in different feedstuffs (Gaillard, 1966; Sauvant et al., 1980), these concentrations were estimated in the diets of the present experiment. These were 82 and 57 g per kg T respectively in the normal diets (A and C) and 125 and 110 g per kg T respectively in the diets rich in crude fibre (B and D). No reliable estimates of the concentration of pectin (as polygalacturonic acid) in the diets could be made due to lack of sufficient data and different methods applied. From grass meal it seems that it has a rather low concentration of pectin with a low degree of esterification (Pilnik and Voragen, 1970).

The increase in the concentration of cellulose is almost the same as in the experiment done by Partridge (when 86 per cent cellulose in Solca Floc is assumed) but the depression in absorption percentage of phosphorus in the present experiment is more: from 40.6 to 36.3, which is, relatively, 10 per cent. However, not only cellulose but also lignin or pectin may have played a role in the negative effect.
Another aspect which, in our experiment, could also have led to a lower absorption of phosphorus, is a different availability of the phosphorus from the ingredients in the diets B and D rich in crude fibre and in the normal diets A and C, because of differences in the presence of phytase, which can influence the availability of phytate phosphorus (Bagheri and Guéguen, 1985). However, barley and wheat bran are the main carriers of phytase, and diets A and C contain barley and the other two wheat bran so that the presence of phytase will not have differed markedly between diets.
We can conclude from this experiment, that a higher crude fibre concentration in the diet results in lower absorption and retention percentages for calcium and phosphorus, but that some of the effect could be due to differences in live weight gain. There were hardly any differences in mineral retention per kg weight gain, when live weight was corrected for differences in gut-fill. The effect of fibre on absorption might be due both to an effect of crude fibre per se and to differences in availability of the minerals in the ingredients. More research is necessary to gain more insight into the cause of the effect of crude fibre on the absorption of phosphorus.

12. EFFECT OF THE CONCENTRATION OF CALCIUM AND THE CA/P RATIO IN THE DIET ON ABSORPTION AND RETENTION OF PHOSPHORUS

12.1. INTRODUCTION

In this chapter the effect of the calcium concentration in the diet, particularly its relation with the phosphorus concentration in the diet, on absorption and retention of phosphorus is described. As already outlined in the literature review (Chapter 2.6.) a significant effect of the dietary calcium concentration could be demonstrated on absorption and retention of phosphorus. However, most of the diets used in the experiments of the review were composed of corn and soybean meal and the diet composition might have influenced the effect. Therefore, studies with diets customary used in the Netherlands were also performed.
First, the results of an experiment will be given in which the effect of calcium on phosphorus absorption and retention was studied followed by a general discussion on this topic. In this discussion, the results of other trials, described in other chapters, will also be included, in which the effect of the Ca/P ratio in the diets was investigated.

12.2. EFFECT OF CA/P RATIO AND P CONCENTRATION IN THE DIET ON THE ABSORPTION AND RETENTION OF Ca, P AND N IN BOARS, BARROWS AND GILTS AND ON THE COMPOSITION OF TWO BONES (TRIALS VV 367 TO VV 378)

12.2.1. Materials and Methods

For this experiment, four diets were used which were composed of the same basal diet. One was equal to the basal diet, the others had additional calcium or phosphorus. The composition of the diets is given in Table 72.

Table 72. Composition of the diets (g/kg)

	diet 1	diet 2	diet 3	diet 4
trials VV	376-378	373-375	367-369	370-372
maize	290	280	280	270
barley	250	250	250	250
milo	150	150	150	150
soybean meal solv.extr.	200	200	200	200
oathusk meal	50	50	50	50
grass meal	50	50	50	50
$CaCO_3$	-	4.4	9.0	9.2
$NaH_2PO_4.2H_2O$	-	-	-	8.6
other minerals + vitamins (incl. starch carrier)	10.0	16.6	11.0	12.2

Because of the large amount of feed needed for this experiment, it was made in three batches. Due to its high nitrogen and phosphorus concentration, the soybean meal was reserved for the whole experiment.
The estimated NE_f value of the basal diet was 9.04 MJ/kg and the DXP content was 146 g/kg, while the lysine concentration was calculated to be 8.2 g/kg.
The animals received the same diet during the whole experiment. When not on metabolism cages, they were group-housed in a straw-bedded pen and group fed. All the animals which received diet 3 were from the same litter. The same was the case with the animals given diet 4. Diet 1 as well as diet 2

was fed to four barrows and four sows, while for each diet three of the barrows were taken for the balance trials. Both diets 3 and 4 were fed to three boars, three barrows and three sows. All these animals were also taken for the balance trials.
During the balance trials the animals were fed 10 per cent under the Dutch standards for energy, but at 85 kg and higher due to the high environmental temperature, the animals were fed 15 per cent under the Dutch standards. Although diets 2 to 4 had a somewhat lower NE_f content, due to the addition of calcium or phosphorus, the amount of diet fed was not adjusted for this. The preliminary period lasted seven days, followed by a collection period of seven days.
At a live weight of about 105 kg the animals were slaughtered and the radius and fifth tail vertebra taken for further analysis. The radii of five animals given diet 1 and five animals from diet 3 were subjected to mechanical examination. The strength of the bones was measured as the bending moment for distortion and breaking. The method is described by Van Kempen et al. (1976). The results of the balances of the animals, given diets 3 and 4, were subjected to an analysis of variance to examine whether there was a significant effect of diet, sex, period and the interactions diet x sex and sex x period on calcium, phosphorus and nitrogen absorption and retention. Statistical analyses of the results in the bones was performed by regression analysis.

12.2.2. Results

During the experiment, some animals had to be withdrawn from the balance trial because of pneumonia. We should also mention that when the animals were taken back to their pen there was some fighting between them. The performance of the animals is given in Table 73.

Table 73. Performance of the animals (between parenthesis number of animals)

	diet			
	1	2	3	4
Ca (g/kg T)	2.1	4.1	6.0	6.0
P (g/kg T)	4.1	4.1	4.0	5.6
initial weight (kg)	26	26	27	26
growth (g/d) barrows	650(4)	656(4)	617(3)	678(3)
growth (g/d) gilts	686(4)	641(4)	627(3)	611(3)
growth (g/d) boars	-	-	667(3)	694(3)
feed conversion ratio	3.17	3.20	3.25	3.05
feed intake (kg/d)	2.11	2.09	2.07	2.01
days in experiment	125	129	128	128

From Table 73 it can be seen that the growth rate of the animals on the different diets was about the same, but the feed conversion ratio on diet 4 was somewhat better than on the other diets.
The results of some chemical analyses in the diets are given in Table 74 while the detailed results of the balance trials are given in Appendix 26. The results of the analysis in the bones are presented in Table 77 and discussed in section 12.2.3.3.

Differences in the phosphorus concentration in diet 4 in the three periods (Table 74) might have been caused by a higher content of water in the phosphorus source, because the same weight of phosphorus source was added to the diet. The lower protein content in diet 4, when compared to diet 3, is probably due to mixing the diets at the mill.

Table 74. Results of the chemical analyses of the diets

		diet 1	diet 2	diet 3	diet 4
batch 1	T (g/kg)	855	864	861	861
	XP (g/kg T)	-	-	182	177
	Ca "	2.2	4.8	6.3	6.3
	P "	4.2	4.0	4.0	5.9
batch 2	T (g/kg)	865	876	865	862
	XP (g/kg T)	-	-	181	173
	Ca "	2.4	3.8	5.8	6.2
	P "	4.1	4.1	4.1	5.7
	phytate P "	2.9	-	-	2.8
batch 3	T (g/kg)	866	862	867	866
	XP (g/kg T)	-	-	190	173
	Ca "	1.6	3.6	6.0	5.5
	P "	4.0	4.1	4.0	5.3
	phytate P "	2.7	-	-	-

12.2.3. Discussion

12.2.3.1. Effect of dietary calcium concentration on absorption and retention of phosphorus

In this section only some general remarks will be made, because in section 12.3. all experiments will be discussed together, with regard to the influence of the calcium concentration on absorption and retention of phosphorus.
From the results given in Appendix 26 it can be seen that as a result of a low calcium concentration in diet 1 quite a lot of the absorbed phosphorus is excreted in the urine. The absorption percentage for phosphorus in diet 1 at 48 kg is higher than at 72 and 92 kg but no satisfactory explanation for this can be given. In other experiments, it was never observed that at a low phosphorus concentration in the diet the absorption percentage for phosphorus at about 40 kg live weight is so much higher than at other live weights. On average, the absorption percentage for phosphorus in diets 1, 2 and 3 was 40 per cent. There were hardly any differences in phosphorus retention between diets 2 and 3. Within each weight range, except at 46 kg, the calcium concentration in the diet was regressed on the absorption and retention percentage of phosphorus (Table 75). The maximum P retention was achieved at a calcium concentration for the two weight ranges of 0.56 and 0.55 respectively, but this was not significant. It can be calculated that the optimum Ca/P ratio in these diets was on average 1.36 (see also section 12.3.).

Table 75. Relationship between dietary Ca (% in T) to P utilization

trials (VV)	weight (kg)	equation	significance
377, 374 and 368	70	absorption % of P = -4.2 ± 12.6 Ca + 42.8	ns
377, 374 and 368	70	retention % of P = 13.1 ± 24.4 Ca + 32.7	ns
378, 375 and 369	98	absorption % of P =-11.8 ± 4.8 Ca + 43.5	ns
378, 375 and 369	98	retention % of P = 23.4 ± 27.6 Ca + 23.7	ns

12.2.3.2. Effect of the addition of phosphorus on absorption and retention of calcium and phosphorus and on nitrogen retention

A summary of the results of the analysis of variance for diets 3 and 4 is given in Table 76. There were no significant differences in calcium and phosphorus absorption and retention when the sexes were compared.
The calcium and phosphorus absorption and retention was in most cases significantly higher on diet 4. There was also usually a significant period effect. As might be expected, there was a significant interaction diet x period ($p < 0.001$) for the phosphorus retention percentage and the calcium and phosphorus retention per day (see also Figure 17). There was a significant decrease in absorption and retention percentage of phosphorus in diet 4 at a higher live weight, but not for diet 3.

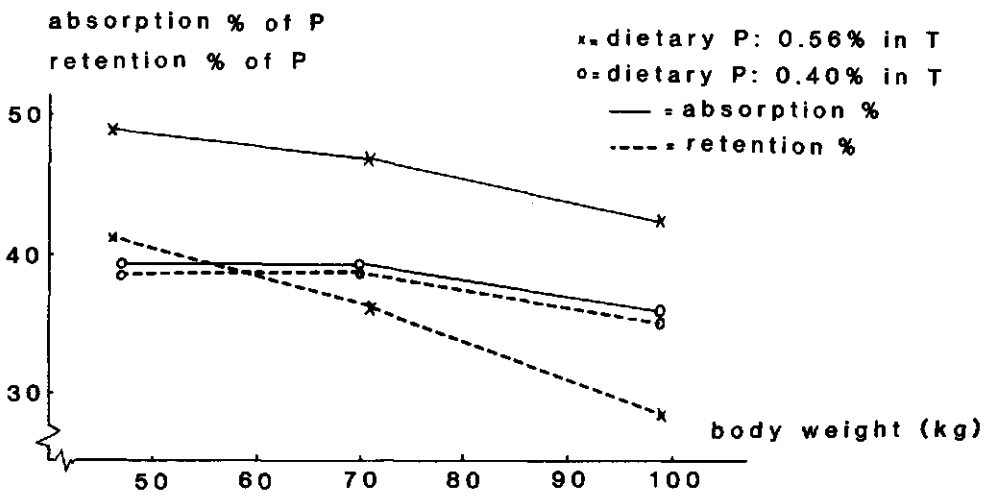

Figure 17 Effect of dietary P level and body weight on absorption and retention of P
(trials VV 367 to VV 372)

As indicated in Figure 18, it can be seen that nitrogen retention is higher when diet 4 is given when compared to diet 3 but the difference was not significant. The digestibility of nitrogen was the same but more nitrogen was excreted in the urine when diet 3 was given ($p < 0.05$), which can mainly be explained by the higher intake of nitrogen with diet 3. Boars retained more nitrogen than gilts and barrows ($p < 0.05$).

Table 76. Summarized results of the balance trials VV 367 to VV 372

	diet 3	diet 4	significance diet	sex	period
Ca (g/kg T)	6.0	6.0			
P (g/kg T)	4.0	5.6			
d_T (%)	79.7	79.7	-	-	-
d_N (%)	79	79	-	-	*
absorption % of Ca	54	46	***	-	*
absorption % of P	38	45	***	-	***
retention % of Ca	32	46	***	-	-
retention % of P	37	35	-	-	***
retention% of N	40	44	***	*	-
retention of Ca (g/d)	3.6	5.1	***	-	***
retention of P (g/d)	2.7	3.4	***	-	***
retention of N (g/d)	21.2	22.3	-	-	***

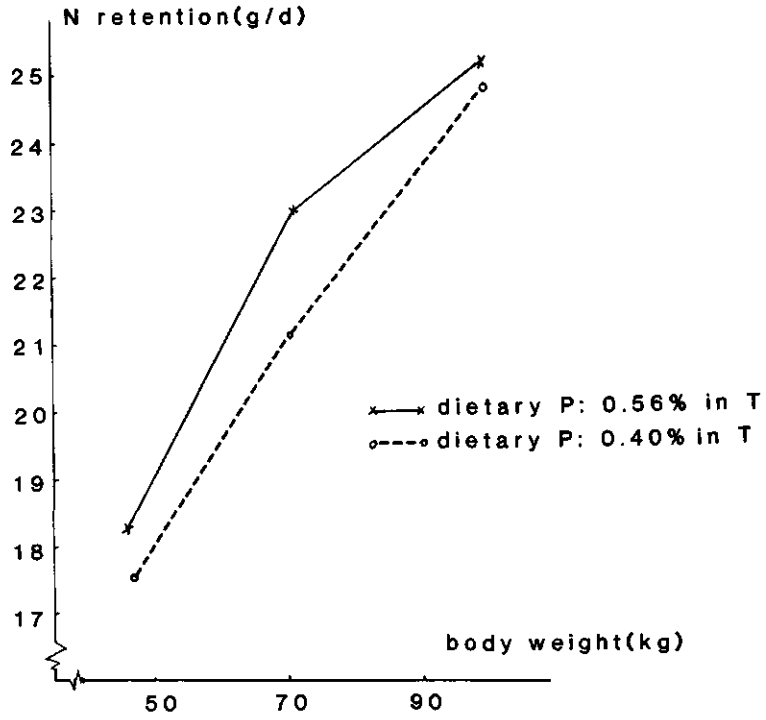

Figure 18 Effect dietary P level and body weight on N retention
(trials VV 367 to VV 372)

12.2.3.3. Mineralization of the bones

The results in Table 77 show great differences in the mineralization of the bones as a result of the calcium and phosphorus concentrations in the diet. Diet 1 resulted in bones with a lower amount of fat-free dry matter and ash and a higher magnesium concentration than the other diets. There were no great differences in results of the bones from diets 2 and 3, except for the phosphorus and magnesium concentrations. The bones of the animals on diet 4 were heavier and had a higher ash concentration.
In general, there were no great differences in the composition of the ash, except for magnesium and the higher phosphorus concentration in the fifth tail vertebra of the animals on diet 1. There was a close negative relationship between the calcium concentration in diets 1, 2 and 3 and the magnesium concentration in the radius (r = -0.90) and also in the fifth tail vertebra (r=-0.86).

Table 77. Measurements of the radii and the fifth tail vertebra

	diet 1	diet 2	diet 3	diet 4	rsd	sign. diet
Ca in diet (g/kg T)	2.1	4.1	6.0	6.0		
P in diet (g/kg T)	4.1	4.1	4.0	5.6		
Radii						
n	8	8	9	9		
fresh weight (g)	52.05 a	55.17 a	55.03 a	64.32 b	3.37	***
volume (cm^3)	41.74 a	43.31 a	43.40 a	48.85 b	3.31	***
length (mm)	97.4	97.8	97.6	100.2	2.4	ns
thickness I (mm)	14.3 a	14.8 ac	14.6 a	15.5 bc	0.7	**
thickness II (mm)	21.8 a	22.5 a	24.0 b	23.8 b	1.0	***
fat-free T (g)	21.38 a	25.45 b	24.46 b	30.73 c	2.25	***
ash (g/kg fat-free T)	625.3	629.3	630.1	641.9	13.3	ns
ash (g)	13.37 a	16.02 b	15.42 b	19.72 c	1.46	***
Ca(g/kg ash)	372.3	374.3	374.4	368.6	4.9	ns
Mg(g/kg ash)	7.23 a	6.64 b	6.01 c	6.72 b	0.24	***
P (g/kg ash)	172.9 a	172.6 a	168.6 b	171.4 a	2.6	*
fifth tail vertebra						
ash (g/kg fat-free T)	599.4 a	616.6 a	610.1 a	630.7 b	17.6	**
Ca (g/kg ash)	371.0	369.1	370.8	373.6	5.2	ns
Mg (g/kg ash)	7.39 a	6.52 b	5.92 c	6.42 b	0.34	***
P (g/kg ash)	182.4 a	178.6 b	177.4 b	178.9 b	2.5	**

From the results of the balance trials, the retention of calcium and phosphorus during the whole experiment was calculated (Table 78). Because the animals were group-fed when not on the metabolism crates, and therefore the feed intake per animal is not known, the standard deviations of the retentions are not given. The amounts of calcium and phosphorus found in the radii are also given in Table 78.

From Table 78 it can be seen that there is a good relation between the retention of calcium and phosphorus based on the balance trials and the amount of these minerals in the radius (for further discussion: see Chapter 17)

Table 78. Estimated total retention of Ca and P from 26 to 106 kg according to the balance trials and the amount of Ca and P in the radii at slaughter (g)

	diet 1		2		3		4		rsd	
	Ca	P	Ca	P	Ca	P	Ca	P	Ca	P
in diet (g/kg T)	2.1	4.1	4.1	4.1	6.0	4.0	6.0	5.6		
based on balance	315	308	490	385	464	347	634	434	-	-
radius	4.98	2.31	6.00	2.77	5.77	2.60	7.26	3.38	0.50	0.25

12.2.3.4. Mechanical examination of the bones

The results of the mechanical examination of the radii are given in Table 79. The results indicate that for diet 3 the surface of the cortex is somewhat greater than for diet 1, and also the breaking force was greater on diet 3. The specific resistance to break the radius was not significantly different between the two diets. This means that the strength of the matrix is not different.

Table 79. Influence of the diet on some physical and mechanical characteristics of some radii (5 per diet)

	diet 1	diet 3
Ca (g/kg T)	2.1	6.0
P (g/kg T)	4.1	4.0
surface of the cortex (mm^2)	160.2 ± 15.4	166.0 ± 9.4
bending moment to distortion (Nm)	36.1 ± 7.6	36.6 ± 10.1
" " " breaking (Nm)	46.7 ± 9.5	57.6 ± 6.9
specific resistance to distortion (N/mm^2)	58.9 ± 13.2	53.4 ± 15.1
" " to breaking (N/mm^2)	76.0 ± 15.1	84.8 ± 18.4

12.3. DISCUSSION ABOUT THE OPTIMUM CA/P RATIO IN THE DIET

In five series of experiments (trials VV 367 to VV 378; trials VV 411 to VV 422; trials VV 431 to VV 445; trials VV 597 to VV 608 and trials VV 672 to VV 675) the effect of the Ca/P ratio in the diet on the absorption and retention percentage of phosphorus could be studied. The detailed results of the above mentioned experiments are described in Chapters 12, 13, 13, 10 and 10 respectively. A summary of the relevant data is given in Table 80.
From nearly all our experiments (see the respective chapters mentioned), it is clearly shown that more calcium in the diet results in -a usually insignificant- lower absorption percentage for phosphorus. This is also found in the literature (see Figure 4 literature review).
The effect of the calcium concentration in the diet on the retention percentage of phosphorus is more complicated. In the diets without supplemented inorganic phosphorus (first eight rows of trials given in Table 80) and

Table 80. Summary of the results of the trials with varying Ca/P ratio in the diets and calculated optima (mean and sem)

trials VV	live weight (kg)	in diet (g/kg T) P	Pi	P added	Ca	digestible P (g/kg T)	optima for maximum P retention Ca(g/kgT)	Ca/P	Ca/Pi	Ca/dig.P
377, 374 and 368	70	4.1	1.3	0	2.4, 3.8 and 5.8	1.7	5.6	1.36	4.28	3.29
378, 375 and 369	98	4.0	1.3	0	1.6, 3.6 and 6.0	1.6	5.5	1.36	4.20	3.41
414, 417 and 420	41	6.7	1.8	0	1.9, 4.0 and 6.4	2.4	7.6	1.14	4.22	3.17
415, 418 and 421	66	6.7	1.8	0	1.9, 4.0 and 6.4	2.6	8.4	1.26	4.66	3.22
416, 419 and 422	98	6.7	1.8	0	1.9, 4.0 and 6.4	2.5	9.1	1.37	5.07	3.65
434, 440 and 443	43	6.3	1.9	0	1.5, 2.5 and 3.7	3.1	7.4	1.16	3.88	2.38
435, 441 and 444	70	6.3	1.9	0	1.5, 2.5 and 3.7	3.0	7.0	1.11	3.70	2.34
436, 442 and 445	99	6.3	1.9	0	1.5, 2.5 and 3.7	3.3	7.5	1.18	3.94	2.27
597 and 603	52	6.1	3.4	1.6	6.8 and 8.9	2.3(3.2)*	9.6	1.57	2.82	2.99*
598 and 604	67	5.8	3.2	1.5	6.3 and 8.4	2.5(3.0)*	9.0	1.54	2.80	2.99*
599 and 605	84	5.8	3.2	1.5	6.3 and 8.4	2.3 (3.0)*	11.0	1.90	3.45	3.68*
673 and 674	90	5.7	4.0	3.0**	8.0 and 1.16	2.2(3.7)*	12.9	2.27	3.23	3.49*
					mean ratios all series n = 12			1.43+ 0.10	3.85+ 0.20	3.07+* 0.14
					mean ratios first 8 series			1.24+ 0.04	4.24+ 0.16	2.97+ 0.19

* In the last four series of trials digestible P (within parentheses) was estimated as: 0.4 x P content in diet without P and P from animal origin + 0.9 x (added Pi and P from animal origin)

** P from skimmed milk powder included.

with calcium levels up to 6.5 g/kg T, usually a significant positive relationship was found with the retention percentage of phosphorus. In the diets with supplemented inorganic phosphorus (last four rows of trials given in Table 80) the effect of the calcium level on the retention percentage of phosphorus was variable. In these trials, the retention percentage of phosphorus was usually not much different at the two calcium levels. Because more available phosphorus is fed than the dietary requirement, this is compensated for more phosphorus being excreted in the urine. Furthermore, in the last four rows of the trials in Table 80 the calcium level was considerably higher than in the first eight trials mentioned in Table 80. In the literature review (see Figure 5), it was shown that high calcium levels in the diet (0.9 per cent and higher) have a negative influence on both the absorption and retention percentage of phosphorus.
As performed for the data from the literature, the mean regression between the calcium level in the diet and the absorption and retention percentages of phosphorus in our experiments was calculated. Moreover, a separate relationship for the diets without supplemented inorganic phosphorus was calculated. The following results were obtained (mean ± sem):

absorption % of P =	-14.2 ± 3.7 Ca% in T + 49.7	n = 12	all trials
retention % of P =	17.6 ± 5.4 Ca% in T + 24.1	n = 12	all trials
absorption % of P =	-10.5 ± 2.6 Ca% in T + 46.3	n = 8	trials without added Pi
retention % of P =	27.0 ± 3.0 Ca% in T + 18.6	n = 8	trials without added Pi

All regression coefficients were significant. When compared to the values obtained from the literature (Chapter 2.6.), no significant differences in regression coefficients for the absorption percentage of phosphorus are observed. There is a tendency for the regression coefficient for the absorption percentage of phosphorus in our experiments to be higher, but not for the diets without the addition of phosphorus. In these diets, also with low calcium concentrations (up to 0.65 per cent Ca), the regression coefficient was lower than for all diets as was the case in the literature with diets below 1.0 per cent calcium.
On the basis of the absorption and retention percentages of phosphorus the optimum Ca/P, Ca/Pi and Ca/dig.P ratios within each series of trials was calculated in order to obtain the maximum P retention (see Table 80). With regard to the optimum Ca/P ratio, it is shown that this ratio is higher when inorganic phosphorus is added or when the calcium content in the diet is higher. The Ca/P ratio (mean ± sd) for all our trials is 1.43 ± 0.35 and for the first eight series of trials 1.24 ± 0.10. In the literature, higher optimal Ca/P ratios were obtained (above 2.0) when the calcium concentration in the diet was higher than 0.9 per cent (Whiting and Bezeau, 1958; Berry et al., 1961; Morgan et al., 1969 and Bayley et al., 1975[a]). This is in good agreement with the results of the last series of trials mentioned in Table 80. In feeding experiments, an optimum performance is achieved when the Ca/P ratio in the diet is between 1.2 and 1.3 (literature review Chapter 5.4.). The results of the first eight series of trials agree well with that value. The higher optimum Ca/P ratio on the basis of the absorption and retention percentages of phosphorus when compared with the optimum Ca/P ratio in feeding experiments might be explained by a smaller range of calcium and the lower concentration of phosphorus in the diets for the feeding experiments and the longer period in which it is measured.
The optimum Ca/Pi ratio, which was calculated in the same way as for the Ca/P ratio, was for all 12 series of trials and for the first eight series of trials 3.85 ± 0.69 and 4.24 ± 0.44 respectively (mean ± sd). These values (all series of trials) for the optimum Ca/Pi ratio are higher (about 0.6 unit) than the values calculated from the literature when the data of Frape et al. (1979) are omitted (see Chapter 2.6.).

Finally, the optimum Ca/digestible P ratio was also calculated. This was not only done for the concentration of measured digestible phosphorus but also for an estimated concentration of digestible phosphorus from diets with supplemented inorganic phosphorus. The estimated concentration of digestible phosphorus was calculated as: 0.4 x (P concentration in the diet without supplemented phosphorus or phosphorus from animal origin) + 0.9 x (added phosphorus and phosphorus from animal origin). The value 0.4 means that 40 per cent of the phosphorus is absorbed while it is assumed that 90 per cent of the supplemented phosphorus or phosphorus from animal origin can be absorbed.
The optimum ratio of Ca/digestible P measured (mean $\pm$ sd) for all, and the first eight, series of trials was 3.50 $\pm$ 1.05 and 2.96 $\pm$ 0.54 respectively. The optimum ratio of Ca/digestible P estimated was for all diets 3.02 $\pm$ 0.47. It is surprising, that when calcium is related to the estimated digestible P content no difference is found between the diets, irrespective of the supplementation of inorganic phosphorus. Reliable data in the literature are too scarce to confirm this but from the data of Whiting and Bezeau (1958) this ratio is 3.0 while for the experiments of Kirchgessner et al. (1960[a]) a value of 3.4 can be calculated.
It is well known that phytic acid has a high affinity to bi- and trivalent cations (Wise, 1983). As the diet contains a large amount of calcium, compared with other bi- and tri-valent cations, it is probable that predominantly calcium ions are bound to phytic acid. On theoretical grounds, one mole of phytic acid can bind about three moles of calcium (Cheryan, 1980). Assuming that a practical diet for pigs contains about 0.25 per cent phosphorus present in phytic acid, this means that 0.125 per cent calcium can be bound to phytic acid. Depending on the degree of hydrolysis of phytic acid by phytase, on theoretical grounds a maximal difference of 0.125 per cent available calcium in the diet can be obtained. This may also bias the results of calculations about the optimum Ca/P ratio. When diets are fed containing a high concentration of phytate phosphorus and no hydrolysis of phytic acid occurs then the Ca/P ratio will probably be higher than that of diets with a low concentration of phytate phosphorus or when a high degree of hydrolysis of phytic acid is obtained.

12.4. CONCLUSIONS

It can be concluded from the discussion in section 12.3. that a reasonable estimation of the optimum Ca/P ratio in a diet for maximum phosphorus utilization can be given when the amount of digestible phosphorus offered is close to the minimum phosphorus requirement of the animal and when the calcium level in the diet is below 0.7 per cent. In these cases, the optimum Ca/P ratio is from 1.2 to 1.3:1 and an increase in 0.1 per cent dietary calcium results in a decrease in the phosphorus absorption percentage of about one percentage unit. A Ca/P ratio of 1.2 to 1.3:1 is also found in feeding experiments in the literature.
When the amount of available phosphorus offered exceeds the requirement, a wide range in the optimum Ca/P ratio is found. High calcium levels (0.9 per cent and higher) increase the variation in optimum Ca/P ratio. Such high levels of calcium for growing pigs should, however, be avoided not only for the lower absorption percentage of phosphorus but also because of the reduction in micromineral availability (a.o. zinc; Whiting and Bezeau, 1958 and Kirchgessner et al., 1960[a]) and a higher risk of stones in the kidneys and bladder.
The Ca/Pi ratio, instead of the Ca/P ratio, offers no improvement in estimating the optimum ratio when compared to the Ca/P ratio. The Ca/digestible P ratio varied between 3.0 and 3.5; the lower value for diets without supplementary phosphorus, the higher value for all diets including those with

supplementary phosphorus. The Ca/digestible P ratio might give a better estimation for an optimum relationship when digestible P is defined as truly digestible P; a ratio of 3.0 was calculated for basal diets without supplementary inorganic phosphorus or for such diets plus supplementary phosphorus and phosphorus from animal origin, when for the latter a digestibility of 90 per cent is used. Further research in this field is necessary.

13. ABSORPTION PERCENTAGE OF INTRINSIC PHOSPHORUS IN MIXED FEEDS AND FEEDSTUFFS

13.1. INTRODUCTION

In this chapter, information is given on the absorption percentage of phosphorus in mixed feeds not supplemented with inorganic phosphorus and of separate feedstuffs; and the extent to which the origin of the phosphorus influences its absorption is also studied. Because studies described in the literature indicate some effect of phytase concentration, special attention was paid to phytase concentration of the feedstuffs because of its possible effect on the absorption of phosphorus. This information can be helpful in formulating diets for pigs because the nutritive value of phosphorus is better characterized by absorbable than by total phosphorus. With this knowledge, the supply of phosphorus can be better adapted to the requirements for phosphorus. In the Netherlands, there is a large variation of feedstuffs used in mixed feeds for pigs. Sufficient data on the absorbability of phosphorus from feedstuffs are lacking; information is available for only a few feedstuffs (see Chapter 2.8.3.).
The effect of intrinsic phosphorus from several feedstuffs in mixed feeds on the absorption of phosphorus was investigated in two series of experiments, experiments 1 and 2. In these two experiments, the phytase level was the main variable, but to some extent the calcium concentration was also varied. Calcium and phosphorus retention was measured as well as their retention in the radius.
In experiment 3, in which mixed feeds were used with great differences in feedstuff composition, the absorption and retention of calcium, phosphorus and nitrogen were measured.
The absorption percentage of phosphorus from several feedstuffs and from diets to which no phosphorus was added, will also be given in this chapter. The order in the last section was chosen because quite a lot of information has been derived from the trials with the separate feedstuffs.

13.2. EFFECT OF PHYTASE AND CALCIUM LEVELS OF MIXED FEEDS ON ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM AND ON THE RETENTION OF THESE MINERALS IN THE RADIUS (FIRST EXPERIMENT: TRIALS VV 411 TO VV 422 AND SECOND EXPERIMENT: TRIALS VV 431 TO VV 445)

13.2.1. Material and methods

In the first and second experiment, two basal diets were used, diets 1 and 3 of Table 81. The first basal diet was composed of several feedstuffs in which the phytase content was known to be low (phytase-deficient). This diet did not differ much from a corn-soybean meal diet. The second basal diet was composed of feedstuffs with a high phytase content (phytase-rich). To these basal diets, inorganic calcium or phosphorus was added to obtain diets 2, 4, 5 and 6 (Table 81). In these diets the Ca/P ratio varied from 0.24 to 0.96.
Using the C.V.B. Feeding Table, the following properties of the two types of diets were calculated:

	phytase-deficient diets	phytase-rich diets
NE_f (est.; MJ/kg)	9.20	8.74
DXP (g/kg)	138	150
XF (g/kg)	49	57
lysine (g/kg)	7.8	7.3

The basal diets were produced as one batch for the whole experiment. Per diet, three barrows were used and balances of calcium and phosphorus established at body weights of about 42, 68 and 99 kg. At about 105 kg live weight, the animals were slaughtered and the radius of most of them removed and stored for analysis of ash, calcium, phosphorus and magnesium. The results of the mineral balances were evaluated using analysis of variance and those of the composition of the bones using regression analysis.
Only with diet 1 in the second experiment was a complete digestion trial also performed. The calculated NE_f content of this diet was 9.03 MJ/kg and a DXP concentration of 142 g/kg.

Table 81. Composition of the diets (g/kg)

	phytase-deficient		phytase-rich			
	diet 1	diet 2	diet 3	diet 4	diet 5	diet
Exp. 1 trials VV	411to413	-	414to416	-	417to419	420to4
Exp. 2 trials VV	431to433	437to439	434to436	440to442	443to445	-
maize	390	390	-	-	-	-
milo	150	150	-	-	-	-
tapioca	100	100	-	-	-	-
barley	70	70	420	420	420	420
wheat	-	-	200	200	200	200
wheat middlings	-	-	220	220	220	220
soybean meal	200	200	120	120	120	120
grass meal	90	90	40	40	40	40
minerals + vit.*	10	10	10	10	10	10
$CaCO_3$*	-	-	-	2.5	5.0	10
$Na_2HPO_4.7H_2O$*	-	13	-	-	-	-

* Minerals and vitamins and also calcium and phosphorus were added to the other ingredients.

13.2.2. Results of the first and second experiment

13.2.2.1. Results of the first experiment

One animal, which received diet 3, broke a leg just after termination of the balance trial at 68 kg live weight, and was replaced by another animal that had received the same diet from 25 kg live weight onwards. At slaughter it appeared that the kidneys of one animal on diet 1 had been infected, but no differences were found in results of the balance measurements when compared with those of the other two animals.
Chemical composition of the diets is given in Table 82, while the performance data of the balance animals are given in Table 83. Detailed results of the mineral balances are given in Appendix 27, and those of the chemical analyses of the bones in Table 89. Further discussion on the results is given in section 13.2.3.

Table 82. Chemical analysis of the diets

	phytase-deficient diet 1	diet 2	phytase-rich diet 3	diet 4	diet 5	diet 6
experiment 1						
T (g/kg)	861	-	851	-	850	850
Ca/P ratio	0.57	-	0.29	-	0.60	0.96
Ca (g/kg T)	2.1	-	1.9	-	4.0	6.4
Mg "	1.7	-	2.3	-	2.4	2.3
P "	3.7	-	6.6	-	6.7	6.7
phytate P "	2.5	-	4.8	-	4.8	4.8
experiment 2						
T (g/kg)	866	863	857	858	857	-
Ca/P ratio	0.50	0.30	0.24	0.39	0.59	-
Ca (g/kg T)	1.9	1.6	1.5	2.5	3.7	-
Mg "	1.7	1.7	2.4	2.4	2.4	-
P "	3.8	5.3	6.3	6.4	6.3	-
phytate P "	1.9	1.9	4.2	4.2	4.2	-

Table 83. Performance data of the balance animals in the first experiment

	phytase-deficient diet 1	phytase-rich diet 3	diet 5	diet 6
Ca (g/kg T)	2.1	1.9	4.0	6.4
weight at start (kg)	27	27	23	24
growth rate (g/d)	741	560	611	636
feed conversion ratio	2.78	3.74	3.57	3.44
feed conversion ratio*	2.92	3.72	3.53	3.38
feed intake (kg/d)	2.06	2.09	2.18	2.19
days in experiment	114	130	137	129

* corrected to a common NE_f concentration of the feed of 8.79 MJ/kg

13.2.2.2. Results of the second experiment

During this experiment, one animal on diet 4 got locomotory disturbances and was, therefore, replaced by another animal for the third balance trial. The performance data of the balance animals are given in Table 84.

Table 84. Performance data of the balance animals in the second experiment

	phytase-deficient diet 1	diet 2	phytase-rich diet 3	diet 4	diet 5
Ca (g/kg T)	1.9	1.6	1.5	2.5	3.7
weight at start (kg)	26	32	26	28	29
growth rate (g/d)	699	716	668	708	734
feed conversion ratio	3.01	2.97	3.13	3.03	2.92
feed conversion ratio*	3.16	3.08	3.10	3.00	2.89
feed intake (kg/d)	2.10	2.11	2.09	2.12	2.14
days in experiment	122	111	131	122	117

* corrected to a common NE_f concentration of the feed of 8.79 MJ/kg

Detailed results of the mineral balances are given in Appendix 28 and those of the chemical analyses of the bones in Table 89. Further discussion on these results is given in section 13.2.3.

13.2.3. Discussion on the first and second experiment

13.2.3.1. General remarks

Although the animals had already received the diets for 24 days before the first collection period started in the first experiment (Appendix 27) on diets 1 and 3, a much lower absorption percentage for calcium and phosphorus was found at about 40 kg than at the other live weights. This was also the case in the second experiment (Appendix 28) for diet 2 and for calcium with diet 3 and to some extent with diet 4. With diets 5 and 6 no such differences were found. This might mean that especially for diets with a low calcium or phosphorus concentration, an even longer adaptation period should be taken than 24 days (see also Chapter 7.1.3.1.).
Within a trial, we also calculated whether there was a correlation between the absorption percentage of calcium or phosphorus and growth rate. Over all trials (n=27), the mean correlation coefficient was -0.03 $\pm$ 0.74 and -0.09 $\pm$ 0.62 respectively, and thus very low (see also Chapter 17.3.). This is not so surprising because the growth rate during the balance period cannot be measured accurately and moreover, in most cases, the amount of available calcium or phosphorus offered was below the requirement. This means that the pig tries to absorb as much calcium and phosphorus as possible.
The absorption percentage of calcium in the diets without supplementation of calcium was high ($\pm$ 60 per cent), indicating adaptation by the animal to a low calcium supply. The daily retention of calcium at 40 kg live weight when diets 1, 2 and 3 were given is low, and the very unfavourable Ca/P ratio in the retention for diet 3 at 40 kg is surprising. In all experiments there is a higher Ca/P ratio of the retention at 60 kg than at 40 kg, which must also be seen with respect to adaptation to the diet.
When the absorption percentages of phosphorus for diet 1 (phytase-deficient) in the first and second experiment are compared (Appendices 27 and 28), it can be seen that they are in good agreement with each other except at 40 kg live weight, in which case it is somewhat lower in the first experiment. The average absorption percentage of the phosphorus in diet 1 is about 35 per cent.
As the animals become heavier, more phosphorus is excreted in the urine. Comparison of the results of the mineral balances of diet 1 with those of diet 2 in the second experiment (Appendix 28) shows that the supplementary inorganic phosphorus in diet 2 did not have much effect on calcium utilization. Although more phosphorus was absorbed from diet 2 when compared with diet 1, this did not lead to a higher phosphorus retention. This was probably due to the low calcium concentration in the diet, because the P retention was considerably higher in diets 4 and 5 containing more calcium. The utilization of the added phosphorus in diet 2 will be discussed in Chapter 14.3.
When the results of the mineral balances of diet 3 (phytase-rich) in the two experiments are compared (Appendices 27 and 28), we see a higher absorption percentage for calcium and phosphorus in the second experiment. The reason for this is not clear but might to some extent be explained by the higher concentration of phytate phosphorus in the diets of the first experiment or by maltreating a phytase-rich feedstuff so that the activity of the phytase was reduced. In both experiments with diet 3, there was a slight tendency for the absorption percentage of phosphorus to increase as the animals became heavier. It is uncertain whether the digestibility of

the dry matter also plays a part in this (Appendices 27 and 28).
For diet 5 of the second experiment, the absorption percentages for calcium and phosphorus are also higher than in the first experiment. In both experiments with diet 5, there is a lower retention percentage for phosphorus in animals with a higher live weight, which is also the case with diets 4 and 6.

13.2.3.2. Phytase concentration and the absorption of total phosphorus and of phytate phosphorus

Unfortunately due to the fire at the laboratory all samples were destroyed, so that we could not perform additional analyses in the diets later on with regard to their phytase activity.
The results of the analysis of variance with the phytase-deficient and phytase-rich diets without calcium and phosphorus supplementation in the first and second experiment are summarized in Table 85.

Table 85. Summarized results of the phytase-deficient and phytase-rich diets (df = 8)

	mean			significance	
	phytase-deficient	phytase-rich	sed	phytase	exp.
d_T (%)	84.1	77.3	0.34	***	***
absorption % of Ca	55.2	50.1	2.34	ns	***
absorption % of P	34.8	45.3	0.94	***	***
retention % of Ca	53.5	49.1	2.05	ns	***
retention % of P	28.8	20.6	0.93	***	ns
retention of Ca (g/d)	2.31	1.84	0.10	***	*
retention of P (g/d)	2.00	2.49	0.11	***	ns
growth rate (g/d)	716	588	29	***	ns

When compared with one or both main effects, there was a small significant interaction of phytase x experiment for calcium and also a small significant interaction for the absorption percentage of phosphorus. It is clearly shown that the phytase content has a significant effect ($p < 0.005$) on the absorption percentage of phosphorus. This can also be seen in Figure 19.

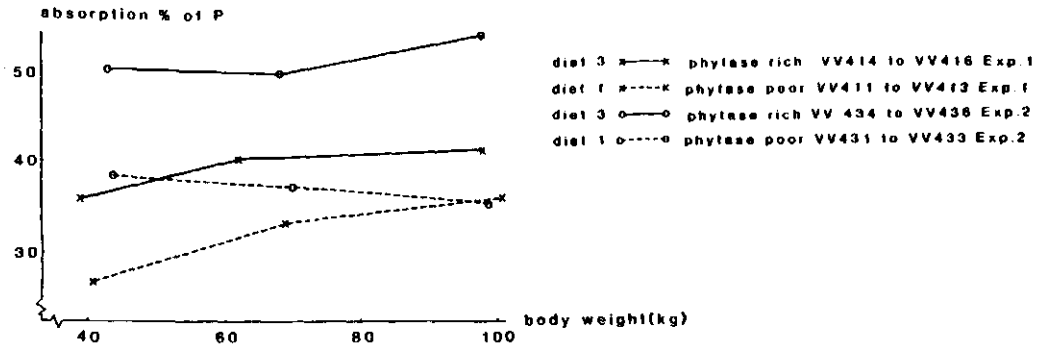

Figure 19 Effect of the phytase content in the diet and body weight on the absorption % of P

The large difference in the absorption percentage of phosphorus in the two diets leads us to the conclusion that there are great differences in the absorption percentage of phosphorus between feedstuffs, in which the concentration of phytase is an important factor.
The absorption percentage of phosphorus in the phytase-deficient diet is in agreement with the results obtained with corn-soybean meal diets in the literature review (Table 5).
Using the results of the mineral balances and the phytate concentration in diets 1 and 3, we tried to estimate the absorption percentage of the phytate phosphorus. In this calculation it was assumed that 100 or 80 per cent of the inorganic phosphorus in these diets is absorbed and in the other calculation an additional excretion of 5 mg endogenous phosphorus per kg live weight in the faeces is assumed. The results of these calculations are given in Table 86.

Table 86. Mean absorption percentage of phytate phosphorus in phytase-deficient and phytase-rich diets without supplemented calcium or inorganic phosphorus

	exp.	abs.% of total P	100% of Pi no endogenous P	absorbed 5 mg endogenous P/kg	80% of Pi no endogenous P	absorbed 5 mg endogenous P/kg
phytase-deficient	1	32	0	7	10	17
	2	37	-23	-14	-4	6
phytase-rich	1	39	17	21	25	28
	2	51	27	31	37	41

From Table 86, we can conclude that in the phytase-deficient diets hardly any phytate phosphorus was absorbed; from the phytase-rich diets on the other hand more than 25 per cent of the phytate phosphorus was absorbed. For feedstuffs such as wheat, wheat bran and wheat middlings, which are phytase-rich, we calculated in Table 5 (Chapter 2.8) that, based on the same asssumptions, at least 25 per cent of the phytate phosphorus was absorbed. This is close to the figure found in our experiments using phytase-rich diets.

13.2.3.3. Effect of calcium concentration in phytase-rich diets on the utilization of phosphorus and calcium

For the two experiments, the effect of the calcium concentration in the diet on the absorption and retention percentage of phosphorus is shown in Figure 20. A summary of the analysis of variance for the two experiments separately is given in Table 87. It can be seen from Table 87 that the absorption percentage of phosphorus was not significantly decreased at a higher calcium level in the diet. The retention percentage of phosphorus as well as the calcium and phosphorus retention per day were, however, significantly higher with more calcium in the diet.
Within each live weight (to avoid the influence of the live weight) the calcium concentration in the diet was regressed on the phosphorus absorption and retention percentages. The results are given in Table 88.

Table 87. Summarized results of the effect of Ca concentration in the diet on Ca and P utilization in experiments 1 and 2 (df=6)

	exp.	Ca concentration diet no Ca added	low	medium	sed	sign. Ca level
d_T (%)	1	75.9	76.3	76.2	0.6	ns
"	2	78.7	79.0	79.3	0.4	ns
absorption % of Ca	1	40.7	44.1	39.3	4.1	ns
"	2	59.6	54.1	55.2	2.1	ns
absorption % of P	1	39.4	37.4	36.4	1.5	ns
"	2	51.3	49.3	47.8	1.2	ns
retention % of Ca	1	39.7	42.9	38.7	4.0	ns
"	2	58.5	53.0	54.6	2.0	ns
retention % of P	1	18.9	24.0	30.6	2.1	***
"	2	22.4	29.0	29.9	1.0	***
retention of Ca	1	1.64	3.53	4.80	0.37	***
(g/d)	2	2.05	2.94	4.23	0.14	***
retention of P	1	2.33	3.04	3.88	0.27	***
(g/d)	2	2.65	3.56	3.62	0.13	***
growth rate (g/d)	1	541	564	619	37	ns
"	2	634	688	761	30	*

Table 88. Relationship between dietary calcium (% in T) to the P utilization

	weight (kg)		se	sign.
Exp. 1	40	absorption % of P = 0.2 Ca % diet + 36.6	3.8	ns
		retention % of P = 29.8 " " + 14.1	2.1	*
"	70	absorption % of P = 5.4 " " + 40.8	5.1	ns
		retention % of P = 28.4 " " + 12.4	5.4	ns
"	100	absorption % of P = -14.6 " " + 44.4	1.8	*
		retention % of P = 19.5 " " + 13.4	0.6	**
Exp. 2	40	absorption % of P = 9.8 " " + 51.7	3.9	ns
		retention % of P = 28.4 " " + 23.3	10.3	ns
"	70	absorption % of P = -22.5 " " + 53.9	0.6	**
		retention % of P = 32.7 " " + 15.1	17.0	ns
"	100	absorption % of P = -15.9 " " + 56.6	0.7	*
		retention % of P = 41.1 " " + 14.0	21.9	ns

Table 88 shows the slightly negative influence of a higher calcium level on the phosphorus absorption percentage but a positive influence on the phosphorus retention percentage in these experiments. Using the equations from phosphorus absorption and retention percentages, we can calculate that the maximum retention of phosphorus is obtained at a Ca/P ratio in the diet of 1.25 in the first experiment and 1.15 in the second experiment. This was discussed in more detail in Chapter 12.

Table 89. Results of the analysis of the radii of balance animals.

Experiment	1					2						
Diet	1	5	6			1	2	3	4	5		
Ca (g/kgT)	2.1	4.0	6.4			1.9	1.6	1.5	2.5	3.7		
P (g/kgT)	3.7	6.7	6.7			3.8	5.3	6.3	6.4	6.3		
n	3	2	3	rsd	sign.	3	3	3	2	3	rsd	sign. diet
fresh weight (g)	51.30a	58.64b	55.74a	3.56	ns	47.12	53.90	54.49	56.39	56.04	4.94	ns
volume (cm^3)	42.40	45.58	41.75	4.11	ns	37.66	43.92	43.82	44.17	44.10	4.28	ns
length (mm)	97.6a	106.1b	100.1a	2.1	*	98.3	98.3	105.0	99.2	96.9	4.3	ns
thickness I (mm)	20.7	20.8	21.3	1.4	ns	20.0a	21.2b	19.9a	21.9bc	22.3bc	0.4	***
thickness II (mm)	14.5	13.8	13.7	0.7	ns	12.1a	14.0b	13.1ab	13.2ab	14.0 b	0.5	*
fat-free dm (g)	19.88a	27.13b	27.85b	2.48	*	21.02a	19.63a	23.32ab	25.72b	25.54b	1.97	*
ash (g/kg ffdm)	623.5	625.6	632.5	6.2	ns	597.4a	586.4a	592.3a	610.3abc	612.6bc	7.2	*
ash (g)	12.40a	16.97b	17.62b	1.58	*	12.56a	11.51a	13.80ab	15.70b	15.63b	1.08	*
Ca (g/kg ash)	393.1a	404.3b	402.3b	3.6	*	386.8	388.8	384.0	384.0	386.7	4.4	ns
Mg (g/kg ash)	7.80	7.40	7.33	0.36	ns	7.50	7.20	8.33	7.95	8.07	0.39	ns
P (g/kg ash)	181.0a	188.1b	186.7b	1.0	**	175.4	174.8	178.2	177.9	175.7	2.3	ns
Ca/P (g/g)	2.17	2.15	2.15	0.02	ns	2.20	2.22	2.15	2.16	2.20	0.05	ns

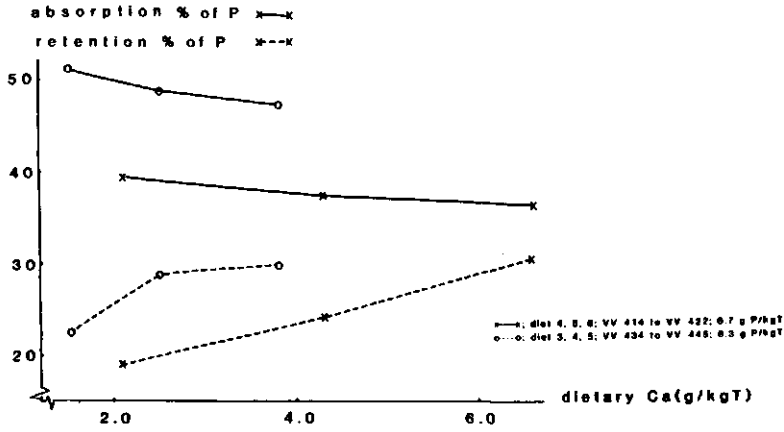

Figure 20 Effect of dietary calcium level on absorption and retention % of phosphorus

13.2.3.4. Mineral retention and mineral contents of the radius

In order to compare the results of the radii with those of the balance experiments, first the retention of calcium and phosphorus according to the balance experiments was estimated. These results are given in Table 89. In this table it can be seen that there is a good relationship between the estimated retention of calcium and phosphorus in the animal based on balance, and the amount of these minerals in the radius. The correlation coefficients for calcium and phosphorus between the two methods in the first experiment were 0.94 and 0.96 respectively, and in the second experiment 0.74 and 0.87 respectively. The correlation with phosphorus is slightly better. One should, however, keep in mind that the standard deviation in the amount of minerals in the radii is rather high, so that we should regard the results found in the radii of the balance animals with caution because of the low number of observations.
For the comparison, we also give the results of the analyses of the radii of group-fed animals, which were also given diets 1 and 3 (see Table 90 and 91). More detailed information on the group-fed animals is given in Chapter 16.2.
Comparison of the results in Tables 90 and 91 gives good agreement concerning diet 1 for both experiments but not for diet 3 in the second experiment. The difference found for diet 3 might be explained by the fact that in the second experiment the balance experiment lasted 15 days longer than the experiment on the group-fed animals.
The Ca/P ratio in the retention increases when the Ca/P ratio in the diet increases. Especially in diets 2, 3 and 4 where the Ca/P ratio in the diet was below 0.4 we found that the Ca/P ratio in the retention was below 1.0. In practical diets with a Ca/P ratio of about 1.5, the Ca/P ratio in the retention is between 1.4 and 1.8 (Chapter 4 and Appendices 6a, 6b and 8).

Table 90. Retention of Ca and P in the experimental period and amount in the radii (g) of the balance animals

Experiment 1 diet	1		5		6		rsd	
	Ca	P	Ca	P	Ca	P	Ca	P
in diet (g/kgT)	2.1	3.7	4.0	6.7	6.4	6.7		
Ca/P ratio diet based on:	1.09		1.15		1.25			
balance	244	224	482	418	608	487	55	39
radius	4.87	2.24	6.86	3.19	7.09	3.29	0.67	0.30

Experiment 2 diet	1		2		3		4		5		rsd	
	Ca	P	Ca	P	Ca	P	Ca	P	Ca	P	Ca	P
in diet (g/kg T)	1.9	3.8	1.6	5.3	1.5	6.3	2.5	6.4	3.7	6.3		
Ca/P ratio diet based on:	1.19		0.97		0.76		0.80		1.16			
balance	280	236	194	200	249	327	328	408	458	394	17	20
radius	4.86	2.20	4.48	2.01	5.30	2.46	6.03	2.79	6.04	2.75	0.41	0.20

Table 91. Amount of Ca and P in the radii of the group-fed animals (g)

Experiment	1				2			
Diet	1	3	control	1	3	7		
Ca (g/kgT)	2.1	1.9	8.0	1.9	1.5	1.5		
P (g/kgT)	3.7	6.6	7.0	3.8	6.3	6.3		
n	12	13	8	8	7	7		
	Ca P	Ca P	Ca P	Ca P	Ca P	Ca P		
	5.09 2.36	4.65 2.19	8.65 3.94	4.70 2.16	4.39 2.05	4.70 2.20		

13.3. EFFECT OF THE TYPE OF DIET ON MINERAL RETENTION (THIRD EXPERIMENT: TRIALS LV 06 TO LV 09)

13.3.1. Introduction

Because there was no information about the effect of by-product based diets on the mineral balance in pigs, such a diet was compared with a cereal based diet. It was considered that less supplemental inorganic phosphorus could be added to a by-product based diet due to the higher concentration of total phosphorus of such diets. Therefore we compared a classical cereal-soybean meal diet with a predominant maize by-products diet, a tapioca-linseed-rice bran diet, and a tapioca-wheat middlings-linseed-citruspulp diet. At the time of this experiment, hardly any information was available about the digestibility of phosphorus in by-products.
This experiment was part of a project in which the effect of type of diet on the digestibility of energy and the utilization of ME in fast growing pigs was studied (Van der Honing et al., 1984).

13.3.2. Material and methods

The animals used were boars of the pure GY-breed. Pairs of litter mates were formed and the treatments allocated according to a latin square design. The feed (for feedstuff composition see Table 92) was offered twice a day and the daily amount of feed was based on the mean live weight of a pair of pigs and was as follows: at 50 kg 18.1 MJ NE_f, at 70 kg 22.0 MJ NE_f and at 90 kg 26.0 MJ NE_f.
Energy and nitrogen balances of all pairs were measured at about 45, 66, 86 and 105 kg live weight, the mineral balances were determined at ± 66 and ± 86 kg live weight. The experimental design was as follows:

	pair 1	pair 2	pair 3	pair 4
± 66 kg	diet B	diet A	diet C	diet D
± 86 kg	diet D	diet C	diet A	diet B

After changing from one diet to the new diet in three days, the new diet was fed for seven days before the next collection period was started. The results of the balances were studied using analysis of variance.

Table 92. Feedstuff composition of the diets (g/kg)

	cereal-based diet A	by-product based diet B	diet C	diet D
wheat	460	-	-	-
barley	274.5	-	-	-
soybean meal solv. extr.	200	190	187.5	187.5
cane molasses	20	19	19	19
soybean oil	20	19	19	19
maize solv. extr.	-	215.8	-	-
maize gluten feed	-	340	-	-
rice bran solv. extr.	-	50	204	-
tapioca (57.5-62.5% starch)	-	142	242.5	289.5
rice bran (<3% hulls)	-	-	170	-
linseed expeller	-	-	127.3	190
wheat middlings	-	-	-	137.1
citrus pulp	-	-	-	140
limestone	9.76	14.70	21.20	8.37
dicalcium phosphate	11.48	5.20	5.20	5.20
premix	1.60	1.60	1.60	1.60
choline chloride (50%)	0.20	0.20	0.20	0.20
salt	2.50	2.50	2.50	2.50

13.3.3. Results

Due to the high level of feeding there were sometimes small feed refusals; the highest was 4.5 per cent of the daily intake. These small feed refusals have probably not influenced the balances measured very much.
The growth rate of all animals during both collection periods was high and on average, between 0.9 and 1.0 kg a day. The chemical composition and the feeding value of the diets is given in Table 93. The detailed results of the mineral and N balances are given in Appendix 29, while a summary is given in Table 94.

Table 93. Chemical analyses and feeding value of the diets

	cereal-based diet A	by-product based diet B	diet C	diet D
T (g/kg)	143	120	119	126
O (g/kg T)	942	910	879	906
XP "	187	213	211	206
XL "	41	39	67	52
XF "	37	69	81	81
XX "	677	590	521	566
NE_f (calc.;MJ/kg T)	10.7	8.8	9.4	9.4
DXP (g/kg T)	160	161	158	152
Ca "	8.5	9.2	13.2	10.0
Mg "	1.6	3.3	5.0	3.4
P "	7.1	8.0	10.7	6.9
phytate P (g/kg T)	3.0	4.8	7.2	4.0

Table 94. Summarized results of the third experiment (df = 11); different characters in the same row indicate significance of differences ($p < 0.05$)

	cereal-based diet A	by-product based diet B	diet C	diet D	sign. diet
absorption % of Ca	52.7 a	38.9 b	26.9 c	42.9 b	***
absorption % of P	50.6 a	28.3 b	19.4 c	34.2 d	***
retention % of Ca	51.4 a	32.4 b	19.5 c	32.1 b	***
retention % of P	41.7 a	28.0 b	19.1 c	33.9 d	***
retention of Ca (g/d)	9.1 a	6.5 b	5.8 b	6.7 b	***
retention of P (g/d)	6.1 a	4.8 b	4.6 b	4.9 b	*
retention of N (g/d)	29.6 a	29.4 a	30.3 a	30.0 a	ns
P in urine (g/d)	1.30 a	0.06 b	0.06 b	0.04 b	***

13.3.4. Discussion

It can be seen from Table 93 that the concentration of calcium and phosphorus in diet C is considerably higher than in the other diets; the concentration of inorganic phosphorus is however ± 1.0 g/kg higher in diet A than in the other diets. The absorption percentage of phosphorus in diet A is much higher, than in the other (by-product) diets. This may be due to the high quantity of wheat with its high phytase activity in the cereal diet and the greater percentage of dicalcium phosphate added to this diet. The significant difference in the absorption percentage of phosphorus between the cereal and by-product diets must lead to the conclusion that, assuming about 90 per cent of added phosphorus is absorbed, the absorption percentage of the plant phosphorus in the by-product diets is much lower than in the cereal diet. Also, the small amount of phosphorus in the urine confirms the low absorption percentage of phosphorus in the by-product based diets.

13.4. THE ABSORPTION PERCENTAGE OF PHOSPHORUS FROM FEEDSTUFFS AND FROM MIXED FEEDS WITHOUT SUPPLEMENTARY PHOSPHORUS

13.4.1. Introduction

At the I.V.V.O. digestibility experiments are performed regularly with feedstuffs and mixed feeds in order to estimate their feeding value. As it became clear from sections 13.2. and 13.3. that, depending on the kind of feedstuffs, the absorption percentage of phosphorus could vary considerably, their absorption percentage was also studied. In this section, these results will be presented first and will be followed by those of mixed feeds.

13.4.2. The absorption percentage of phosphorus from separate feedstuffs

13.4.2.1. Materials and methods

In most of the trials in which the absorption percentage of phosphorus was determined, barley or maize served as a basal feed. We tried to include 50 per cent or more of the feedstuff to be studied in the diet, but the pigs sometimes refused to eat such diets. Essential vitamins and minerals, apart from phosphorus, were added. The Ca/P ratio in the diet was kept at 1.3 to 1 by the addition of limestone, with a minimum Ca concentration of 5.0

Table 95. Survey of the feedstuffs studied, composition of the diet, intake of T and live weight of the pigs

Trial VV	number of animals*	basal diet	feedstuffs	% of feedstuff in total ration (T basis)	intake of T (g)	live weight (kg)
732	4 (1)	-	barley	98	1516	62
777	4 (1)	-	barley	98	1424	53
691	4	starch + sugar + soybean oil	coconut expeller	77	1231	62
779	4 (1)	barley (VV777)	coconut meal solv. extr.	40	1929	76
768	4	maize (VV790)	groundnut expeller	51	1791	82
692	4	starch + sugar	linseed expeller	76	1656	72
731	4	barley (VV732)	linseed meal extracted	39	1498	56
790	3 (1)	-	maize	99	1717	84
689	4	sugar	maize gluten feed (XP ⩽200 A⩽60)	93	1755	66
730	4 (1)	barley (VV732)	maize gluten feed (XP ⩽200 A>60)	49	1318	43
736	4	barley (VV732)	maize gluten feed (see VV730)	83	2238	109
784	4 (1)	barley (VV777)	maize gluten feed (ensiled)	76	1961	74
800	4	barley (VV777)	maize gluten feed (XP > 200 A>60)	49	2179	106
802	4	maize (VV790)	maize gluten feed (XP > 200 A⩽60)	49	1648	68
733	4	barley (VV732)	hominy feed USA	49	1640	72
752	4	barley (VV732)	hominy feed	98	1865	87
776	4 (1)	maize (VV790)	hominy feed solv. extr.	97	1386	44
744	4 (1)	barley (VV732)	maize grain (ensiled)	98	1166	50
788	4	-	corn cob mix (ensiled)	93	1778	100
789	4	-	peas	49	2060	117
690	4	-	rice bran (<3% husks)	82	1437	74
770	4	maize (VV790)	rice bran (<3% husks)	49	1788	112
738	3	barley (VV732)	soybeans full fat	50	1736	114
767	4	maize (VV790)	soybean meal solv. extr.	50	1474	66
734	4	barley (VV732)	sunflower meal solv. extr.	49	2232	91
780	3	barley (VV777)	tapioca meal	75	1860	80
688	4	starch + soybean oil	wheat bran	70	1492	56
778	4	barley (VV777)	wheat middlings	65	1862	63

* number of missing values in parentheses.

g/kg. We tried to give a feed to the animals equal in quantity to 80 per cent of the amount of NE_f according to the C.V.B. feeding standard. About 2.5 l water was supplied to 1 kg diet just before feeding time. The diet was offered twice a day.
Per trial, usually four animals were used in the live weight range of 45 to 115 kg. The procedure for sampling, weighing, etc. was the same as for the balance experiments.
The absorption percentage of phosphorus in the feedstuff to be tested was calculated by assuming that the absorption percentage of phosphorus in the basal diet (barley or maize) was constant.

13.4.2.2. Feedstuffs

The composition of the diets in which the feedstuffs were tested, together with the number of animals, intake of dry matter and mean live weight, are given in Table 95. All diets contained 1 to 2 per cent minerals and vitamins. Ten of the feedstuffs tested were maize or maize by-products (maize gluten feed or hominy feed), eight feedstuffs originated from oil-containing seeds (coconut, groundnut, linseed, soybean and sunflower) and furthermore one or two batches of barley, rice bran, tapioca, wheat by-products and ensiled maize were tested.

13.4.2.3. Results

In a few experiments, the results from one animal deviated considerably from those of the others and were therefore deleted. This is indicated in Table 95 in the column "number of animals". In some cases, the ratio in the basal diet and tested feedstuff had to be raised or the amount of ration offered reduced, mainly due to the taste of the ration.
The chemical composition of the rations, the feedstuffs tested and the absorption percentages are given in Table 96. In trial VV 690, the concentration of calcium in rice bran was extremely high, an observation often found in practice. This indicates that a considerable amount of limestone had been added to the rice bran.

13.4.2.4. Discussion

The absorption percentage of phosphorus from feedstuffs
In the literature review (see Chapter 2.8.3., Table 5 and Appendix 4), most values on absorbability of feedstuffs are based on availability studies. It has already been pointed out in the literature review (Chapter 5.2.), that availability is approximately 2 or 3 percentage-units higher than absorption percentage.
The results in Table 96 show that the absorption percentages of phosphorus vary widely depending on the feedstuff. The absorption percentage of phosphorus in the dry maize products (n=10) is rather low and varies from 14 to 24 per cent with an average of 16.9 $\pm$ 3.0. A low absorption percentage of phosphorus in maize was also found in the availability studies done by Miracle et al. (1977), Stober et al. (1979), Huang and Allee (1981) and Ross et al. (1983). When maize is ensiled as moist grain or as corn cob mix, the absorption percentage of phosphorus in our studies is considerably higher and, on average, is 40 per cent. In the literature, the mean availability of ensiled moist maize amounted to 47 per cent, and in the experiment described by Trotter and Allee (1979[a]) on sorghum the availability increased from 19 to 42 per cent. The absorption percentage of phosphorus in soybean (meal) is rather high in our experiments, on average 42 per cent. This is much higher than the average availability of phosphorus of 26 per cent found in the literature. The values found for barley are somewhat

Table 96. Chemical composition of the ration and feedstuff tested and absorption % of P and of phytate P

trial	in ration (g/kgT)			in feedstuff (g/kgT)			absorption % of P			absorption % of phytate P in the feedstuff			feedstuff
VV	Ca	P	phyt. P	Ca	P	phyt. P	total ration	feed-stuff	feedstuff corrected*	assumed absorption% of Pi 100	80	80 + 5 mg*	
732	6.4	4.4	2.8	1.4	4.5	2.9	36.4	36.4	41.1	1	12	19	barley
777	5.4	4.2	2.5	1.1	4.3	2.4	43.3	43.3	47.8	-2	14	22	barley
691	7.1	4.5	2.2	1.9	6.0	3.0	24.6	24.6	30.1	-51	-31	-22	coconut expeller
779	6.1	5.0	2.5	1.3	6.1	2.8	28.2	12.4	15.8	-91	-67	-60	coconut meal solv.extr
768	6.1	5.1	3.2	2.2	6.8	4.3	21.5	24.8	28.0	-19	-7	-2	groundnut expeller
692	7.7	5.7	4.0	3.6	7.7	5.4	18.4	18.4	22.2	-16	-8	-4	linseed expeller
731	8.7	6.4	4.3	4.1	9.5	6.5	17.9	6.0	7.9	-39	-30	-27	linseed meal solv.extr
790	3.6	3.2	2.1	0.4	3.2	2.1	14.3	14.3	21.9	-31	-20	-8	maize
689	8.8	7.2	4.4	0.5	7.7	6.1	19.4	19.4	22.0	-2	4	6	maize gluten feed
730	8.7	6.6	3.6	1.9	8.7	4.2	22.8	15.7	16.6	-75	-53	-49	maize gluten feed
736	12.3	7.8	3.9	1.9	8.7	4.2	15.3	14.4	17.4	-78	-57	-51	maize gluten feed
784	9.2	6.4	4.1	0.6	7.2	4.7	22.3	18.7	22.3	-24	-14	-10	maize gluten feed
800	12.3	7.9	4.8	9.1	11.8	7.3	20.9	14.8	15.4	-38	-25	-22	maize gluten feed
802	7.5	6.9	4.3	0.6	10.6	6.5	21.9	24.0	25.8	-24	-11	-8	maize gluten feed
733	9.8	6.8	5.0	1.3	9.3	7.2	22.4	16.0	18.4	-9	-3	0	hominy feed USA
752	9.1	8.3	5.5	4.8	8.4	5.7	17.0	17.0	19.8	-22	-13	-9	hominy feed
776	11.9	7.5	5.6	0.1	7.8	5.8	14.8	14.8	17.0	-15	-8	-5	hominy feed solv.extr.
744	4.4	3.4	1.5	0.1	3.5	1.5	35.3	35.3	41.6	-51	-24	-10	maize grain (ensiled)
788	4.5	3.8	1.1	0.1	3.7	0.9	45.0	45.4	53.5	-123	-61	-29	corn cob mix (ensiled)
789	7.2	5.1	2.6	4.0	6.0	2.8	42.6	42.0	48.4	-24	-1	9	peas
690	43.0	16.2	11.6	43.6	18.8	13.5	11.2	11.2	12.8	-24	-16	-14	rice bran (3% husks)
770	10.7	8.1	5.6	5.7	13.0	9.2	10.0	9.0	12.4	-29	-20	-17	rice bran (<3% husks)
734	9.6	6.6	4.5	3.8	9.0	6.3	22.4	15.5	17.7	-21	-12	-9	sunflower meal solv.
738	6.5	5.3	3.2	2.1	6.3	3.7	42.1	46.0	53.2	8	22	31	soybeans full fat
767	5.3	4.9	2.9	4.5	6.6	3.7	30.2	38.0	41.1	-11	5	11	soybean meal solv.extr
780	2.8	2.3	1.1	3.2	1.7	0.6	32.4	23.8	36.7	-116	-79	-55	tapioca meal
688	14.9	11.1	8.4	1.2	15.6	11.9	23.5	23.5	25.2	0	6	8	wheat bran
778	12.6	9.0	6.4	1.5	11.9	8.7	22.1	18.4	19.8	-12	-4	-2	wheat middlings

* additionally 5 mg endogenous P per kg live weight

higher than the values found in the literature. In contrast to the values in the literature, the values for the wheat by-products in trials VV 688 and VV 778 are considerably lower. The values found for the by-products of the oil- containing seeds are rather low and variable.
In most of the digestibility trials, barley or maize were used as a basal diet. As barley has a moderate concentration of phytase and maize has none, it remains questionable whether the type of basal diet has a significant effect on the absorption percentage of phosphorus of the feedstuff tested. In the trials reported here no direct comparison was done on the effect of the basal diet; this has recently been performed in other trials. Though no direct comparison was made, the values for maize gluten feed do not indicate that the absorption percentages of phosphorus are higher with barley than with maize or without a basal diet (16, 14 and 15 versus 19 and 24 in the trials 730, 736, 800, 689 and 802 respectively). The same can be said for coconut meal (12 per cent in trial VV 779 with barley as a basal diet and 25 per cent without a basal diet in trial VV 691) and for linseed meal (6 per cent in trial VV 731 with barley as a basal diet and 18 per cent in trial VV 692 with a basal diet containing no phosphorus).
Because the influence of the excretion of endogenous phosphorus in the faeces is considerable in diets low in phosphorus (e.g. in our basal diets barley and maize), we also calculated the true absorption percentage of phosphorus in the feedstuffs when corrected for 5 mg faecal endogenous phosphorus per kg live weight (see literature review Chapter 2.8.2.). The results of this calculation are given in column 10 of Table 96. The estimated mean true absorption percentage of phosphorus in the maize products is 19.7 $\pm$ 3.3. As expected, the true absorption percentages of phosphorus so obtained were higher than the apparent absorption percentages, especially in feedstuffs with a low phosphorus concentration. Those feedstuffs are punished when the apparent absorption percentage of phosphorus is given. However, when the phosphorus requirement of pigs are based on apparent digestible phosphorus also the concentration of the feed has to be expressed so.

The absorption percentage of phytate phosphorus.
To gain more insight into the differences in absorption percentages of phosphorus between the feedstuffs, we calculated the absorption percentage of phytate phosphorus. This was done with various assumptions:

a) 100 per cent of the inorganic P is absorbed;
b) 80 per cent of the inorganic P is absorbed;
c) as b) but, in addition, a faecal excretion of endogenous P of 5 mg P/kg live weight.

The results of the above mentioned calculations are given in Table 96, which indicate that it is unlikely for any of the phytate phosphorus to be absorbed from maize products, or from most of the by-products of oil-containing seeds. This is because there is little or no phytase in these products. As barley has a moderate amount of phytase, 10 to 20 per cent of the phytate phosphorus can be absorbed. In contrast to the powerful phytase(s) in wheat, hardly any phytate phosphorus is absorbed from wheat by-products. The reason for this is not clear but could possibly be caused by the destruction of phytase during processing. In soybeans, about 20 per cent of the phytate phosphorus can be absorbed.

Table 97. Mixed feeds not supplemented with inorganic P: composition, absorption% of phosphorus and of phytate phosphorus

trials VV	in diet (g/kg T) Ca	P	phytate P	apparent absorption% of phosphorus determined	calculated from the feedstuffs (Table 99)	abs.% of WB[a] 20[b]	40[b]	presence[c] in feed wheat	WB	barley	absorption% of phytate P assumed abs. % of Pi 100	80	80+5mg[d]	Details in Chapter
328,329, 330,342	6.4	4.3	3.1	39	35	35	35	-	-	+	15	23	30	7
367-369, 373-375	4.1,6.0	4.0	2.7	40	34	34	34	-	-	+	12	20	28	12
411-413	2.1	3.7	2.5	32	34	34	34	-	-	+	0	10	17	13
414-420	1.9-6.4	6.6	4.8	38	29	32	42	+	+	+	15	22	26	13
431-433	1.9	3.8	1.9	37	36	36	36	-	-	+	-23	-4	6	13
434-436, 440-445	1.6-3.7	6.3	4.2	49	30	34	43	+	+	+	25	34	39	13
487-489, 493-495	6.1	4.8	3.1	39	33	38	42	+	+	+	4	16	21	15
534-536	5.0	3.9	2.7	40	32	36	38	+	+	+	14	23	29	14
588	5.2	4.3	2.7	40	31	33	38	+	+	+	4	16	24	13
614	6.9	4.9	3.1	36	29	29	35	-	+	-	0	11	19	13
680	7.2	5.7	3.8	27	27	27	34	-	+	-	-9	1	6	13
735	10.2	6.9	4.6	23	23	23	23	-	-	+	-16	-6	-1	13
740-743	7.2	6.0	4.3	33	23	23	29	-	+	-	4	13	18	16
749	7.8	5.6	3.7	30	26	26	32	-	+	-	-6	4	12	13
769	8.6	7.3	4.6	31	19	19	26	-	+	-	-5	5	11	13

a: WB = wheat by-products
b: assumed absorption percentage of only wheat = 48
c: + = present - = not present
d: = additionally 5 mg faecal endogenous excretion of P per kg live weight

13.4.3. The absorption percentage of phosphorus from mixed feeds without supplementary phosphorus

The absorption percentage of phosphorus was determined in 15 mixed feeds containing four or more feedstuffs and no supplementary inorganic phosphorus. For more details see Table 97. The composition of the mixed diets not mentioned elsewhere, can be found in Table 98. Some additional calculations were performed on these diets, the main aim being to see if it was possible to estimate the absorption percentage of phosphorus of feedstuffs according to their origin by means of regression analysis.

Table 98. Composition of mixed feeds not mentioned elsewhere (g/kg)

	Trial					
	VV588	VV614	VV680	VV735	VV749	VV769
maize	363	-	-	-	-	197
barley	50	-	-	490	-	-
wheat	70	-	-	-	-	-
wheat middlings	80	140	-	-	140	197
wheat bran	-	-	140	-	-	-
rice bran	-	-	-	-	35	197
hominy chop	-	100	100	123	100	-
maize gluten feed	-	55	55	123	50	-
tapioca	120	260	263	-	225	-
citrus pulp	-	120	120	-	50	197
grass meal	60	-	-	-	-	-
cane molasses	20	40	40	-	50	-
soybean meal solv. extr.	220	240	250	-	235	-
animal fat	-	20	20	-	35	-
sunflower meal solv. extr.	-	-	-	123	-	-
linseed meal solv. extr.	-	-	-	123	-	-
coconut expeller	-	-	-	-	50	-
potato protein dried	-	-	-	-	15	-
groundnut expeller	-	-	-	-	-	197
minerals + vitamins	17	18	12	20	15	12

13.4.3.1. Calculations and results

First, for each of the diets, the amount of phosphorus originating from the separate feedstuffs was calculated. This was based on the concentration of phosphorus and the amount of feedstuff in the diet. The concentration of phosphorus was, in most cases, obtained by analysis of the feedstuffs concerned but in some cases it was estimated. So, in three experiments (trials VV 328 and others, trials VV 487 and others, trials VV 534 and others) soybean meal and wheat middlings were not analysed for phosphorus.
After these calculations, some feedstuffs were grouped according to their origin. These groups are given in Table 99. The feedstuffs in the last group of this table are taken together. This was done because the phosphorus in these feedstuffs is almost entirely inorganic and it can be assumed that the absorption percentages of the phosphorus in these are high.
It was assumed that the absorption percentage of phosphorus of the feedstuffs within a group is the same. This assumption can, for example, be supported by the results in the digestion trials on maize products (see Table 96). The assumed absorption percentage of phosphorus for each product group is given in Table 99.

The absorption percentage of phosphorus in each feed was calculated, based on the amount of phosphorus from the feedstuff and its absorption percentage. The results of these calculations are given in Table 97. The difference between determined and calculated absorption percentage of phosphorus was 6.2 ± 5.5 units and is rather high. It can be seen from Table 97 that in some experiments there was a good agreement in the determined and calculated absorption percentage of phosphorus. In other experiments this was not the case. This appeared to be true of feeds containing wheat products.

Table 99. Groups of feedstuffs and assumed absorption percentage of P

Group	feedstuffs in the group	abs. perc. of P (apparent)
maize	maize, hominy feed, maize gluten feed	17
barley	barley	40
wheat	wheat, wheat middlings, wheat bran	20
oats	oats bran	20
rice	rice bran	10
tapioca	tapioca meal	24
soybean	soybeans, soybean meal solv. extr.	42
coconut	coconut expeller, coconut meal solv. extr.	18
linseed	linseed expeller, linseed meal solv. extr.	12
groundnut	groundnut expeller	25
sunflower	sunflower meal solv. extr.	16
citrus	citrus pulp	20
remainder	potato protein dried, grass meal, cane molasses	80

As already mentioned in section 13.4.2.4. the absorption percentage of phosphorus for wheat by-products in our experiments was low compared with values in the literature. In recent experiments (not published) we have found that the absorption percentage of phosphorus in wheat is as high as that found in the literature and that there might be an interaction between wheat and other feedstuffs with regard to the absorption percentage of phosphorus due to its phytase content. Therefore, diets containing wheat products were divided into wheat and wheat by-products. In 5 series of trials (see Table 97) this was the case (trials VV 414 to VV 422, trials VV 434 to VV 436 + VV 440 to VV 445, trials VV 487 to VV 489 + VV 493 to VV 495 and trials VV 534 to VV 536). In these series, the amount of wheat in the diet was 200, 200, 200, 150 and 70 g/kg respectively.
When an absorption percentage of 48 and 20 for wheat and wheat by-products, respectively, was assumed we can see that the estimations of the absorption percentage of phosphorus in the mixed feeds were still too low (see Table 97). When for wheat and wheat by-products absorption percentages of phosphorus of 48 and 40 per cent are taken, respectively, the mean deviation is 1 ± 4 per cent but still, for some trials there are, rather large differences also when considering only wheat by-products (trials VV 680 and VV 769). This might partly be explained by the presence of either little or no powerful phytase in the wheat by-products, which may be destroyed to a large extent during processing.
When the results of diets with barley are considered, it appears that for these trials in which barley but no wheat or wheat by-products were fed, little or no positive difference between the determined and calculated absorption percentage could be detected. The feedstuffs in trial VV 735 had also been in a separate digestion trial. It can be seen from Table 97 that the determined and calculated absorption percentage of phosphorus was the same.

13.4.3.2. Regression analyses

Another approach for estimating the absorption percentage of phosphorus of feedstuffs is regression analysis. Because oats, rice, coconut, groundnut, sunflower, citrus and linseed were only taken up in a few trials, regression analysis was not possible for these products. Therefore, the amount of absorbable phosphorus was calculated based on the assumption in Table 99. The absorption percentage of phosphorus for citrus and oats is assumed to be 20 per cent, but the level of it is not so important for our calculations due to their small contribution of phosphorus in the total amount of phosphorus in the diet (less than 2 and 5 per cent respectively). The groundnut expeller in trial VV 769, the extracted sunflower meal in trial VV 735 and the extracted linseed meal in trial VV 735 had also been in separate digestion trials (VV 768, VV 734 and VV 731 respectively).
The amount of digestible phosphorus from oats, rice bran, coconut, groundnut, sunflower, citrus and linseed were subtracted from the amount of total digestible phosphorus in the feeds, which gave the corrected digestible phosphorus (dig. P-corr). Regression analyses were then performed on maize, barley, wheat, soybean, tapioca and the remainder as independent variables and the corrected digestible phosphorus as a dependent variable. The model used can be derived from Table 100.
Calculations showed a high but negative correlation between maize and wheat (r= -0.80), barley and soybean meal (r= -0.68), barley and tapioca (r= -0.78) and a positive one for tapioca and soybean meal (r= 0.70). It should also be remarked that these calculations are only justified if there is no interaction between the independent variables, which is doubtful for wheat (see section 13.4.3.1.). The result of the regression analysis without a constant is given in Table 100. Because the estimate for tapioca was very negative and therefore not reliable, the high correlation between tapioca and barley and soybean meal respectively, and because the amount of the phosphorus from tapioca in the total diet was small (less than 5 per cent) the same calculations were performed without tapioca, while an absorption percentage of the phosphorus in tapioca of 24 was assumed. The results of these calculations are also given in Table 100.

Table 100. Estimated regression coefficients (apparent absorption percentage of P) for the groups tested

group of feedstuffs	tapioca included		tapioca excluded	
	estimate	se	estimate	se
maize	28	16	16	13
barley	25	18	42	12
wheat	49	8	43	7
soybean meal	54	19	40	16
remainder	78	68	116	63
tapioca	-195	152	-	-
R^2	0.72		0.70	

It can be seen from Table 100, as expected, that the absorption percentage of phosphorus for the wheat products together is considerably higher than 20 per cent. The standard error of the estimates for the different product groups is rather high. The values, when tapioca is excluded are, however, quite close to the assumed ones given in Table 99.
Regression analysis with the sum of remainder and tapioca together, instead of remainder and tapioca apart, gave a R^2 of 0.62, which is lower than in

Table 100, while the standard error of the estimates again increased.
Estimations of the absorption percentages when wheat by-products were taken separately as independent variables, gave no further improvement of the estimates as presented in Table 100.
As the results of the regression analysis based on the true absorption percentage of phosphorus did not show a more accurate estimate than when based on the apparent absorption percentage of phosphorus, these results are not given in a table.

13.4.3.3. The absorption percentage of phytate phosphorus from mixed feeds

The same calculations which were applied to the feedstuffs separately to estimate the absorption percentage of phytate phosphorus were also done on the mixed feeds without supplementary inorganic phosphorus. The assumptions were the same. The results of the estimated absorption percentage of phytate phosphorus are given in Table 97. It can be seen that the absorption percentage can vary from zero to 40 per cent when an 80 per cent absorption of inorganic phosphorus and an excretion of 5 mg endogenous phosphorus per kg live weight are assumed.
In trials VV 411 to VV 413 and VV 431 to VV 433 we had diets with feedstuffs containing less phytases and this resulted in a low absorption percentage of phytate phosphorus. Trials VV 414 to VV 420 and VV 434 to VV 436 plus VV 440 to VV 445 had feedstuffs with powerful phytases which resulted in a high absorption percentage of phytate phosphorus (see also section 13.2.3.2.).
In most of the other mixed feeds, several of the feedstuffs included had powerful phytases but it is difficult to explain the absorption percentage of phytate phosphorus calculated. In addition, no information about the phytase concentration of some feedstuffs can be found in the literature. This implies that more research is necessary in this field.

13.5. CONCLUSIONS

In this chapter we have seen, that depending on the feedstuff, there are great differences in the absorption percentage of phosphorus. This, amongst other things, is caused by the phytate phosphorus concentration and the presence of (powerful) phytases. For quite a lot of feedstuffs in our experiments, no information is available with regard to the presence of phytases. In our experiments we calculated that the absorption percentage of phytate phosphorus in mixed feeds varied from negative to about 40 per cent.
More research is necessary to find out if the absorption percentage of phosphorus in feedstuffs from the same product group (e.g. maize) can be assumed to be equal. Furthermore, it is not certain whether even within the same product the absorption percentage of phosphorus is always the same, because values in the literature, for some feedstuffs, show considerable differences compared with our results. This might also be due to the methods used. So far, information is poor.

It must made clear whether the type of basal diet is significant for the determination of the digestibility of phosphorus from feedstuffs, due to the presence of (powerful) phytases. More attention should be paid to the interaction between wheat or wheat by-products and other feedstuffs in a mixed feed.
From our calculations we have shown that by using regression, the absorption percentage of phosphorus for different product groups can be reasonably estimated. However, these calculations are only justified if the assumptions made are correct. Because of the small number of observations

for these calculations and because of the dependency of some of the product groups with each other and the small variation in product groups, more observations are necessary.

14. THE ABSORPTION AND RETENTION OF PHOSPHORUS OF SOME INORGANIC PHOSPHORUS SOURCES

14.1. INTRODUCTION

In this chapter, the results will be presented on the value to pigs of phosphorus sources. Because the method used in the first experiment did not give satisfactory results, in subsequent work the main attention was paid to find the most suitable method for establishing the value of phosphorus sources to pigs.
In the first experiment various phosphorus sources were added to a basal diet and differences in their phosphorus values derived from the absorption and retention of phosphorus. The results of other trials from which the absorption and retention of the added inorganic phosphorus could be calculated are also given. In the second experiment, performed with young pigs, different criteria were taken and evaluated. Details of this experiment have been described by Mulder and Jongbloed (1985). The literature on phosphorus sources for pigs has been reviewed in Chapter 2.8.4.

14.2. THE ABSORPTION AND RETENTION OF ADDED PHOSPHORUS IN TRIALS VV 534 TO VV 548

14.2.1. Materials and methods

In this experiment, the absorption and retention of phosphorus in four inorganic phosphorus sources was measured. A basal diet was used to which 0.16 per cent phosphorus from either phosphorus source was added (Table 101). $CaCO_3$ was added to the diets to obtain a Ca/P ratio of 1.25:1. This basal diet was chosen because its feedstuff composition and phosphorus concentration was close to those used in practice. The five diets were fed from a live weight of 28 kg until slaughter.

Table 101. Composition of basal and supplemented diets (g/kg)

diet	basal	dicalcium phosphate	Hostaphos	Curaphos	Super-phosphate
trials VV	534-536	537-539	540-542	543-545	546-548
maize	330	330	330	330	330
wheat	150	150	150	150	150
soybean meal solv. extr.	200	200	200	200	200
barley	100	100	100	100	100
wheat middlings	20	20	20	20	20
tapioca	150	150	150	150	150
grass meal	50	50	50	50	50
mixture of minerals and vitamins*	30	30	30	30	30
including $CaCO_3$	6.24	5.59	9.19	0.79	0.38
P source	-	8.47	9.29	12.07	18.67

* made up to 30 g/kg with maize

Four barrows were used for the basal diet and three barrows for each of the other diets. At about 40, 70 and 100 kg live weight the mineral balances were measured. At a live weight of 103 kg the animals were slaughtered.
Complete proximate analysis and bomb calorimetry of the basal diet were done during the balance trial at 70 kg and the feeding value calculated from the results.
The results were subjected to an analysis of variance. The results obtained with animals which had received Superphosphate had a very substantial residual standard error, being the reason why the final analysis was performed without using the Superphosphate data.

14.2.2. Results

This experiment ran smoothly except for the group given Superphosphate as a phosphorus source. From about 75 kg live weight onwards, these animals refused to eat the same quantities of feed as the other groups. Their feed intake above 75 kg was about 85 per cent rather than 95 per cent of the C.V.B. scheme. Also, their growth rate during the balance trial at 90 kg was very low. At slaughter, the bones of one animal of the Superphosphate group were paler than those of the other animals. The differences observed in the Superphosphate group might be caused by the fluorine content of this phosphorus source, what might also explain the low digestibility of dry matter. The performance of the animals is given in Table 102.
Proximate analysis and feeding value of the basal diet were as follows (g/kg T):

O = 948, XP = 180, XL = 22, XF = 61, DXP = 146, NE_f (MJ/kg T) = 10.44

Table 102. Performance of the animals used for the balance trials

diet	basal	dicalcium phosphate	Hostaphos	Curaphos	Super-phosphate
initial weight (kg)	27	29	28	30	28
growth rate (g/d)	708	693	710	701	529
feed conversion ratio	3.02	3.12	3.06	3.12	3.96
feed intake (kg/d)	2.13	2.16	2.17	2.18	2.07
days in experiment	108	107	107	103	113

Some chemical analyses of the diets are given in Table 103, in which the calcium and phosphorus concentrations of the phosphorus sources are also given.

Table 103. Chemical composition of diets and phosphorus sources used

	basal	dicalcium phosphate	Hostaphos	Curaphos	Super-phosphate
T (g/kg)	859	859	861	870	862
Ca (g/kg T)	5.0	7.1	7.1	7.6	7.2
Mg "	1.8	1.8	2.2	1.8	1.8
P "	3.9	5.5	5.6	5.6	5.6
phytate P (g/kg T)	2.7	2.7	2.7	2.7	2.7
composition of P source:					
Ca (g/kg)	-	258	94	327	221
P (g/kg)	-	192	178	134	89

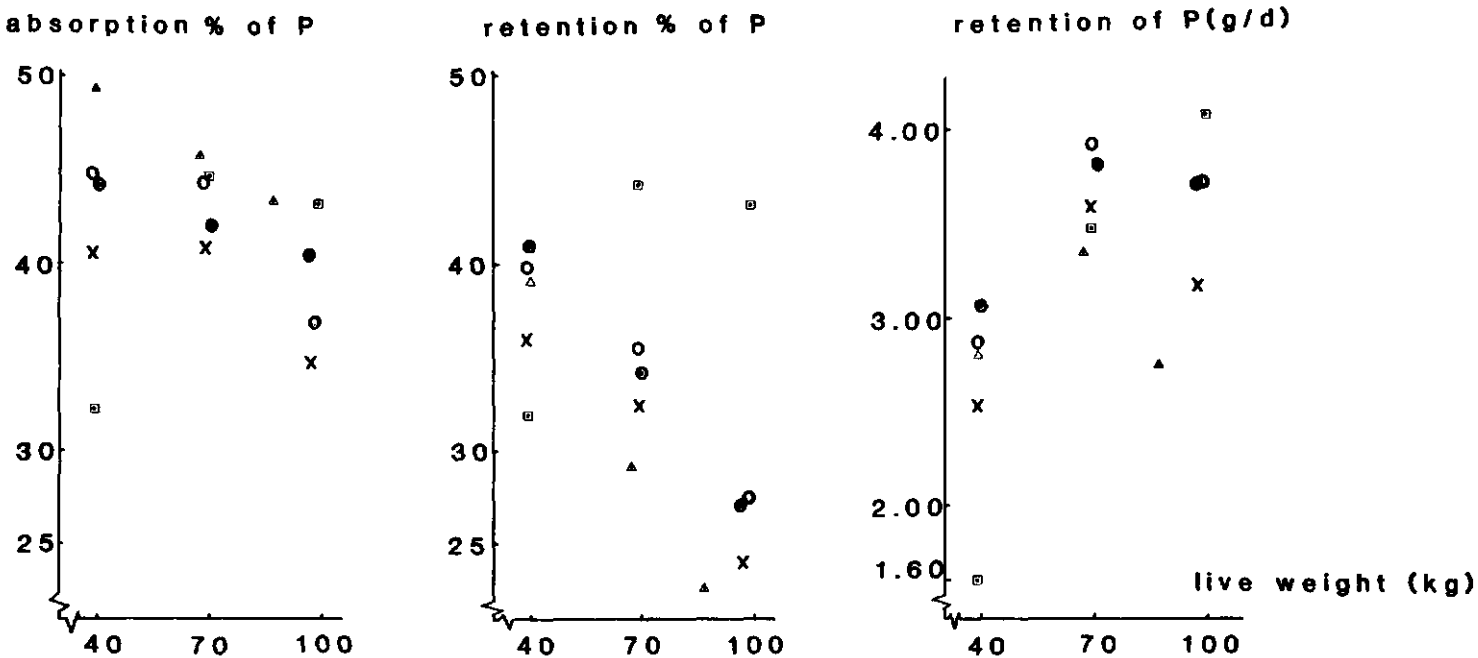

Figure 21 Influence of the diets on absorption and retention of total P (trials VV 534 to VV548)

▫ = basal diet ○ = Hostaphos △ = Superphosphate
× = Dicalcium phosphate ● = Curaphos

The detailed results of the mineral balances are given in Appendix 30 and shown in Figure 21. A summary of the results is given in Table 104.

Table 104. Summarized results of the balance trials on P sources (df = 9)**

	basal	dicalcium phosphate	Hostaphos	Curaphos	Super-phosphate	sed
d_T (%)	84.7a	83.6b	83.9ab	84.3ab	82.9	0.4
absorption % of Ca	57.3a	39.8b	41.6b	41.4b	39.4	2.5
absorption % of P	40.2ab	38.7a	42.0b	42.4b	46.1	1.3
retention % of Ca	43.9b	39.0a	40.9ab	40.1ab	37.6	1.9
retention % of P	39.8a	30.8b	34.2b	34.0b	30.3	1.5
retention of Ca*	4.6a	5.3b	5.6bc	6.0c	5.0	0.21
retention of P*	3.1a	3.1a	3.5b	3.5b	3.0	0.13
P in urine (g/d)	0.1a	0.9b	0.9b	1.0b	1.7	0.16

* (g/d)
**data on Superphosphate not used for analysis of variance; a different letter in the same row means significantly different ($p < 0.05$).

14.2.3. Discussion

When the live weight increased from 40 to 70 kg an enhancement in the absorption percentage of calcium and phosphorus was only found for the basal diet, and not for the other diets. This might partly be explained by the increase in digestibility of the dry matter on the basal diet at 70 kg. For the basal diet, the correlation coefficient between digestibility of T and absorption percentage of phosphorus was 0.94, but for the supplemented diets this correlation coefficient was lower and on average 0.63. This lower correlation can probably be explained by the fact that in the supplemented diets the amount of available phosphorus was above the requirement and hence the absorption in these diets can be regulated by a feedback mechanism.
The lower retention of calcium and phosphorus of the Superphosphate diet at 90 kg is probably caused by the very low growth rate of the animals during that period. In general only a small decrease in the absorption percentage of phosphorus, with advancing body weight, is found in the supplemented diets (see Figure 21). This means that excretion of phosphorus in the urine increased strongly (Table 105).

Table 105. Intake of P and excretion of P in the urine for the different P sources (g/d)

live weight	intake of P	excretion of P in the urine on supplemented diets			
		dicalcium phosphate	Hostaphos	Curaphos	Super-phosphate
40 kg	7	0.32	0.35	0.29	0.74
70 kg	11	0.92	1.00	0.92	1.93
100 kg	13	1.43	1.43	1.83	2.42

Table 106. Absorption and retention% of added P in trials with pigs on metabolism crates

phosphorus source		$NaH_2PO_4.2H_2O$			$Na_2HPO_4.7H_2O$			dicalcium phosphate				dicalcium phosphate	Hostaphos	Curaphos	Superphosphate
basal diet	trial VV	367	368	369	431	432	433	487-489	487-489	487-489	493-495	534-536	534-536	534-536	534-536
supplemented diet	trial VV	370	371	372	437	438	439	478-480	481-483	484-486	490-492	537-539	540-542	543-545	546-548
in basal diet (g/kg T)	Ca	6.3	5.8	6.0	1.9	1.9	1.9	6.0	6.0	6.0	6.2	5.0	5.0	5.0	5.0
"	P	4.0	4.1	4.0	3.8	3.8	3.8	4.8	4.8	4.8	4.8	3.9	3.9	3.9	3.9
in supplemented diet (g/kg T)	Ca	6.3	6.2	5.5	1.6	1.6	1.6	7.5	7.6	7.9	7.8	7.1	7.1	7.6	7.2
"	P	5.9	5.7	5.3	5.0	5.3	5.6	6.0	6.2	6.4	6.4	5.5	5.6	5.6	5.6
absorption% of added P at ± 40 kg		70	-	-	62(86)*	-	-	30	41	39	36	60	73	73	87
± 70 "		-	57	-	-	84(98)	-	50	49	37	33	32	44	36	48
± 100 "		-	-	64	-	-	108(90)	50	22	15	26	11	22	34	42
retention% of added P at ± 40 kg		47	-	-	-16	-	-	15	13	15	10	46	58	61	55
± 70 "		-	29	-	-	5	-	24	16	14	14	4	15	10	-3
± 100 "		-	-	7	-	-	10	27	0	-10	-8	-22	-8	-6	-22

* the value in parentheses is corrected for d_T

Analysis of variance showed that in the supplemented diets (with the exclusion of the diet with Superphosphate), the diet with dicalciumphosphate gave the lowest phosphorus absorption percentage ($p < 0.05$), retention percentage (ns) and phosphorus retention per day ($p < 0.05$). No differences were detected between diets with Hostaphos and Curaphos; and of the supplemented diets, Superphosphate gave the highest phosphorus absorption percentage. The retention percentage of the phosphorus from this diet, however, was lower except at 40 kg. Especially the higher excretion of phosphorus in the urine of animals given Superphosphate should be mentioned (Table 105). As a result of the higher excretion of phosphorus in the urine, there might be a feedback mechanism, leading to a higher absorption of phosphorus from that diet, although we are not able to explain this mechanism physiologically. These animals also might suffer from renal failure. From our results it can be concluded that the addition of phosphorus from Superphosphate, in the quantities used, is not suited to pigs.
To compare the different phosphorus sources used in this experiment, we calculated the absorption and retention percentages of the added phosphorus, assuming that the phosphorus of the basal diet in the supplemented diets had the same absorption and retention percentages as those found in the trials using the basal diet only. These results are based on the same dry matter intake of all groups at a given body weight (Table 106). The low values at the higher body weights are an indication that the assumption made above is not permissible.

14.3. THE ABSORPTION AND RETENTION OF ADDED PHOSPHORUS IN TRIALS OTHER THAN VV 534 TO VV 548

14.3.1. Introduction

In this section, the results will be given of the absorption and retention of added phosphorus sources to diets in trials other than VV 534 to VV 548. An overview of these trials is given in Table 106.
To calculate the absorption and retention of the added phosphorus, we assumed that the phosphorus addition did not change the excretion of faecal endogenous phosphorus and that phosphorus absorption and retention of the basal and supplemented diets showed no interaction.

14.3.2. Trials VV 370 to VV 372 vs trials VV 367 to VV 369 (diet with and without $NaH_2PO_4.2H_2O$)

Three different batches of the basal diet were offered during the growing period, so that the phosphorus concentration in the diet was not always precisely the same. Details of this experiment have been presented in Chapter 12. The digestibility of the dry matter in VV 370 to VV 372 was on average only 0.2 unit higher than in VV 367 to VV 369 so that both series can be compared well. The absorption and retention percentages of the phosphorus source used in this experiment ($NaH_2PO_4.2H_2O$) are given in Table 106.

14.3.3. Trials VV 437 to VV 439 vs trials VV 431 to VV 433 (diet with and without $Na_2HPO_4.7H_2O$)

The basal diet in these trials contained only 1.9 g calcium/kg T. Although the basal diet was from the same batch, the digestibilities of the dry matter of both diets used differed 1.6 units. This spoils a good comparison because the absorption percentage of the intrinsic phosphorus in the supplemented diet might be different from that of the basal diet.
Therefore, before calculating the absorption and retention percentages of

the supplement we changed the digestibility of the basal diet to the digestibility of the dry matter of the supplemented diet and assumed that the phosphorus concentration in the dry matter of the faeces of the basal diet remained the same. The results of these calculations are given in Table 106. Details of this experiment have already been presented in Chapter 13.

14.3.4. Trials VV 478 to VV 489, trials VV 481 to VV 483, trials VV 484 to VV 486 resp. vs VV 487 to VV 489 (diets with and without $CaHPO_4$)

The only difference between trials VV 478 to VV 480, VV 481 to VV 483 and VV 484 to VV 486 was the copper concentration which was 9, 120 and 229 ppm Cu in the dry matter respectively (details of this experiment will be given in Chapter 15). The copper concentration in trials VV 487 to VV 489 was the same as in VV 484 to VV 486. The absorption and retention percentages of the phosphorus in the added dicalcium phosphate are given in Table 106. It can be seen that these values in VV 478 to VV 480 deviate in most cases from those of VV 481 to VV 483 and VV 484 to VV 486.

14.3.5. Trials VV 493 to VV 495 vs trials VV 490 to VV 492 (diet with and without $CaHPO_4$)

In these trials, pelleted diets were used (details of these trials will be presented in Chapter 15). The absorption and retention percentages of the added phosphorus are given in Table 106.

14.4. DISCUSSION

In the review of the literature (Chapter 2.8.4), it was shown that most comparisons of phosphorus sources were done in feeding trials, with growth rate, feed intake and feed conversion ratio as criteria. Such data are very interesting to the farmer, but these criteria are not sensitive enough to show differences in absorption or availability between phosphorus sources. Some research workers used the absorption percentage of phosphorus as the criterion (Ammerman et al., 1963; Guéguen et al., 1968; Cupak et al., 1972; Procházka et al., 1972; Partridge, 1981; King, 1980; Grimbergen, 1981; Grimbergen et al., 1985). In these studies, except in those of the last three research workers, labelled phosphorus was used. In most experiments, pigs with a live weight of 25 to 40 kg were used. In most experiments presented in the literature, the standard error of the absorption percentage of phosphorus from the phosphorus source is high so that no significant differences in absorption percentage could be shown. There is also a wide variation in absorption percentage of the phosphorus from the same phosphorus source (dicalcium phosphate) between batches of the different experiments (from 32 by King to 80 in the experiment described by Cupak et al., 1972). However, there can be differences between batches of dicalcium phosphates as shown by Grimbergen et al. (1985). The effect of the live weight of the pig on the absorption percentage of added phosphorus was clearly shown by Partridge (1981). He found on average 70 and 52 per cent at 4 to 9 week pigs and 20 to 50 kg pigs respectively. The remarks given above lead us to the conclusion that the comparison of our results with those given in the literature is useless and that a comparison must be made within an experiment.

The results given in Table 106 show a wide variation in absorption percentage of the added phosphorus. The cause of this variation will be discussed here. It can be seen in Table 106 that at a normal calcium concentration in the diet (more than 6 g/kg T), the absorption percentage of the added phosphorus generally declines at an increasing live weight. The main reason for

this is that the amount of available phosphorus offered exceeds the amount required by the animal more and more. This follows from the sharp decline in the retention percentage of the added phosphorus. A decline in the surplus of available phosphorus, when compared to requirement, will certainly lead to a smaller decline in absorption percentage for added phosphorus. However, for a reliable comparison it is necessary for a fairly large amount of phosphorus from the experimental phosphorus source to be added to the diet. Our basal diets (more or less practical diets) already contained high amounts of available phosphorus. At ± 100 kg live weight, the basal diet had sufficient phosphorus as can be concluded from the negative retention percentage of the added phosphorus. This leads to the conclusion that when phosphorus sources are to be compared by means of the absorption percentage of the added phosphorus, the basal diet must contain a low amount of available phosphorus. This means that a (semi) synthetic basal diet must be chosen.

Another problem which arises while calculating the absorption percentage of the added phosphorus, is that small differences can appear in the digestibility of the dry matter between the pigs receiving the basal and those on the supplemented diet (see e.g. VV 431 to VV 433 vs VV 437 to VV 439). This may also lead to differences in absorption percentages of the intrinsic phosphorus in both diets. Between animals at the same live weight and the same diet there is a clear tendency for a higher digestibility of the dry matter to correspond with a higher absorption percentage of phosphorus (see Chapter 17.4.). This observation pleads again in favour of using a (semi) synthetic basal diet with a low concentration of phosphorus. In this case, the amount of intrinsic phosphorus is small when compared to the amount of added phosphorus. In trials VV 431 to VV 433 vs VV 437 to VV 439 the influence of correcting the absorption of intrinsic phosphorus in the basal and supplemented diet to the same digestibility of the dry matter is shown. This way of correction can, however, be criticized. Another possibility for avoiding differences in digestibility of the dry matter between the basal and supplemented diet is to take more animals per diet. This also permits the use of the digestibility of the dry matter of the diets as a covariable. This is not justified in the present experiments because of the small number of observations.

In trials VV 437 to VV 439 it is shown that at a low calcium concentration in the diet a high absorption percentage for added phosphorus can be achieved and that the absorption percentage does not decline with increasing live weight. Comparison of different phosphorus sources by means of absorption percentage of phosphorus at a low calcium level might give more perspective than at normal calcium levels in the diet. In practice however, most phosphorus sources used in pig feeding also contain a considerable amount of calcium so that the calcium concentration of the supplemented diet cannot be kept as low as that of the basal diet.

The method described by Boyd (1980) and Cromwell (1980), in which a semi-synthetic diet is used and phosphorus sources are evaluated by the slope ratio technique on the grounds of the bone breaking strength and bone ash percentage seems more promising. In the next section this procedure will be discussed in more detail.

The conclusion drawn from our experiments using different phosphorus sources is that the absorption percentage is not a very useful criterion for evaluating different phosphorus sources; the basal diet often contains too much phosphorus, and differences in digestibility of the dry matter (between animal variation) enhance the variation in the absorption percentage of phosphorus. Thus, the basal diet should have a low phosphorus concentration and the quantity of supplemented phosphorus should not be too large. More animals (observations) per diet have to be used to eliminate the differences in digestibility of the dry matter. To prevent the phospho-

rus supply exceeding requirement, and so influence phosphorus absorption, it might be better to do the measurements in the live weight range of 30 to 60 kg.

14.5. ASSESSMENT OF THE VALUE OF FEED PHOSPHATES USING MORE THAN ONE SUPPLEMENT LEVEL IN PIGS AND USING VARIOUS CRITERIA

14.5.1. Introduction

In the preceeding sections of this chapter, it was shown that absorption and retention studies of feed phosphates supplemented to more or less practical diets are not well suited for assessing the value of feed phosphorus. In this section, an experiment will be described in which special attention was paid to the methodology. This experiment was done on five to ten week old piglets, with six or seven piglets per pen. The absorption percentage was determined by means of a marker. The advantage of such an experiment using piglets is that it is less laborious and that more feed phosphates can be compared at the same time than in experiments with pigs from 35 kg live weight onwards on metabolism crates. So much of each of five sources of phosphorus was added to the semi-synthetic diet that the supplemented diet contained three distinct levels of each phosphorus source. The results were compared and discussed, using various criteria. This experiment was described in detail by Mulder and Jongbloed (1985), so that only its main aspects will be given in this thesis.

14.5.2. Materials and methods

For this experiment, two trials were performed using piglets from five to ten weeks old. In the first trial, 107 animals of the GY-breed were used, in the second trial 97 animals, 71 of which were crossbred (DL x GY) and 26 were of the GY-breed.
After weaning at a mean age of five weeks, the animals remained in the farrowing pen for four days, after which time they were allocated to the treatments according to age (litter) and live weight at four days after weaning. These piglets were group-housed and group fed with six or seven animals per pen; no straw-bedding or sawdust was used because digestibility was to be measured.
The composition of the basal diet is given in Table 107. The feedstuffs were from one batch and were analysed in advance. This was also done with the five feed phosphates.

Table 107. Feedstuff composition of the basal diet and estimated chemical composition (g/kg)

babycorn	400	moisture	119
barley	200	O	835
cane molasses	40	XP	200
potato pulp dried	20	XL	59
soybean oil	40	XF	33
potato protein dried	60	lysine	12.5
soybean meal (>7 % XF)	80	cystine + methionine	7.2
beet pulp dried		Ca	7.0
(20-25 % sugar)	35	P	2.9
acid casein	70	digestible P	1.3
corn starch	32.4	NE_f (est.;MJ/kg)	10.35
limestone	14.6		
salt	4.5		
minerals + vitamins	3.5		

The indigestible marker, chromic oxide, was first mixed in a small mixer with corn starch in a weight ratio of 1 : 3, and then ground in a hammer-mill through a sieve with a diameter of 0.5 mm. This ground mixture was then mixed in the small mixer with the premix, salt and choline chloride, together with, only for the basal diet and the treatments with the highest level of phosphorus, an amount of limestone or phosphate. The calcium concentration in the diets was kept constant at 0.7 per cent.
In the feedmill, the appropriate premixes were added to the basal diet and after thoroughly mixing, the diets were pelleted. At the Institute, the diets for the other treatments (Table 108) were made in a Nauta mixer by mixing the basal diet and the diet with the highest level of phosphorus of each phosphorus source in a ratio of 2 to 1 or 1 to 2 respectively. The diets were stored at 4°C.
The phosphorus sources A, B and C were monocalcium phosphates of different origin, phosphorus source D was a non-crystalline dicalcium phosphate and source E was disodium phosphate.

Table 108. Survey of the treatments (diets were adjusted to 0.70 % Ca)

treatment	diet
1	basal
2, 3 and 4 resp.	basal + 0.06 %, 0.12 % and 0.18 % resp. of P source A
5, 6 and 7 resp.	basal + 0.06 %, 0.12 % and 0.18 % resp. of P source B
8, 9 and 10 resp.	basal + 0.06 %, 0.12 % and 0.18 % resp. of P source C
11, 12 and 13 resp.	basal + 0.06 %, 0.12 % and 0.18 % resp. of P source D
14, 15 and 16 resp.	basal + 0.06 %, 0.12 % and 0.18 % resp. of P source E

The animals were fed ad libitum and their feed intake and weight recorded weekly. In the third and fifth week, fresh faecal samples were taken to determine the absorbability of phosphorus. Faecal samples were taken in the morning and afternoon of Tuesday and Thursday and combined for further analysis. In the second trial, in the morning and afternoon, during the third and fifth weeks, fresh urine samples of those animals receiving the highest levels of phosphorus were also collected. The concentration of phosphorus in the urine samples was determined. Diets and faeces were analysed for dry matter content together with the concentrations of calcium, phosphorus and chromium.
After the fifth week, from each pen the four animals that had best approached the mean growth rate of all the animals were slaughtered. The third and fourth metatarsal bones of both hind legs were removed and desiccated and the day after slaughter bone breaking strength determined (see Chapter 6.7.5.). The bones were then stored at -20°C. Before chemical analysis, the bones were cleaned of adhering tissue and the epiphyses were removed. In the diaphysis, the fat-free weight and concentration of ash were determined. After ashing, per trial a composite sample was made of the ash of one treatment and the concentration of calcium and phosphorus determined. The breaking moment of the bones was calculated according to Crenshaw et al., (1981):

$$\text{breaking moment (N.m)} = \frac{\text{force (N) x distance between supporting devices (m)}}{4}$$

The distance between the supporting devices in this experiment was 2 cm. The solubility of the phosphorus sources was determined in water and in a solution of 2 per cent citric acid according to the method described by Guéguen (1977), but instead of using 1.0 g of the phosphorus source per 100 ml solution we used 0.5. The results of the measurements were statistically analysed by regression analysis.

14.5.3. Results

The trials ran smoothly and no pigs needed to be removed from the experiment. The mean initial weight was 10.1 kg in both trials while the mean final weight after five weeks was 25.0 and 26.6 kg respectively in trials 1 and 2. The feed conversion ratio was 1.59 and 1.56 respectively. There was a tendency towards a better performance at the higher phosphorus levels but no differences between phosphorus sources could be detected.
The results of the analysis in the phosphorus sources are given in Table 109 and those of the diets in Table 110.

Table 109. Some characteristics of the P sources used

P source	Ca (g/kg)	P (g/kg)	solubility (%) in water	solubility (%) in citric acid (2%)
A ($Ca(H_2PO_4)_2$)	175	222	76.3	100.0
B (")	177	223	69.8	98.8
C (")	162	221	76.3	100.0
D ($CaHPO_4$)	260	201	5.7	94.8
E ($NaH_2PO_4.7H_2O$)	-	174	100.0	100.0

The sources A, B and C (monocalcium phosphates) hardly differed in chemical properties, were fairly soluble in water and completely soluble in 2 per cent citric acid. Source D (dicalcium phosphate) was hardly soluble in water but highly soluble in 2 per cent citric acid, while source E (disodium phosphate) was completely soluble both in water and in 2 per cent citric acid.

Table 110. The mineral content of the diets (g/kg T)

treatment	diet	Ca	P	Cr
1	basal	8.21	3.63	0.382
2	basal + 0.06 % P of P source A	8.65	4.31	0.369
3	basal + 0.12 % P of P source A	8.90	5.07	0.362
4	basal + 0.18 % P of P source A	9.08	5.93	0.357
5	basal + 0.06 % P of P source B	8.55	4.28	0.373
6	basal + 0.12 % P of P source B	8.80	4.97	0.370
7	basal + 0.18 % P of P source B	8.83	5.74	0.365
8	basal + 0.06 % P of P source C	8.65	4.36	0.374
9	basal + 0.12 % P of P source C	8.30	4.90	0.374
10	basal + 0.18 % P of P source C	8.42	5.67	0.371
11	basal + 0.06 % P of P source D	8.47	4.28	0.377
12	basal + 0.12 % P of P source D	8.35	4.85	0.369
13	basal + 0.18 % P of P source D	8.33	5.58	0.367
14	basal + 0.06 % P of P source E	8.27	4.19	0.372
15	basal + 0.12 % P of P source E	8.82	4.83	0.368
16	basal + 0.18 % P of P source E	8.39	5.53	0.373

The calcium concentration between the diets showed slight, undirected variation but this probably did not influence phosphorus metabolism. There was also a small variation in phosphorus content of the diets, but within the same source of phosphorus the differences were almost equidistant. The differences in mineral concentrations between the diets with the different phosphorus sources is due to a somewhat higher or lower concentration of calcium and phosphorus in the phosphorus sources than was initially analysed.
Statistical analysis showed that the digestibility of the dry matter and the absorption percentages of calcium and phosphorus of the diets were significantly higher in the second trial and in the fifth week ($p < 0.01$). The values were 83.3, 50.9 and 44.5 in the first trial and 84.7, 57.7 and 51.3 respectively in the second trial. The mean values of both trials in the third week were 83.5, 51.6, and 46.8 and in the fifth week 84.8, 57.0 and 49.0 respectively.
For the third and fifth weeks separate regression analyses, in which the absorption percentage of phosphorus was regressed on the amount of added phosphorus and corrected for trial and difference with the mean digestibility of the dry matter, gave the following results (Table 111).

Table 111. Estimates of the regression coefficients of absorption percentage of P based on added P for the P sources used and t-value (df = 24); different characters in the same column indicate significance of differences ($p < 0.05$)

	absorption% of P in third week			absorption% of P in fifth week		
	estimate	se	t-value	estimate	se	t-value
constant	36.4	0.9	39.7	39.9	0.5	81.1
trial	2.6	1.4	1.9	2.0	0.7	2.6
d_T	3.3	0.8	4.3	3.0	0.5	6.4
P source A	73.2 a	9.1	8.0	70.8 ac	5.2	13.6
P source B	63.7 a	7.6	8.4	61.8 a	4.4	14.2
P source C	76.4 a	7.7	9.9	71.6 c	4.5	15.8
P source D	43.0 b	8.1	5.3	34.1 b	4.6	7.4
P source E	108.0 c	9.2	11.8	86.4 d	5.3	16.2

For the third week, the effect of the trial approached significance and in the fifth week there was a significant effect of the trial($p < 0.01$). Correction for differences with the mean digestibility of the dry matter reduced the variance significantly. In the third week as well as in the fifth week the tendency in the order of the absorption percentage of phosphorus was the same: source E had the highest and source D the lowest.
We also calculated for each diet separately the absorption percentage of phosphorus by means of difference with the basal diet. These results are given in Table 112. It can be seen in this table that a great variation in the absorption percentages of phosphorus can be found. Excluding the lowest levels of addition considerably reduces the standard deviation in most cases. At the low inclusion level of 0.6 g phosphorus added to a diet with 3.6 g phosphorus per kg T, small analytical errors cause large errors in the estimation of the absorption percentage of added phosphorus. Without the lowest inclusion levels the mean absorption percentages for sources A to E change from 72 ± 14, 73 ± 14, 83 ± 12, 60 ± 19 and 92 ± 20 to 72 ± 10, 76 ± 12, 81 ± 13, 65 ± 11 and 88 ± 12 respectively.

The concentration of phosphorus in the urine was low (6 to 18 mg/l) which indicates that the phosphorus supply was below requirement. On diets above

requirement 150 to 400 mg P/l is found in the urine.

Table 112. Absorption percentage of P of the P sources used (calculated by means of difference with the basal diet)

P source	P added (g/kg)	treat-ment	third week 1st trial	third week 2nd trial	fifth week 1st trial	fifth week 2nd trial
	- -	1	--	--	--	--
A	0.6	2	60.3	102.2	47.9	72.1
A	1.2	3	70.1	90.7	69.7	70.2
A	1.8	4	56.9	78.8	71.0	71.3
B	0.6	5	65.7	88.6	52.1	56.2
B	1.2	6	75.0	93.6	67.2	76.6
B	1.8	7	58.4	90.2	69.3	79.2
C	0.6	8	81.0	101.6	76.9	86.7
C	1.2	9	81.2	100.4	56.6	81.7
C	1.8	10	81.2	91.2	73.1	84.5
D	0.6	11	19.4	87.5	36.5	55.6
D	1.2	12	58.7	87.6	55.7	68.0
D	1.8	13	60.8	74.9	53.3	62.9
E	0.6	14	106.1	139.3	66.7	89.8
E	1.2	15	82.8	111.1	78.5	97.3
E	1.8	16	90.4	91.8	77.7	73.6

Statistical analysis showed no interaction between the treatment and its effect on either the results of the third and fourth metatarsal bones or on those of the left or right bones. Therefore, the results of the four bones per animal were combined for further statistical analysis. The mean amount of fat-free dry matter, ash and concentration of ash in the fat-free dry matter of the metatarsal bones was 2.23 g, 1.31 g and 586.6 g/kg respectively. Regression analysis showed that when initial weight was used as a covariable, R^2 increased considerably. Also in this analysis, trial and breed were taken as independent variables. The results of this analysis are given in Table 113.

From Table 113 it can be seen that there is a significant breed effect and that there are significant differences between the sources of phosphorus. P source E gave the highest amounts of fat-free dry matter and ash in the bones and tended to give the highest concentration of ash in the fat-free dry matter; P source B on the contrary, resulted in the lowest amounts of fat-free dry matter and ash in the bones.

For all bones, the mean concentrations of calcium and phosphorus in the ash were 344 and 167 g/kg respectively. The concentration of phosphorus in the ash tended to increase at a higher phosphorus level in the diet. The results of the regression analysis for the concentration of phosphorus in the ash of the bone and the Ca/P ratio in that ash are given in Table 114; no difference between trials could be detected. The concentration of phosphorus in the ash of the bones from pigs fed on the basal diet was significantly lower than from pigs fed the diets with supplemented phosphorus; there were no differences in this respect between the phosphorus sources. The Ca/P ratio in the ash of the bones was higher for the basal diet than for the diets with supplemented phosphorus; that for source E was lower than for the other phosphorus sources. No effect of either level or source of phosphorus on the concentration of calcium in the ash of the bones could be demonstrated.

Table 113. Estimates of the regression coefficients of regressing fat-free dry matter, ash or ash concentration in fat-free dry matter of metatarsal bones on added P for the P sources used and t-value (df=121); different characters in the same column indicate significance of differences

	fat-free dry matter (g)			ash (g)			ash (g/kg ffdm)		
	estimate	se	t-value	estimate	se	t-value	estimate	se	t-value
constant	0.377	0.097	3.89	0.030	0.054	0.56	499.0	7.5	66.83
trial	0.066	0.058	1.13	0.018	0.032	0.56	-10.6	4.5	-2.36
breed DL*GY	0.148	0.060	2.48	*0.120	0.033	3.59	15.1	4.6	3.28
initial weight	0.140	0.009	16.17	0.095	0.005	19.72	5.9	0.7	8.90
P source A	2.577 b	0.313	8.24	1.979 b	0.175	11.32	213.7 ab	24.1	8.86
P source B	1.730 a	0.336	5.15	1.487 a	0.188	7.91	227.7 ab	25.9	8.78
P source C	3.246 b	0.348	9.34	2.381 c	0.194	12.24	219.1 ab	26.8	8.17
P source D	2.809 b	0.363	7.74	2.045 bc	0.203	10.07	191.1 a	28.0	6.83
P source E	4.054 c	0.374	10.85	2.933 d	0.209	14.04	253.3 b	28.8	8.79

Table 114. Estimates of the regression coefficients of regressing concentration of P in the ash of bones and the Ca/P ratio in the bones on added P for the P sources used and the t-value (df = 10)

	concentration of P (g/kg ash)			Ca/P ratio in ash		
	estimate	se	t-value	estimate	se	t-valu
constant	162.9	0.8	214.79	2.109	0.009	235.9
P source A	34.3 a	6.6	5.24	-0.378 a	0.077	4.8
" B	31.6 a	7.1	4.44	-0.337 a	0.084	4.0
" C	28.3 a	7.4	3.85	-0.302 a	0.087	3.4
" D	27.6 a	7.7	3.58	-0.340 a	0.091	3.7
" E	35.4 a	7.9	4.48	-0.604 b	0.093	6.4

There were no effects of the treatments on the width of the bones. Measurements on bone breaking strength showed that in various bones breaking occurred gradually. First, the upper shaft of the bone broke (this is called the breaking moment 1) and after that the lower shaft (called the breaking moment 2); this sometimes caused problems when determining the correct force. The results of the regression analyses on the breaking moments of the bones are given in Table 115; the model used can also be derived from this table.

Table 115. Estimates of the regression coefficients of regressing breaking moments on added P for the P sources used and t-value (df = 113 and 103 resp.)

	breaking moment 1 (Nm)			breaking moment 2 (Nm)		
	estimate	se	t-value	estimate	se	t-value
constant	0.32	0.18	1.73	1.32	0.22	6.11
trial	0.11	0.11	0.99	-0.12	0.13	0.98
breed DL*GY	0.06	0.11	0.52	0.14	0.13	1.13
initial weight	0.16	0.02	9.61	0.08	0.02	4.15
P-source A	5.42 ab	0.61	8.85	3.86 a	0.72	5.35
" B	4.20 a	0.68	6.19	3.34 a	0.80	4.16
" C	6.31 bc	0.66	9.62	4.62 a	0.80	5.77
" D	5.37 ab	0.69	7.83	4.09 a	0.81	5.06
" E	7.11 c	0.71	10.02	7.30 b	0.87	8.36

The results of the analyses show a significant effect of the different P sources used and of the initial weight; no effect of trial or breed could be detected. Only for the breaking moment 1 can some significant differences between the phosphorus sources be seen; P source E tended to give the highest values and was significantly higher than the other P sources for breaking moment 2. However, breaking moment 2 does not supply much additional information when compared with breaking moment 1.

14.5.4. Discussion

A summary of the main results of this experiment together with R^2 and CV values of the regression, is given in Table 116 and in Table 117 the ranking order is given.

Table 116. Relative values of the estimates of the P sources A to D with regard to source E (=100) for the various criteria and R^2 and CV

P source	absorption % of P		in metatarsal bones						
	3rd week	5th week	ffdm (g)	ash (g)	ash (g/kg ffdm)	breaking moment 1	breaking moment 2	P (g/kg ash)	Ca/P ratio	P (g)
A	67.7 a	81.9 ac	63.6 b	67.4 b	84.4 ab	76.2 ab	52.9 a	85.3 a	56.9	57.4 a
B	58.9 a	71.5 a	42.7 a	50.7 a	89.9 a	59.1 a	45.7 a	78.8 a	51.0 a	56.5 a
C	70.8 a	82.9 a	80.1 b	81.2 c	86.5 ab	88.7 bc	63.3 a	70.9 a	46.0 a	74.2 ab
D	39.8 a	39.4 b	69.3 b	69.7 bc	75.4 a	75.5 ab	56.0 a	69.1 a	51.6 a	78.5 ab
E	100.0 c	100.0 d	100.0 c	100.0 d	100.0 b	100.0 c	100.0 b	100.0 a	100.0 b	100.0 b
R^2 (%)	90	95	77	84	62	66	44	68	74	85
CV	4.4	2.3	8.4	8.0	2.5	13.0	14.7	0.8	0.8	4.9

Table 117. Ranking order of the relative values of the P sources used (1 = best; 5 = worst)

P source	abs.% of P 3rd week	abs.% of P 5th week	ffdm (g)	ash	ash (g/kg ffdm)	in metatarsal bones breaking moment 1	in metatarsal bones breaking moment 2	P (g/kg ash)	Ca/P ratio	P (g)
A	3	3	4	4	4	3	4	2	2	4
B	4	4	5	5	2	5	5	3	4	5
C	2	2	2	2	3	2	2	4	5	3
D	5	5	3	3	5	4	3	5	3	2
E	1	1	1	1	1	1	1	1	1	1

It can be seen in Table 116 that the criterion absorption percentage of phosphorus has the highest R^2. The bending and breaking moments have the lowest R^2. Table 117 shows that according to the various criteria the phosphorus sources used were not always ranked in the same order. This can for instance be seen for source D, which had the lowest absorption percentage of phosphorus, but the bone measurements usually showed an intermediate ranking order. These differences in ranking order are difficult to explain. To some extent they will be due to experimental error; performing more comparisons would probably help. As expected phosphorus source E (disodium phosphate) was for all criteria the best one. Phosphorus source C was for nearly all criteria second best although, except for the amount of ash in the bone, no significant differences could be demonstrated between sources A and C. Differences in bone measurements between phosphorus sources A and B were small and variable; the absorption percentage of phosphorus from source B tended to be lower than from source A.

The absorption percentage of phosphorus from the diets significantly increased ($p < 0.01$) from 46.8 in the third week to 49.0 in the fifth week. This was probably mainly caused by the increase in the absorption percentage of phosphorus in the basal diet. In this experiment, the increase in the absorption percentage of phosphorus was closely associated with the increase in digestibility of the dry matter ($r = 0.91$). Regression analysis was therefore performed with the digestibility of the dry matter as a covariable which reduced the variance by about half and increased R^2 from 0.86 to 0.93. It may be assumed that, as the animals had already received the experimental diets for 15 days, they had already adapted to the diets. No differences were observed in the ranking order of the absorption percentage of the phosphorus sources to each other between the third and fifth week. However, the estimates of the absorption percentages of phosphorus of the best source (E) decreased significantly but not those of the other sources (Table 111). Therefore, it may be useful to measure the absorption percentage of phosphorus at more live weights.

The high absorption percentage of phosphorus of disodium phosphate (almost 90) was also found in balance trials VV 437 to VV 439. With regard to dicalcium phosphate, the absorption percentage of phosphorus (± 65) was higher than in the earlier experiments with the pigs on metabolism crates; all the dicalcium phosphates used came from the same factory but were from different batches.

With regard to the bone measurements, it was shown that using the initial weight of the piglets at the start of the experiment as a covariable improved the fit of the data to the model. As already outlined in section 14.5.2. for the bone measurements those piglets were chosen which best approached the average growth rate of all piglets in the trial. This was

done because it was assumed that at the same growth rate the same feed intake would also take place. However, this selection of piglets may be criticized and may have biased the results. Also, the wide variation in body weight of the piglets at the start and the even wider variation in their final weight may be disturbing factors, despite the use of a covariable for the initial weight.
The high R^2 for bone breaking strength, as is reported in the literature, was not found in our experiment, despite the fact that we used eight animals per treatment compared with five or six in the literature. The reason for this is not clear. Some differences in our studies with similar experiments in the literature will be mentioned. Our experiment lasted five weeks against the usual six weeks quoted in the literature. Furthermore, our experiment started with piglets at a mean age of 39 days, while in the literature six week old piglets are usually used, but it is doubtful if such a small difference in the age of the piglets at the start could have affected the results. Also, the difference in duration of the experiment can hardly explain the difference in R^2, but it may be that it takes two or three weeks before the reserves of phosphorus in the bones present at the start of the experiment are completely exhausted, and that a subsequent period of only two or three weeks is too short to show clear differences in bone breaking strength. Moreover, the growth rate in the last one or two weeks of the experiment was much higher than at the start, so that differences in bone breaking strength may become more pronounced.
One can query whether the metatarsals or metacarpals are the most suitable bones to use, because not much research has been done in this field. They are usually used because they can be obtained rather easily without loss of slaughter value. Only Günther et al. (1966/1967; 1967/1968), Günther and Rosin (1970/1971) Koch et al. (1984), Koch and Mahan (1985; 1986) have shown that the metacarpals are the most sensitive for the amount of phosphorus supply. However, Pointillart (1986) observed that differences were much more marked in tibias than in metatarsals.
From a statistical point of view the measurements at the inclusion level of 0.06 per cent phosphorus does not supply much information. Therefore, this level can be exchanged for more observations at the basal diet and at the highest level of phosphorus, provided its requirement is not exceeded.
It may be concluded from this experiment that by using a semi-synthetic diet with a low phosphorus concentration, better estimates can be obtained than by means of a practical basal diet because higher levels of supplemented phosphorus from inorganic sources can be used. Nevertheless, also in the present experiment the standard error of the estimates for the absorption percentage of phosphorus - about 7 percentage units - was rather high. More research is needed to discover why the same ranking order of the value of phosphorus from various sources is not always obtained when different criteria are used.

14.6. CONCLUSIONS

To prove the existence of differences for a pig's phosphorus metabolism between phosphorus sources it is necessary to use a basal diet with a low concentration of phosphorus. This means that a semi-synthetic diet must be chosen. Basal diets composed of ordinary feedstuffs contain so much phosphorus that the pig's requirement for phosphorus is almost met. Moreover, in such basal diets intrinsic phosphorus plays too great a part and biases the results.
In the experiment using the piglets, the highest R^2 was found when the absorption percentage of phosphorus and the amount of ash in the metatarsal bones were regressed on the phosphorus concentration in the diet. In contrast to the results in the literature, a low R^2 was obtained with bone

breaking strength as a dependent variable. Some possible causes for these differences were discussed. The same ranking order of the phosphorus sources was not always obtained when various criteria were used. There were clear differences in phosphorus sources used but the three monocalcium phosphates from different factories did not differ very much. Measurements using synthetic basal diets with a low phosphorus concentration are recommended.

15. EFFECT OF STEAM-PELLETING AND COPPER CONCENTRATION IN THE DIET ON ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM

15.1. INTRODUCTION

In this chapter, the effect of steam-pelleting a mixed diet on absorption and retention of phosphorus and calcium is described as well as the effect of dietary copper concentration on the mineral balance. For this purpose two experiments were set up, which have been combined because one diet was the same in both experiments. The effect of pelleting and copper concentration was studied in balance experiments on barrows. The mineral balances were measured three times on the same animal from 35 to 100 kg live weight. According to the literature (Chapter 3.2.2.), the effect of pelleting may depend on the phosphorus concentration in the diet. Therefore, the effect was studied at two phosphorus concentrations.
In most Western European countries, copper salts are added to the diets of slaughter pigs in order to achieve better performance (Jongbloed, 1984). However, as nearly all the ingested copper is excreted, in those regions where there is a high concentration of piggeries, such copper additions can lead to environmental problems (Reports M.I.K., 1975; 1979; 1985). In order to reduce these problems, the copper concentrations in the diets have recently been lowered. In an experiment set up to study the influence of copper addition on the digestibility of protein and amino acids (Lenis, 1980), the influence on the absorption and retention of calcium, phosphorus and copper was also measured. The relevant literature has been reviewed in Chapter 2.11.2.

15.2. INFLUENCE OF STEAM-PELLETING ON ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM (TRIALS VV 484 TO VV 495)

15.2.1. Materials and methods

For this experiment the same basal diet was used. One half of it received no additional phosphorus (low P diet) and the other half 0.15 per cent phosphorus from dicalcium phosphate (normal P diet). One half of the two diets was steam-pelleted while the other half remained as meal. During the pelleting process, the diets were treated with steam of 150°C. The press had a diameter at 4.8 mm. After leaving the press, the pellets had reached a temperature of 80°C and were subsequently air-cooled to 40°C. The composition of the diets is given in Table 118.
The estimated NE_f concentration of the diets was 8.93 MJ/kg for the low phosphorus and 8.84 MJ/kg for the high phosphorus diets, the concentration of DXP was 130 g/kg, that of XL was 28 g/kg, that of XF was 60 g/kg and that of lysine was 6.2 g/kg. Each diet was fed at 95 per cent of the C.V.B. scheme to three barrows of the GY x DL breed and the calcium and phosphorus balances were measured three times during the growing period. Besides the mineral balances, the digestibilities of energy and proximate components of the diets were also determined at about 67 kg live weight to estimate the NE_f content. The results were subjected to analysis of variance.

Table 118. Composition (g/kg) and chemical analyses of the diets

trials VV	Low phosphorus meal 487 to 489	Low phosphorus pelleted 493 to 495	Normal phosphorus meal 484 to 486	Normal phosphorus pelleted 490 to 492
maize	116	116	108	108
barley	300	300	300	300
wheat	200	200	200	200
soybean meal solv.extr.	160	160	160	160
wheat middlings	70	70	70	70
grass meal	50	50	50	50
tapioca	70	70	70	70
cane molasses	20	20	20	20
limestone	9.3	9.3	8.3	8.3
dicalcium phosphate	-	-	8.7	8.7
other minerals+vitamins	5.0	5.0	5.0	5.0
T (g/kg)	854	852	853	844
XP (g/kg T)	167	169	165	168
Ca "	6.0	6.2	7.9	7.8
P "	4.8	4.8	6.4	6.4
phytate P (g/kg T)	3.1	3.1	3.1	3.1

15.2.2. Results

During the balance period at 35 kg, one animal in trial VV 493 developed a prolapse of the rectum so it had to be replaced by another animal of 40 kg. A second animal receiving that diet could not be used for the balance period at 100 kg, because of locomotory disturbances. About a month before that balance period, this animal was replaced by one that weighed 78 kg. The performance of the balance animals is given in Table 119.

Table 119. Performance of the balance animals

	Low phosphorus meal	Low phosphorus pelleted	Normal phosphorus meal	Normal phosphorus pelleted
initial weight (kg)	23	25	25	24
growth rate (g/d)	618	624	694	665
feed conversion ratio*	3.43	3.19	3.14	3.16
feed intake (kg/d)	2.17	2.18	2.24	2.16
days in exp.	135	133	128	126

* corrected to a common NE_f concentration of 8.79 MJ/kg diet.

The results from Table 119 indicate a lower performance for the animals receiving the diets with a low phosphorus concentration.
The results of some chemical analyses of the diets are given in Table 118 and the detailed results of the mineral balances in Appendix 31. A summary of the results of the balance experiments is given in Table 121. The analysis of variance showed no interactions of the phosphorus level with the physical form of the diet for all variables. Steam-pelleting improved the absorption and retention percentage of phosphorus significantly irrespective the phosphorus concentration in the diet. The results of the digestibility trials at 65 kg and the feeding value are given in Table 122.

Table 121. Summarized results of the balance experiments (df = 8)

	Low P		Normal P			level of sign.	
	meal	pelleted	meal	pelleted	sed	P level	pelleting
d_T(%)	81.1	81.9	80.4	81.4	0.38	ns	*
absorption % of Ca	41.5	42.8	35.2	33.8	1.61	***	ns
absorption % of P	37.6	40.5	35.9	38.4	0.66	*	**
retention % of Ca	38.7	41.0	34.4	33.1	1.44	**	ns
retention % of P	35.7	39.8	28.5	31.5	1.10	***	*
ret. of Ca (g/d)	4.8	5.1	5.2	5.0	0.22	ns	ns
ret. of P (g/d)	3.3	3.7	3.4	3.8	0.14	ns	*

Table 122. Chemical composition, digestibility of some components and feeding value of the diets

	Low phosphorus		Normal phosphorus	
	meal	pelleted	meal	pelleted
T (g/kg)	858	845	853	850
O (g/kg T)	933	934	928	928
XP "	167	169	162	168
XL "	26	27	26	29
XF "	65	66	66	64
XX "	674	672	674	667
GE (MJ/kg T)	17.95	17.91	17.87	17.78
d_T (%)	81.0	81.7	80.8	81.3
d_O "	84.1	84.7	84.2	84.4
d_{XP} "	78.5	81.0	78.4	79.2
d_{XL} "	70.8	70.3	69.2	73.2
d_{XF} "	38.6	40.4	43.4	38.3
d_{XX} "	90.4	90.5	90.2	90.6
d_E "	81.9	82.5	81.7	82.3
NE_f (calc.; MJ/kg T)	9.97	10.04	9.91	10.02
DXP (g/kg T)	131	137	127	133

15.2.3. Discussion

15.2.3.1. Influence of pelleting on the feeding value of the diet

From the results given in Table 122 it can be concluded that the chemical analyses indicate that the diets with the same phosphorus concentration were almost identical. This means that with regard to the effect of pelleting on digestibility these diets can be compared quite well. For the values given in this table, a positive effect of pelleting was found on digestibility but it was not statistically significant. Pelleting the diets resulted in a higher concentration of DXP ($p < 0.01$) and gave an increase in NE_f content of about 0.8 to 1.0 per cent ($p < 0.10$). When the digestibility of the dry matter is taken as a parameter and all the balance periods of these diets are taken into account, then the digestibility of the dry matter in the pelleted diets is 0.9 units higher than in the non-pelleted diets, a difference that is significant ($p < 0.05$). The improvement in feeding value found is in agreement with other reports (e.g. Vanschoubroek et al., 1971; Lawrence, 1976; Just et al., 1978).

15.2.3.2. Influence of pelleting on absorption and retention of phosphorus

The results of the balance experiments (see Table 121) indicate that the absorption and retention percentage of phosphorus were higher with the pelleted diets. The differences amounted, on average, to 2.7 and 3.6 units for absorption and retention percentage and to 0.4 g phosphorus retained per day higher with the pelleted diets. According to the analysis of variance these differences were significant ($p < 0.025$) and there was no interaction between phosphorus level and pelleting, which means that the effect of pelleting on phosphorus absorption and retention was the same at the low and normal phosphorus levels. An effect of pelleting on the calcium absorption and retention could not be detected.
Bayley and Thomson (1969) and Bayley et al. (1975[a]) found an improvement as a result of pelleting on the absorption percentage of phosphorus in their unsupplemented diet but not in the diets supplemented with inorganic phosphorus. However, when the Ca/P ratio in the unsupplemented diet was about 2.5:1 there was no improvement. Trotter and Allee (1979[b]) found a slight increase in the absorption of phosphorus in a non-supplemented diet as a result of pelleting. Harmon et al. (1970[a]) and Ross et al. (1983), however, found no differences. The higher absorption of phosphorus due to pelleting, especially in diets with a low phosphorus content, might be due to the increase in total surface area of the decreased size of the feed particles enhancing the hydrolysis of phytate phosphorus by phytase. If this is the case, care should be taken that the temperature and exposure time during the pelleting process don't exceed limits so that phytase is inactivated. The retention of phosphorus, as a result of pelleting, was on average increased by 0.4 g phosphorus/d and this effect increased with live weight. The improvement in retention due to pelleting is well worth while.

15.3. EFFECT OF COPPER CONCENTRATION IN THE DIET ON ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM (TRIALS VV 478 TO VV 486)

15.3.1. Materials and methods

Low, medium and high copper diets were prepared by fortifying the same basal diet with 0, 400 and 800 mg $CuSO_4.5H_2O$ per kg and 215, 335 and 455 mg $ZnSO_4.H_2O$ per kg (Table 123). The zinc was added because at higher Cu levels, the Zn level in the diets must also be raised (Mills, 1970; Van Campen, 1970). It is not known, however, at the Zn levels used, whether the absorption and retention of calcium and phosphorus will be affected. The estimated NE_f and DXP concentrations for the diets were 8.84 MJ/kg and 130 g/kg, respectively, the concentration of XL was 28 g/kg, that of XF 60 g/kg and that of lysine 6.2 g/kg. Each diet was fed at 95 per cent of the C.V.B. scheme to three barrows of the GY x DL breed and the calcium and phosphorus balances measured three times during the growing period from 25 to 110 kg live weight. The animals had received the experimental diets for 18 days before the first collection period started.
Copper balances were determined at 35 and 95 kg. Because of the very low copper concentration in the urine (0.2 to 0.6 mg Cu/l at the high level of copper in the diet) the amount of copper in the urine was neglected.
The results were subjected to analysis of variance.

15.3.2. Results and discussion

Data on growth rate, feed conversion ratio, feed intake and total length of the experiment are given in Table 124. In this table, the concentration of copper in the liver and its rather high standard deviation is also given.

Some chemical analyses of the diets are given in Table 123, detailed results of the balance experiments in Appendix 32 and a summary in Table 126.

Table 123. Composition (g/kg) and chemical analyses of the diets

trials VV	L(ow) Cu 478 to 480	M(edium) Cu 481 to 483	H(igh) Cu 484 to 486
maize	108	108	108
barley	300	300	300
wheat	200	200	200
soybean meal solv.extr.	160	160	160
wheat middlings	70	70	70
tapioca	70	70	70
grass meal	50	50	50
cane molasses	20	20	20
limestone	8.3	8.3	8.3
dicalcium phosphate	8.7	8.7	8.7
other minerals and vitamins	5.0	5.0	5.0
$CuSO_4.5H_2O$ (mg/kg)	-	400	800
$ZnSO_4.H_2O$ (mg/kg)	215	335	455
T (g/kg)	854	846	853
XP (g/kg T)	160	167	165
Ca "	7.5	7.6	7.9
Mg "	2.0	2.0	2.0
P "	6.0	6.2	6.4
phytate P (g/kg T)	3.1	3.1	3.1
Cu (mg/kg T)	9	120	229

Table 124. Performance of the pigs and copper concentration in liver

	L Cu	M Cu	H Cu
Cu in diet (mg/kg T)	9	120	229
initial weight (kg)	26	26	25
growth rate (g/d)	652	653	694
feed conversion ratio	3.22	3.19	3.12
feed intake (kg/d)	2.16	2.15	2.24
days in experiment	131	126	128
Cu in liver (mg Cu/kg T)	51 ± 19	-	101 ± 15

Table 126. Summarized results of the balance experiments (df=6)

	L Cu	M Cu	H Cu	sed	level of significance
Cu in diet (mg/kg T)	9	120	229		
d_T (%)	81.4	81.1	80.4	0.31	*
absorption% of Ca	40.1	37.0	35.2	1.92	ns
absorption% of P	38.8	37.5	35.9	1.35	ns
retention% of Ca	39.4	36.3	34.4	1.86	ns
retention% of P	33.0	29.8	28.5	1.24	*
retention of Ca(g/d)	5.9	5.3	5.2	0.34	ns
retention of P (g/d)	3.8	3.4	3.4	0.18	ns
P in urine (g/d)	0.71	0.90	0.92	0.17	ns

The chemical analyses in the diets (Table 123) showed that the calcium and phosphorus concentrations increased somewhat with increasing copper levels, which may be due to accidental errors during mixing the diet, sampling or analysis errors. There were no differences in the absorption and retention percentages for calcium and phosphorus when the diet contained 120 or 229 mg copper per kg. The absorption and retention percentages of the treatment with 9 mg copper per kg diet were somewhat higher than at the other two levels of copper, but only the retention percentage of phosphorus was significantly ($p < 0.05$) higher. The somewhat higher concentrations of calcium and phosphorus in the treatments with the medium and high levels of copper might also have depressed the absorption and retention percentages of calcium and phosphorus.

In the low copper treatment less phosphorus tended to be excreted in the urine, as a result the retention of phosphorus and of calcium also tended to be higher than at the medium and high levels of copper. No effect of the treatments was observed on the excretion of calcium in the urine. A higher urinary excretion of phosphorus in the high copper treatments was also found by Kirchgessner et al. (1963) and by Galik (1971), which may be due to a change in the acid-base balance. The effect on the acid-base balance in the present experiment is not only affected by the copper sulphate but is probably also raised by the zinc sulphate.

Appendix 32 shows that, as expected, almost all the ingested copper is excreted again in the faeces.

15.4. CONCLUSIONS

Steam-pelleting improved the absorption and retention of phosphorus of diets either with or without supplementary inorganic phosphorus when compared with non-pelleted diets. The difference was about three percentage-units. The effect seemed to increase with live weight.

A reduction in the copper and zinc concentrations (as sulphates) of the diets for growing pigs had no negative effect on calcium and phosphorus retention. There might possibly be even a slightly positive effect on these balances.

16. EFFECT OF PHOSPHORUS, CALCIUM AND VITAMIN D CONCENTRATIONS IN THE DIET ON THE ABSORPTION OF PHOSPHORUS, PERFORMANCE, LOCOMOTORY DISTURBANCES AND BONE DEVELOPMENT OF GROWING PIGS

16.1. INTRODUCTION

In this chapter, various feeding experiments are described which were done to obtain more information about the effect of the level of calcium, phosphorus and vitamin D in the diet on performance, appearance of locomotory disturbances and bone development of pigs. Furthermore, feeding trials were done using diets with lowered phosphorus levels to study their effect on performance.
First, some studies on the effect of an extremly low concentration of phosphorus in the diet on the possible appearance of locomotory disturbances (leg weakness) are discussed. These early studies were done because it was thought that too low a level of phosphorus was responsible for leg weakness. Because in experiments with broiler chicks ammonium chloride (NH_4Cl) in the diet induced dyschondroplasia (Sauveur and Mongin, 1978) due to a disturbed acid-base balance, its effect on growing pigs was also investigated.
From the review of the literature (Chapters 1.4.4.4. and 1.4.4.6.) it was not clear whether pigs on diets high in phytate phosphorus concentration required more vitamin D. Therefore, three trials were performed to find out whether a higher absorption of phosphorus could be obtained at higher levels of vitamin D in the diet.
In the last experiment, the effect of the phosphorus concentration in the diet on the performance of fast-growing pigs was studied. This experiment comprised six trials with boars and gilts which were fed individually. Only a summary of this experiment will be given, because its results have already been published (Jongbloed, 1983).

16.2. EFFECT OF LOW CONCENTRATIONS OF CALCIUM AND PHOSPHORUS AND ELEVATED LEVELS OF VITAMIN D AND NH_4CL IN THE DIET ON LOCOMOTORY DISTURBANCES IN PIGS: EXPERIMENT 1

16.2.1. Materials and methods

The trials were performed in straw-bedded pens with a brick floor; no slatted floors were used. The size of pen was 5 x 4 m with seven or eight animals per pen, which were group-fed. There were eight such pens in a naturally ventilated stall, four or five of which were usually used for the feeding trials.
The animals (barrows and gilts) were purchased from farms in the neighbourhood at about 22 kg. On the day of arrival at the Institute, the animals were weighed and allocated to the treatments based on sex, litter and live weight. For one week, the animals received the same starter diet as before their arrival at the Institute, after which time the experimental diets were given (Table 127). The feedstuffs used in successive trials came from different batches. The diets were offered twice a day in a trough with 2.5 kg water per kg diet; the diet was not soaked. The intention was to feed near ad libitum, because leg weakness is observed more frequently at higher levels of feeding and higher growth rates (Chapter 5.5.). Feed intake was recorded daily; the animals were weighed weekly. At about 110 kg live weight the animals were slaughtered and the bones were removed for further analysis. Now, some detail of the four trials will be presented.

Table 127. Composition of the diets for the feeding trials of experiment 1

trial	(g/kg) diet 1[a] 1, 2	diet 3[a] 1, 2, 3	diet 7[b] 2, 3	control 1	NH_4Cl 3, 4
maize	390	-	-	332	235
maize gluten feed	-	-	-	-	70
milo	150	-	-	200	125
tapioca	100	-	-	144	200
barley	70	420	420	-	-
wheat	-	200	200	-	-
wheat middlings	-	220	220	144	175
soybean meal solv. extr.	200	120	120	72	105
hominy feed	-	-	-	48	-
grass meal	90	40	40	-	-
minerals + vitamins	10	10	10		
limestone	-	-	-		
dicalcium phosphate	-	-	-	60	70
protein concentrate	-	-	-		
ammonium chloride	-	-	-	-	20

a) see also Chapter 13.2.
b) in diet 7 the added vitamin D concentration was 3800 IU/kg diet instead of 1750 IU/kg as in the other diets.

Trial 1
Diets 1 and 3 were each fed to 2 x 7 pigs (in 2 pens) and the control diet fed to 8 pigs in one pen. The animals were of the GY-breed. At slaughter, the radius and fifth tail vertebra were removed for further analysis. Some radii were also taken to determine the bending moment to distortion and breaking.

Trial 2
Diets 1 and 3 were each fed to 2 x 8 pigs (in 2 pens). Per diet, one pen was equipped with three railway sleepers to see what their effect was on leg weakness. Diet 7 was fed to another group of animals; in that pen there were also three railway sleepers (+ of - behind the diet number means: with or without railway sleepers resp.). The animals were of the GY-breed.
During the trial, the animals were judged for leg score three times. Just before the slaughter of five animals with locomotory disturbances, Röntgen pictures of the pelvis (ventral and dorsal), the left tarsal, carpal and radius + ulna were taken at the Department of Radiology of the Veterinary Faculty of the University of Utrecht (Dr. Van de Watering).
At slaughter, the radii of the animals from the pens with the railway sleepers were removed for further analysis.

Trial 3
Diets 3 and 7 were each fed to 2 x 8 pigs (in 2 pens). Per diet in one pen there were three railway sleepers. The diet with NH_4Cl was fed to ten pigs in one pen, eight barrows and two gilts. All animals were of the DL-breed. The animals that received the diet with NH_4Cl had water freely at their disposal. During the experiment, all animals were judged for leg score three times. At slaughter, the radii were removed for further analysis except from the animals which had received NH_4Cl in the diet.

Trial 4
The diet with NH_4Cl was fed to eight GY-pigs in one pen from 32 kg onwards. Water was freely available. After 14 days, two animals were slaughtered and

the bones of the legs removed for further examination. Fourteen days later, the same was done with another two animals. The animals were slaughtered so soon because it was assumed that in the third trial the possible appearance of dyschondroplasia might later have healed, before the animals had reached slaughter weight. The bones were examined at the Department of Veterinary Pathology of the Veterinary Faculty of the University of Utrecht (Dr. Goedegebuure).

16.2.2. Results

The results of the chemical analyses are presented in Table 128 while the main results of the feeding experiments are given in Table 129.

Table 128. Mineral composition of the diets (g/kg T)

trial	diet	Ca	Mg	P	phytate P	Cl	NH_3
1	1	2.1	1.7	3.7	2.5	-	-
	3	1.9	2.3	6.6	4.8	-	-
	control	8.0	2.3	7.0	-	-	-
2	1	1.9	1.7	3.8	1.9	-	-
	3	1.5	2.4	6.3	4.2	-	-
	7	1.5	2.4	6.3	4.2	-	-
3	3	1.8	2.4	6.9	-	-	-
	7	1.8	2.4	6.9	-	-	-
	NH_4Cl	10.5	2.2	7.7	-	19.8	4.5
4	NH_4Cl	10.8	2.3	7.7	-	18.3	6.6

In trial 1, one animal which had been given diet 1 was sent to the slaughterhouse at a live weight of 74 kg because of lung bleeding. Another animal which had been given diet 3 was moved to the metabolism cage at 90 kg to replace one of the balance animals.
In trial 2, it appeared at slaughter that the kidneys of three animals receiving diets 1, 3 and 7 showed signs of earlier infections, but the growth rate of these animals did not seem to have been affected. One animal receiving diet 3+ did not grow for three weeks after it had reached 80 kg live weight and was therefore slaughtered. The films of the Röntgen exposures showed that the calcification of the bones of this animal was insufficient and, in most cases, a greater or lesser degree of epiphysiolysis was observed. While at the slaughterhouse, two of the animals had a leg fracture.
In trial 3, one barrow, which had received diet 3-, died from acute cardiac arrest four weeks after the start of the trial. One gilt, receiving the same treatment, had bad legs and a low growth rate, so it was slaughtered at 90 kg live weight. At the end of this trial, one gilt, receiving diet 3+, had a fracture at 100 kg and died from acute cardiac arrest. One gilt, receiving diet 7- and one receiving diet 3- lost body weight due to locomotory disturbances and were slaughtered at about 90 kg. At slaughter, it appeared that some joints in the legs of one animal receiving diet 7+ had been infected; this animal also scored high for locomotory disturbances. The animals receiving NH_4Cl in the diet consumed the diet slowly, drank a lot of water and urinated a great deal. No signs of dyschondroplasia were observed.
In trial 4, the growth rate and feed intake of the first animals that were

Table 130. Analyses of the radii (+ = with 3 railway sleepers per pen; - = without railway sleepers; diet 7: 3 800 instead of 1 750 IU vit.D_3/kg in diet 3
Different characters in the same row indicate significance of differences ($p < 0.05$)

trial	1					2					3						
diet	1	3	control	rsd	sign. diet	1	3	7	rsd	sign. diet	3	3	7	7	rsd	significance	
Ca (g/kg T)	2.1	1.9	8.0			1.9	1.5	1.5			1.8	1.8	1.8	1.8			
P (g/kg T)	3.7	6.6	7.0			3.8	6.3	6.3			6.9	6.9	6.9	6.9			
railway sleepers	-	-	-			+	+	+			-	+	-	+		diet	railway sleepers
n	12	13	8			8	7	7			6	7	7	8			
fresh weight (g)	50.12a	47.90a	61.89b	3.13	***	48.23	49.37	48.16	5.24	ns	46.12	48.33	47.80	50.00	5.24	ns	ns
volume (cm^3)	40.13a	38.95a	44.64b	2.72	***	38.90	40.80	38.81	4.77	ns	37.24	39.24	38.50	40.49	4.26	ns	ns
length (mm)	96.7 a	98.4 ab	101.2 b	4.5	ns	95.8	97.9	99.8	5.0	ns	94.0	95.9	94.9	96.8	3.4	ns	ns
thickness I (mm)	20.4 a	19.5 b	22.2 c	1.7	**	19.7	19.5	19.0	1.1	ns	19.2	19.2	19.6	19.7	0.8	ns	ns
thickness II (mm)	14.0 ab	13.6 a	14.4 b	0.7	ns	13.0	13.0	11.9	1.0	ns	13.0	13.4	13.2	13.6	0.7	ns	ns
fat free dm (g)	21.08a	19.86a	33.64b	1.69	***	21.61	20.18	21.23	1.90	ns	21.32	18.74	21.59	19.00	2.13	ns	**
ash (g/kg ffdm)	608.2a	589.4 b	640.6 c	11.9	***	564.6	560.5	571.5	13.5	ns	553.6	618.4	555.6	620.4	13.0	ns	***
ash (g)	12.83a	11.70b	21.55c	1.11	***	12.20	11.29	12.13	1.04	ns	11.76	11.57	12.01	11.83	1.27	ns	ns
Ca (g/kg ash)	397.2 a	397.0 a	401.4 b	4.10	*	385.0	388.7	387.7	4.06	ns	383.7	-	384.8	-	1.26	ns	-
Mg (g/kg ash)	7.63a	9.03b	6.81c	0.47	***	7.95a	10.23b	9.67c	0.53	***	9.08	-	8.63	-	0.40	ns	-
P (g/kg ash)	183.8 a	187.5 b	182.6 a	2.72	***	177.5 a	181.8 b	181.2 b	1.80	***	181.1	-	180.9	-	1.47	ns	-
Ca/P (g/g)	2.16a	2.12b	2.20c	0.03	***	2.17a	2.14b	2.14b	0.03	ns	2.12	-	2.13	-	0.02	ns	-

slaughtered were only 160 g/d and 1.13 kg/d respectively and of the second group only 207 g/d and 1.04 kg/d respectively. Examination of the bones of these animals did not reveal any sign of dyschondroplasia.

Table 129. Results of the feeding trials (+ and - = with or without three railway sleepers per pen)

trial	diet	initial weight (kg)	final weight (kg)	days in trial	growth rate (g/d)	feed conversion ratio	feed conversion ratio (EW=1.00)	feed intake (kg/d)	sequence gait score (1= best)
1	1	25	110	110	765	3.20	3.36	2.45	-
1	3	25	110	120	684	3.56	3.49	2.47	-
1	control	24	112	117	737	3.31	3.44	2.44	-
2	1-	28	112	105	802	3.01	3.16	2.42	1
2	1+	27	109	103	796	2.97	3.12	2.36	4
2	3-	28	111	110	755	3.19	3.16	2.46	2
2	3+	28	113	117	721	3.40	3.36	2.45	5
2	7+	28	109	119	682	3.52	3.48	2.46	3
3	3-	28	114	105	829	3.29	3.22	2.67	2
3	3+	27	116	114	791	3.50	3.43	2.73	4
3	7-	27	116	112	790	3.58	3.51	2.73	1
3	7+	27	118	122	752	3.55	3.48	2.68	4
3	NH_4Cl	26	99	149	535	4.04	4.08	2.16	3

The results of the analyses of the radii of trials 1, 2 and 3, those of the fifth tail vertebra and the bending moment of distorting and breaking of the radii of animals in trial 1 are presented in Tables 130, 131 and 132 respectively.

Table 131. Measurements of the fifth tail vertebra in trial 1

	diet 1	diet 3	control	rsd	sign. diet
Ca (g/kg T)	2.1	1.9	8.0		
P (g/kg T)	3.7	6.6	7.0		
n	12	13	8		
ash (g/kg fat-free T)	571.1 a	545.4 b	602.3 c	23.1	***
Ca (g/kg ash)	399.6 a	388.4 b	397.2 a	6.23	***
Mg (g/kg ash)	8.50 a	10.12 b	7.08 c	0.56	***
P (g/kg ash)	188.7 ab	189.2 a	185.2 b	3.25	*

Table 132. Influence of diet on the bending moment to distortion and breaking of radii in trial 1 (mean and sd)

	diet 1	diet 3	control
Ca (g/kg T)	2.1	1.9	8.0
P (g/kg T)	3.7	6.6	7.0
n	5	5	3
bending moment to distortion (Nm)	29.1 ± 5.3	26.8 ± 8.1	56.0 ± 4.7
bending moment to breaking (Nm)	31.3 ± 4.4	32.6 ± 8.6	60.8 ± 6.0

The results in Table 130 clearly show that in the first trial the control diet (8.0 and 7.0 g Ca and P resp./kg T) resulted in a higher amount of fat-free T of the radius and a higher concentration of ash in the fat-free T than those from animals on diets with a low calcium and available phosphorus concentration (2.0 g Ca/kg T). The concentration of calcium and phosphorus in the ash is somewhat different; that of magnesium can be explained by its higher concentration in diet 3. The radii of animals receiving a diet that contained 1.9 g Ca and 6.6 g P/kg T were less mineralized than those on a diet containing 2.1 g Ca and 3.7 g P/kg T; this was also the case with the fifth tail vertebrae (Table 131). The results given in Table 132 show, as expected, the greater strength of the bones of pigs fed the control diet.
In the second trial there were hardly any differences in bone measurements between the three diets. No significant positive effect of the vitamin D_3 concentration in the diet (3 800 vs 1 750 IU vitamin D_3/kg diet) could be demonstrated, although there was a tendency towards a higher concentration of ash and amount of ash in the radius (Table 130).
In the third trial again no significant differences but the same tendency as in the second trial could be detected in bone measurements as a result of an increased (3 800 vs 1 750 IU/kg) vitamin D_3 concentration of the diet.

16.2.3. Discussion

The results of the feeding trials clearly show that despite very low concentrations of calcium and phosphorus in the diet a reasonable growth rate can be obtained. Also, in general, no severe signs of leg weakness in the animals were observed although the calcification was poor and insufficient and a fracture occurred in two animals at the slaughterhouse, probably due to fighting. In one animal, a fracture was observed at 100 kg.
Infection of the kidney was also found by Libal et al. (1969) in some pigs when an extreme Ca/P ratio in the diet was present.
In the absence of railway sleepers, the score for gait was better than when they were present. This confirms the general idea that obstacles in the pen lead to more leg weakness in pigs (Stevens, 1975). Why the railway sleepers in trial 3 led to a higher ash concentration in the fat-free T of the radius is not known. In fact, the amount of fat-free T of the radii was lower with railway sleepers so that the total amount of ash in the radii of animals in pens with or without the railway sleepers was about the same (Table 130).

Extra vitamin D gave no more calcification of the bones, which is not so surprising because of the lack of calcium in the diet; therefore we performed experiment 2 to overcome this problem (section 16.3.). In trial 3 there was a small interaction between diet and railway sleepers for the fresh weight and volume of the radius. No explanation for this can be given.
The results given in Table 130 show that the ash concentration of the fat-free T of the radius is not the same on the same diet in the three trials. This means that one must be careful when comparing results from different experiments.

16.3. EFFECT OF EXTRA VITAMIN D IN THE DIET ON THE ABSORPTION AND RETENTION OF PHOSPHORUS AND ON BONE MINERALIZATION: EXPERIMENT 2

16.3.1. Materials and methods

The basal diet for this experiment (Table 133) was composed in such a way that a rather high phytate phosphorus concentration was obtained. No inorganic phosphorus was added. To the basal diet (diet A = control) the usual amount of vitamin D was added (2 000 IU/kg), while extra amounts of vitamin D were added when composing diets B and C (in total 14 500 and 27 000 IU vitamin D/kg diet resp.). The vitamin D_3 preparation was bought from BASF, Ludwigshafen, GFR.
On the basis of the calcium and phosphorus concentrations of the ingredients, 11.5 g limestone per kg diet was added to obtain a Ca/P ratio in the diet of about 1.3:1. The diets were made in one batch, pelleted, and stored at 4°C.
In this experiment, 36 pigs (boars and gilts) of the pure GY-breed were used. At a live weight of about 22 kg, blocks were formed of three, and in some cases two pigs, on the basis of sex, litter and live weight. The three treatments were allocated to the pigs within a block by chance. From 22 to 35 kg a commercial pig starter was offered after which time the experimental diets were fed. All pigs were fed restrictedly twice a day on the basis of their live weight.

Table 133. Composition of the diets (g/kg)

diet	A	B	C
hominy feed USA	110	110	110
cane molasses	40	40	40
tapioca chips	254	254	254
soybean meal solv. extr. (50%)	155	155	155
wheat middlings	155	155	155
animal fat	20	20	20
linseed expeller	150	150	150
maize	100	100	100
minerals + vitamins (total)	16	16	16
- limestone	11.5	11.5	1.5
- extra vitamin D_3* (mg/kg diet)	-	25	50

* 1 g contains 500 000 IU vitamin D_3.

At about 70 kg, two pairs of boars and one pair of gilts, which had received per pair diets A and C, were put on metabolism crates to determine the absorption and retention of calcium and phosphorus. Of the two animals on each diet, the digestibility of XP, XL, XF, XX and E was determined to calculate the feeding value of these diets. Due to pneumonia the gilts had such great feed refusals that they had to be replaced by one more pair of boars.
At about 100 kg live weight the pigs were slaughtered, with the restriction that pigs of the same block were slaughtered at the same time, to reduce the influence of time on the amount of mineral retention. One day before slaughter, the backfat thickness was measured ultrasonically on four places on either side of the median line.
The performances of all animals in the blocks from which the pigs were removed for the balance measurement, were calculated up to the day of removal.
After slaughter, the radius of the right leg was removed for further analysis. Because it had been found in former experiments that the concentrations of calcium and phosphorus in the ash hardly altered, we only analysed one half of the radii for calcium and phosphorus. Statistical analyses were performed by regression analysis with sex, block and vitamin D as independent variables.

16.3.2. Results and discussion

16.3.2.1. The balance experiment

The results of the chemical analyses of the diets and the feeding value are given in Table 134.

Table 134. Chemical composition and feeding value of the diets

diet	A	B	C
vitamin D_3 (IU/kg)	2 000	14 500	27 000
T (g/kg)	894	896	893
O (g/kg T)	939	940	940
XP "	208	205	207
XL "	54	53	54
XF "	55	54	54
DXP "	170	170	170
NE_f (calc.;MJ/kg T)	10.55	10.55	10.55
Ca (g/kg T)	7.1	7.1	7.1
Mg "	3.0	3.0	3.0
P "	6.0	6.0	6.0
phytate P (g/kg T)	4.3	4.2	4.2

A summary of the results of the balance experiment is given in Table 135.

Table 135. Summarized results of the balance experiment (df=4)

	diet A	diet C	sed	sign.
vitamin D_3 (IU/kg)	2 000	27 000		ns
d_T (%)	82.3	81.9	0.8	ns
absorption % of Ca	37.8	35.2	5.9	ns
absorption % of P	33.0	32.1	2.3	ns
retention % of Ca	35.4	32.9	4.5	ns
retention % of P	31.4	29.4	3.6	ns
retention of Ca (g/d)	5.3	4.7	0.54	ns
retention of P (g/d)	3.7	3.5	0.38	ns

From Table 135 it can be seen that there was no positive effect of the high vitamin D level on the absorption and retention of calcium and phosphorus. It is not probable that toxic levels of vitamin D_3 were fed, because it was concluded in the literature review (Chapter 1.4.4.8.) that 200 000 IU vitamin D_3/kg diet is toxic for pigs. There were for all variables in Table 134 no statistically significant differences.

16.3.2.2. The feeding experiment

The performance of the animals in the feeding experiment is given in Table 136. It should be noted that in two blocks, two animals on diet B were not slaughtered at the same time as the other animals in the block, because of rather poor performance. This block was therefore divided into two sub blocks.

Table 136. Performance of the animals

diet	A	B	C	rsd	sign.
vitamin D_3 (IU/kg)	2 000	14 500	27 000		
number of animals	12	12	12	-	
initial weight (kg)	31.8	32.8	32.5	2.4	ns
final weight (kg)	92.0	97.3	90.4	7.8	ns
growth rate (g/d)	736	704	705	52	ns
feed conversion ratio	2.61 a	2.78 b	2.71 ab	0.19	*
feed intake (kg/d)	1.92	1.90	1.90	0.10	ns
days in experiment	82	85	82	3.2	ns
backfat thickness (mm)	10.8	11.2	10.5	-	-
dressing %	76.2	75.8	76.3	0.8	ns

Statistical analysis showed no significant difference of the parameters mentioned in Table 136 between the treatments except for the feed conversion ratio, which was better on diet A (2 000 IU vitamin D_3/kg) than on the diets with enhanced vitamin D_3 concentrations.

16.3.2.3. Analyses of the radii

In Table 137, the results of the analyses of the radii of the animals are given. Because there was no difference in results between boars and gilts within a treatment the results are given as an average of both sexes. The standard error was the same between the treatments and therefore the standard error over all treatments is given. The results of Table 137 show that there was no effect of diet on the results of the measurements in the radius.

Table 137. Analyses of the radii

diet	A	B	C	rsd
vitamin D_3 in diet (IU/kg)	2 000	14 500	27 000	
n	12	12	12	
days in experiment	91.5	93.6	91.2	4.9
length (cm)	9.44	9.22	9.33	0.38
width (cm)	1.38	1.39	1.40	0.06
fresh weight (g)	52.6	51.1	51.8	3.6
volume (cm^3)	40.4	39.1	40.3	3.3
ffdm (g)	26.7	26.3	26.6	2.0
ash (g/kg ffdm)	634	634	634	8.6
ash (g)	16.9	16.6	16.9	1.35
n	6	6	6	
Ca (g/kg ash)	367	366	369	2.6
P (g/kg ash)	173	173	173	0.9
Ca (g)	6.2	6.1	6.2	0.4
P (g)	2.9	2.9	2.9	0.2
Ca/P	2.12	2.11	2.13	0.02

16.4. EFFECT OF THE PHOSPHORUS CONCENTRATION IN THE DIET ON THE PERFORMANCE OF FAST-GROWING PIGS: EXPERIMENT 3

16.4.1. Material and methods

In six feeding trials with, in total, 359 modern, fast-growing boars and gilts (mostly crossbred) from 30 to 110 kg live weight, the effect of the phosphorus concentration in the diet on performance and leg score was investigated. In each trial, different levels of phosphorus were realized by adding dicalcium phosphate to the diet in three or four steps of 0.75 g phosphorus per kg. All diets had a Ca/P ratio of about 1.3:1. There were, depending on the trial, 10 to 22 animals per treatment.
In four trials, the phosphorus concentration was changed in some treatments during the course of the trial. In four trials, the pigs were fed ad libitum; in two of these trials, a by-product-based diet was fed. In two other trials, the pigs were fed at a high level but restrictedly; a predominantly cereal and, in the other, a by-product-based diet was used.
The diets were formulated to have a NE_f and lysine concentration of at least 9.05 MJ and 8.5 g per kg respectively. All diets were pelleted and the water supply was ad libitum. All animals were fed individually; they were also housed individually in five of the six trials. The live weight and, in most cases, feed intake were recorded weekly or every two weeks.
The growth rate and feed conversion ratio from 30 to 110 kg were calculated

by means of growth and feed intake curves, which were based on orthogonal polynomials. The digestibility of several components and of phosphorus was measured in the diets without any supplementation of dicalcium phosphate. The results were analysed by analysis of variance.

16.4.2. Results

The chemical analyses and feeding values of the diets are given in Table 138. It appeared from the concomitant digestibility trials that the concentration of digestible phosphorus in the cereal- and by-product-based diets without any phosphorus supplementation was almost the same: 1.6 to 1.8 g/kg T (see also Chapter 13.4.3.: trials VV 588, VV 614, VV 680 and VV 749 respectively of Tables 97 and 98). Thus, concerning digestible phosphorus concentration, both types of diets could be compared well with each other. According to the digestibility of crude protein, crude fat, crude fibre and nitrogen-free extracts it was calculated that the mean NE_f concentration in the diets was 10.0 MJ/kg T.
From 30 to 110 kg live weight the mean growth rate (of the pigs in all treatments over all trials) was 850 g/d, the feed conversion ratio 25.39 MJ NE_f/kg live weight gain and the feed intake 2.47 kg/d. Detailed information on performance is given in Tables 139 and 140. Within a trial, there were no statistically significant differences as a result of the different phosphorus concentrations in the diet, and no interactions between the sex of the animal and the phosphorus concentration in the diet could be demonstrated. However, there was a tendency for animals in the treatment without any inorganic phosphorus supplementation to have a somewhat lower feed intake and growth rate than animals which had received diets to which 0.75 g inorganic phosphorus or more per kg was added. There was no effect of the phosphorus concentration in the diet on slaughter quality or on leg score.

16.4.3. Discussion

In the pigs receiving the diets without any supplementary inorganic phosphorus there was a tendency towards lower performance. This is mainly due to the somewhat lower feed intake. There were no differences in performance of the pigs receiving diets supplemented with 0.75 g inorganic phosphorus or more. The basal diets contained on average 1.5 g digestible phosphorus per kg diet. If it is assumed that the apparent digestibility of the phosphorus of the inorganic phosphorus source used is 80 per cent, then a concentration of $1.5 + 0.8 \times 0.75 = 2.1$ digestible phosphorus per kg diet of 8.7 MJ NE_f will be sufficient. It may be recommended, therefore, that an ordinary diet in the Netherlands with 9.05 MJ NE_f should contain 2.2 g digestible phosphorus for pigs from 30 kg live weight onwards. Further research is necessary to see whether the concentration of 2.2 g digestible phosphorus per kg diet can be lowered and what may be the effect if the starter diet contains less phosphorus than is normally used in practice.

16.5. CONCLUSIONS

The experiments in this chapter have shown that when slaughter pigs from about 30 kg live weight onwards received diets with very low concentrations of calcium or phosphorus, signs of leg weakness were not observed anymore frequently than when on diets with higher levels of these minerals. However, calcification of the bones was poor and fractures are more likely. Obstacles in the pen resulted in a worse score for gait.
The inclusion of two per cent NH_4Cl in the diet for pigs from 25 kg live weight onwards did not lead to dyschondroplasia, in contrast to such an inclusion demonstrated in broiler chickens.

Table 138. Chemical analyses of the diets in feeding experiment 3 (g/kg T), and feeding value DXP (g/kg T), NE_f (MJ/kg T)

Trial and diet	T in fresh	A	XP	XL	XF	Ca	Mg	P total	phytate P	inorganic P[1]	digestible P	DXP	NE_f
1A	853	73[3]	191	39	67	5.1	2.0	4.3	2.8	1.5	1.7	157	10.27
1B	850	-	-	-	-	6.3	2.0	5.0	2.8	2.2	-	-	-
1C	855	-	-	-	-	7.6	2.0	6.1	2.8	3.3	-	-	-
1D	851	-	-	-	-	8.3	2.0	6.8	2.8	4.0	-	-	-
2A	869	-	-	-	-	5.3	2.2	4.5	2.7	1.8	-	-	-
2B	871	-	-	-	-	6.2	2.1	5.3	2.7	2.6	-	-	-
2C	868	64	187	31	79	7.3	2.1	6.1	2.7	3.4	-	147	9.53
2D	862	-	-	-	-	8.7	2.1	6.8	2.7	4.1	-	-	-
3A	860	76	204	45	72	7.0	2.5	5.1	3.2	1.8	1.8	168	10.07
3B	860	-	-	-	-	7.8	2.6	5.7	3.2	2.5	-	-	-
3C	860	-	-	-	-	8.6	2.6	6.6	3.2	3.4	-	-	-
4A	866	65	195	30	58	7.3	2.2	5.8	3.2	2.6	-	165[2]	10.36[2]
4B	869	69	193	30	62	8.4	2.2	6.8	3.2	3.6	-	-	-
5A	875	70	226	42	74	7.3	2.9	5.9	4.0	1.9	1.6	171	9.60
5B	879	-	-	-	-	8.2	2.8	6.4	4.0	2.4	-	-	-
5C	882	-	212	-	-	9.2	2.8	7.3	4.0	3.4	-	-	-
6A	871	75	205	62	75	7.7	2.7	5.6	3.7	1.9	1.7	160	10.19
6B	872	79	206	61	72	8.5	2.7	6.4	3.7	2.7	-	-	-
6C	870	82	198	62	72	9.9	2.6	7.1	3.7	3.4	-	-	-
2starter	875	69	239	30	48	10.1	1.8	7.8	-	-	-	-	-
3starter	891	66	205	31	-	9.9	1.8	7.9	-	-	-	-	-
4starter	866	73	186	23	45	9.8	3.2	7.3	-	-	-	-	-
6starter	878	68	182	39	34	11.1	1.6	7.3	-	-	-	-	-

1= inorganic P = total P minus phytate P

2= estimated values from the Feeding Table (C.V.B., 1977)

3= is not determined

Table 139. Performance on cereal-based diets in feeding experiment 3

Trial	1						2						3		
level of feeding	ad libitum						ad libitum						restricted		
treatment	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3
added P to diet (g/kg)	0	0.75	1.50	2.25/ 0.75[B]	1.50	1.50/ 0.75	0	0.75	1.50	2.25/ 0.75	1.50/ 0.75	1.50/ 0.75	0.85	1.70	1.70/ 0.85
P concentration in diet (g/kg T)	4.3	5.0	6.1	6.8/ 5.0	6.1/ 4.3	6.1/ 5.0	4.5	5.3	6.1	6.8/ 5.3	6.1/ 4.5	6.1/ 5.3	5.8	6.8	6.8/ 5.8
number of animals	12	9	10	10	11	10	10	8	10	10	12	10	21	22	20
initial weight (kg)	31.5	29.8	30.8	32.0	30.0	31.4	30.3	30.9	30.5	30.4	30.9	31.0	29.5	29.6	29.7
final weight (kg)*	110.0	112.8	111.2	113.3	113.1	112.8	109.5	114.0	113.9	113.5	111.9	113.6	109.2A	108.6A	109.4A
growth rate (g/d)	874	987	932	921	907	915	882	910	904	937	912	937	823	832	819
feed conversion ratio (8.79 MJ NE_f/kg growth)	2.96	2.96	2.92	2.98	2.93	2.92	2.75	2.81	2.72	2.70	2.62	2.70	3.03	3.00	3.08
feed intake (kg diet/d)	2.58	2.86	2.72	2.76	2.66	2.68	2.55	2.67	2.60	2.68	2.52	2.66	2.45	2.45	2.47
backfat thickness (mm)	22.6	23.1	22.5	23.6	23.2	24.0	25.7	26.1	26.5	25.4	23.3	25.5	25.0	25.3	26.3
mean classification	0.77	0.75	0.77	0.77	0.75	0.80	0.80	0.77	0.75	0.73	0.77	0.78	0.71	0.75	0.71
% EAA + 1 A	75	89	100	100	82	80	70	88	70	50	100	80	90	95	80
dressing %	-	-	-	-	-	-	-	-	-	-	-	-	78.5W	78.3W	78.6W
number of animals taken out of experiment	0	1	0	0	1	0	2	2	0	0	0	0	1	0	0

* cold slaughter weight x 1.3

A = delivery weight

W = based on warm slaughter weight

B = 2.25 g/kg to 55 kg live weight, 0.75 g/kg thereafter

Table 140. Performance on by-product based diets in feeding experiment 3

trial	3				5			6		
level of feeding	ad libitum				restricted			ad libitum		
treatment	1	2	3	4	1	2	3	1	2	3
added P to diet (g/kg)	0	0.75	1.50/0.75	1.50	0	0.75	1.50	0	0.75	1.50
P concentration in diet (g/kg T)	5.1	5.7	6.6/5.7	6.6	5.9	6.4	7.3	5.6	6.4	7.1
number of animals	18	15	14	14	13	13	13	20	20	22
initial weight (kg)	31.3	32.3	30.8	31.2	28.8	28.2	28.2	36.0	36.8	36.0
final weight (kg)	109.0*	109.0*	110.6*	107.4*	101.5A	102.4A	102.6A	106.9A	106.8A	107.3A
growth rate (g/d)	807	854	901	846	745	740	769	826	823	824
feed conversion ratio (8.79 MJ NE_f/kg growth)	3.01	3.01	3.01	2.99	2.73	2.82	2.67	2.90	2.90	2.88
feed intake (kg diet/d)	2.46	2.60	2.67	2.56	2.10	2.11	2.09	2.34	2.38	2.34
backfat thickness (mm)	22.0	24.5	22.1	22.7	-	-	-	12.4US	12.8US	12.1US
mean classification	0.85	0.78	0.83	0.82	0.86	0.75	0.79	0.75	0.81	0.81
% EAA + IA	89	100	86	86	100	100	100	90	95	95
dressing %	-	-	-	-	72.1K	71.7K	71.8K	76.9W	77.0W	77.3W
number of animals taken out of the trial	0	3	0	0	0	0	0	0	2	0

* = cold slaughter weight x 1.3
A = delivery weight
US = ultra sonic backfat thickness
K = based on cold slaughter weight
W = based on warm slaughter weight

Adding 12 500 or 25 000 IU vitamin D_3 per kg to a diet containing 2 000 IU per kg which was rich in phytate phosphorus did not affect the absorption and retention of phosphorus or bone mineralization.

Diets with 1.5 g digestible phosphorus per kg tended to lead to a lower feed intake of pigs from 30 kg live weight onwards; therefore, a tendency towards lower growth rates was also observed. Improvements in performance were found at levels of 2.1 g digestible phosphorus per kg diet containing 8.70 MJ NE_f, but no further increase above this level.

17. SOME CALCULATIONS ON THE WHOLE MATERIAL

17.1. INTRODUCTION

In this chapter, some aspects will be presented which could not be incorporated well in the preceeding chapters. It concerns calculations performed on data from many or all experiments together.
For calculations on the surplus of phosphorus in pig slurry per hectare of land, the concentration of phosphorus in the mixed diet will probably be the deciding factor. So for the controlling organization it is important to know whether the concentration of phosphorus in the diet is indeed lower than the normal level, in order to give a bonus to the farmer. Therefore, the standard error of sampling and the analytical error of phosphorus in mixed diets was calculated.
Next the course of the absorption and retention percentages and of their retentions was calculated from 30 to 110 kg live weight, as were factors which affected this course. Furthermore, the correlation was calculated between the digestibility of dry matter of the mixed diets and the absorption percentages of phosphorus and calcium and their relation with growth rate to find out whether they could be used as covariables to reduce the variance.
Finally, it was evaluated whether the radius or fifth tail vertebra could be used as reference bones for evaluating whether mineral supply meets the mineral requirement of the pig or not (see also Chapter 2.8.4.).

17.2. SAMPLING AND ANALYTICAL ERRORS WHILE ASSESSING PHOSPHORUS AND CALCIUM CONCENTRATIONS IN MIXED FEEDS

17.2.1. The errors of sampling and analysis

From all mixed feeds used in the experiments described in this thesis the error of sampling could be calculated for 120 different diets; 33 of these diets contained no added inorganic phosphorus. The number of samples taken from the same batch of diets varied from 2 to 13 samples (Table 141).

Table 141. Number of samples taken from the same batch of different mixed feeds

number of samples	1	2	3	4	5	6	7	8	9	10	11	12	13
number of diets	4	16	22	20	6	23	6	10	9	1	-	1	2

The size of the analytical error was calculated from duplicate or triplicate analyses of phosphorus and calcium in the dry matter of the same sample of mixed diets. For phosphorus, the results of 93 duplicates and 7 triplicates were available and for calcium 100 and 5 respectively. Duplicates and triplicates were not always done by the same analyst, but always in separate series. By means of analysis of variance estimations for the various components were calculated.
The standard deviations of the analytical error for phosphorus and calcium in the diets were 0.13 and 0.26 g/kg dry matter respectively. These values are low and for practical mixed diets for growing pigs with a dietary phosphorus and calcium concentration in the dry matter of about 6.6 and 8.5 g/kg dry matter a coefficient of variation of 2.0 and 3.1 per cent can be calculated.
The standard deviations of the errors of sampling for phosphorus and calcium of all diets were 0.11 and 0.07 g/kg dry matter respectively. For phosphorus, the errors of sampling were significantly higher ($p < 0.001$) in the diets with supplementary inorganic phosphorus. The standard deviations

of the errors of sampling for diets whether or not they were supplemented with inorganic phosphorus were 0.12 and 0.07 g/kg T respectively for phosphorus. Because the diets for our experiments were more thoroughly mixed in the factory than is usual in practice it can be assumed that the error of the calcium and phosphorus concentrations of practical diets estimated from the analysis of one sample will be higher, but by how much is not known.

17.2.2. Discussion

In a study between 40 laboratories it was shown that for a sample of alfalfa (2.8 g P and 22.7 g Ca/kg T) the standard deviations of analyses for phosphorus and calcium were 0.17 and 1.16 g respectively, and for a sample of mixed feed (7.7 g P and 40.2 g Ca/kg T) these were 0.45 and 2.05 g respectively (I.A.G., 1986). These standard deviations of analysis are much higher than the ones found in our study, possibly caused by different analytical methods applied.
When the results of the errors of sampling and analysis are taken together the standard deviations of both for calcium and phosphorus concentrations in one sample of a diet with supplementary inorganic phosphorus are 0.27 and 0.18 g/kg T respectively. This means that when in practice the analytical error of the concentration of phosphorus is the same as the one we found, and the error of sampling is 1.5 times the value found for diets supplemented with inorganic phosphorus, then the standard deviation of both errors together in practice for phosphorus is 0.24 g/kg T.

17.3. CHANGES IN ABSORPTION AND RETENTION OF PHOSPHORUS AND CALCIUM FROM 30 TO 110 KG LIVE WEIGHT

Using the data obtained in the balance experiments some additional calculations were performed to obtain some information on changes in the absorption and retention of phosphorus and calcium from 30 to 110 kg live weight. This was done by means of regression analysis.
First for each animal, three or four measurements of which were available from 30 to 110 kg live weight, absorption and retention percentages and retention of phosphorus and calcium were regressed on live weight. Then a model was fitted with the following independent variables: the experiment, the concentration of calcium and phosphorus in the diet, the mean growth rate of the animal during the experiment (from ± 25 kg to slaughter) and the level of energy intake (as MJ $NE_f/W^{0.75}$).
For the calculations, total phosphorus concentration varied from 0.37 to 0.80 per cent and calcium from 0.20 to 1.01 per cent in the dietary dry matter. The growth rate varied from 550 to 960 g/d and the level of energy intake from 0.7 to 1.0 MJ $NE_f/W^{0.75}$. It should be remarked that the estimates are not univariate, because the material is not homogeneous; for instance, in most cases a high concentration of dietary calcium was also associated with a high concentration of phosphorus. Therefore, the estimates indicate only a tendency.
The results of the calculations are given in Table 142. As an example, the value of -4.2 for the absorption percentage of phosphorus means that when the calcium concentration in the diet increases by one per cent, the decrease in the absorption percentage of phosphorus per 10 kg increase in body weight is 4.2 percentage units more (see also Figure 22). It can be seen from Table 142 that in all cases a higher dietary calcium concentration significantly resulted in a greater decrease in the absorption and retention of phosphorus and calcium at higher live weights. With regard to absorption and retention of phosphorus, the concentration of phosphorus in

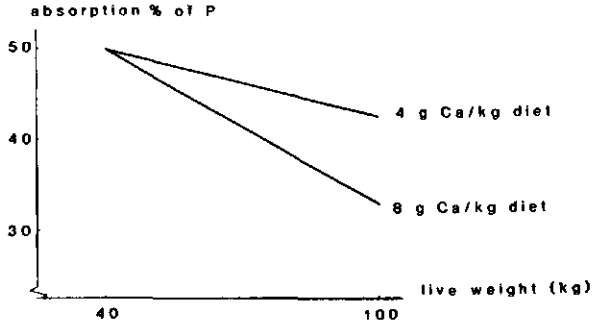

Figure 22 Schematic representation of changes of absorption % of P from 40 to 100 kg live weight as affected by the dietary Ca concentration

the diet had no significant effect on their change; estimates did not differ from zero. The R^2 of the model for absorption and retention of phosphorus was only 0.29, while that for calcium was 0.46.
Although not significant, the growth rate had a slightly positive effect on the change of the absorption and retention of phosphorus and calcium. The level of feeding had in some cases a significant effect on the rate of decrease with live weight, but its relevance is minor, because the levels of feeding varied only from 0.7 to 1.0 $MJ/W^{0.75}$

Table 142. Effect of body weight on absorption and retention (change per 10 kg increase of body weight; n=100) For further explanation see foregoing text

	Ca (% in dietary T)		intake of NE_f ($MJ/W^{0.75}$)	
	estimate	sign.	estimate	sign.
absorption % of P	- 4.2	***	-	-
retention % of P	- 4.5	***	-	-
retention of P (g/d)	-	-	-	-
absorption % of Ca	-10.4	***	-1.4	*
retention % of Ca	-12.2	***	-1.9	**
retention of Ca (g/d)	-0.5	*	-0.2	*

17.4. CORRELATIONS OF DIGESTIBILITY OF DRY MATTER AND GROWTH RATE WITH THE ABSORPTION PERCENTAGES OF PHOSPHORUS AND CALCIUM

Using all observations of the balance trials, correlations between digestibility of the dietary dry matter and absorption and retention percentages of phosphorus and calcium were calculated. Using the digestibility of organic matter might be preferred to that of dry matter, but these data were available in only twenty-five per cent of the experiments. It is unlikely that the results of the calculations will be affected when digestibility of dry matter is taken because ash contents were not very high and did not vary very much. The procedure was as follows. For each diet and live weight group separately (i.e. at about 40, 70 or 100 kg) the correlation coefficients were calculated between the digestibility of the dietary dry matter and the absorption percentages of phosphorus and calcium. Next, the mean

and standard deviations of all correlation coefficients were calculated. The same procedure was followed for the growth rate during each separate balance trial. The results of the calculations are given in Table 143.

Table 143. Correlations of d_T and growth rate respectively with absorption percentages of P and Ca based on each trial with three or more observations or on the same diet

	d_T(%)				growth rate (g/d)		
	based on	mean	sd	n	mean	sd	n
absorption % of P	trial	0.52	0.60	167	0.10	0.64	150
absorption % of P	diet	0.53	0.52	99	0.14	0.55	81
absorption % of Ca	trial	0.46	0.56	167	0.18	0.64	150
absorption % of Ca	diet	0.52	0.44	99	0.16	0.55	81

The table shows a positive correlation between the digestibility of dry matter and the absorption percentages of phosphorus and calcium respectively. When based on the diet, the standard deviations are somewhat lower. Only in the experiment with piglets, in which the digestibility was based on chromic oxide and grab samples of the whole pen (Chapter 14.4), did the correlation coefficients vary slightly. In all other experiments, there was a considerable variation in the correlation coefficient. So it can be doubted whether the absorption percentages of phosphorus and calcium determined with individual animals on metabolism crates can be corrected for differences in digestibility of the dry matter because of the small number of observations. In the experiment with the piglets, for sixteen diets the mean correlation coefficient between digestibility of dry matter and the absorption percentages of phosphorus and calcium were 0.91 $\pm$ 0.13 and 0.90 $\pm$ 0.13 respectively. When the digestibility of the dry matter was used as a $a_2$covariable for estimating the absorption percentage of phosphorus, R^2 increased from 0.86 to 0.93.
The correlation coefficients between growth rate and the absorption percentages of phosphorus and calcium respectively did not differ significantly from zero. So it is unlikely that for the same diet, differences in growth rate will affect these absorption percentages.

17.5. THE RADIUS AND FIFTH TAIL VERTEBRA AS AN INDICATOR OF MINERAL SUPPLY

17.5.1. Introduction

In order to evaluate the supply of minerals, in particular phosphorus, to animals from the composition of their bones, various bones are used. The choice of bone is not an easy one and may depend on the aim of the study (see also Chapter 2.8.4.). Therefore, in some of our studies the radius or fifth tail vertebra of pigs at slaughter were removed and analysed.

17.5.2. The radius

17.5.2.1. Relationships between properties of the radius and the concentration of retainable phosphorus in the diet

In various balance experiments (trials VV 367 to VV 378: Chapter 12; VV 411 to VV 422 and VV 430 to VV 445: Chapter 13; VV 693 to VV 708: Chapter 8) and feeding experiments (Chapter 16), several measurements of the radius were made. These were fresh weight, volume, length, width, amount of fat-free dry matter, ash concentration in fat-free dry matter (ash/ffdm), and the concentrations of calcium, magnesium and phosphorus in the ash. Occasionally, breaking strength was also determined. The mean results of the measurements for all animals receiving the same diet were used for further calculations. Also, the concentration of retainable phosphorus in the diets was taken into account, although it should be remarked that this was not always measured in feeding experiment 1 (Chapter 16.2.) so that these values were then taken from earlier experiments with diets of the same feedstuff composition. The mean values and also the mean coefficient of variation of the observations of the radii are given in Table 144. The coefficient of variation was calculated first for each experiment separately, and then its mean of all experiments was calculated. The values of trials VV 566 to VV 571 were not taken into account because most of the animals were slaughtered before reaching slaughter weight of about 100 kg (Chapter 8).

Table 144. Minimum, mean and maximum values measured in the radii, and coefficient of variation (ret. P = retainable P)

	minimum	mean	maximum	CV (%)
Ca (g/kg dietary T)	1.5	4.1	9.9	-
Mg "	1.6	2.1	3.0	-
P "	3.7	5.7	8.0	-
ret. P "	1.1	1.7	2.9	-
initial live weight (kg)	18	25	32	-
final live weight (kg)	97	109	116	-
number of days in exp.	85	115	137	-
fresh weight (g)	46.1	52.9	64.3	8.4
volume (g)	37.2	41.8	48.8	9.3
length (mm)	93.3	98.4	106.1	3.7
width 1 (mm)	19.0	21.0	24.0	5.2
width 2 (mm)	11.9	13.7	15.5	5.1
fat-free T (g)	19.6	24.4	33.6	9.1
ash (g/kg ffdm)	554	610	652	1.7
ash (g)	11.3	15.0	21.6	8.8
Ca (g/kg ash)	359	382	404	0.9
Mg "	6.0	7.7	10.2	4.7
P "	169	178	188	1.0

It can be seen from Table 144 that there is a wide variation (CV up to 9 per cent) in most values mentioned except for concentration of ash in the fat-free dry matter and the concentrations of phosphorus and calcium in the ash, which have a coefficient of variation of only one or two per cent. The CV of the length and width is moderate.

When the results are compared within an experiment then at higher concentrations of calcium or retainable phosphorus in the diet calculations showed that:

a) the fresh weight, volume, amount of ffdm, ash in ffdm and amount of ash in the radius increase;
b) there is no evidence of a longer and wider radius;
c) at the same phosphorus concentration, more calcium in the diet results in a higher Ca/P ratio of the bone.

Before the results of the calculations for all experiments together are given some remarks should be made. First, the initial weight differed considerably between the experiments, which might have resulted in different weights and composition of the radii at the start of the experiments and this might have affected the values at slaughter. Second, the final weight and number of days that the animals were in the experiments differed considerably and also affect the values measured. In trials VV 367 to VV 378 for instance, it was found that when the number of days that the animals were in the experiment was taken as a covariable, this gave a significant reduction of variance in the length and volume of the radius; the same was the case with the final weight as a covariable for the width of the radius. In trial 3 of feeding experiment 1, the number of days significantly influenced the ash concentration of the ffdm. In most experiments, there was a tendency towards higher values as the number of days increased. So there are several disturbing factors affecting the relationships between mineral supply and the values measured in the radius.
Regression analyses were performed with the mean of the values of the radii per diet as a dependent variable. It appeared from these calculations that R^2 increased considerably when first corrected for the experiment. This was done in the following calculations. The main results of these calculations for all experiments together are given in Table 145.

Table 145. Relationship between mineral supply and several items of the radius (ret. P = retainable P in g/kg dietary T)

equation	rsd	R^2	n	sign.
ash (g/kg ffdm) = 570 + 23.3 ± 4.7 ret. P	7.8	0.94	25	***
ffdm (g) = -10.14 + 8.6 ± 1.0 ret. P	1.6	0.82	25	***
ash (g) = 5.07 + 5.9 ± 0.7 ret. P	1.1	0.86	25	***
fresh weight (g) = 39.1 + 8.8 ± 1.8 ret. P	2.7	0.71	20	***
volume (cm^3) = 35.8 + 3.8 ± 1.4 ret. P	2.1	0.52	20	*
ash (g) = -1.84 + 0.69 ± 0.01 ffdm (g)	0.2	0.99	25	***
ash (g/kg ffdm) = 546 + 2.6 ± 0.4 ffdm (g)	7.3	0.94	25	***
fresh weight (g) = 29.1 + 1.0 ± 0.14 ffdm (g)	2.1	0.83	20	***

It can be seen from Table 145 that there is a close linear relationship between the concentration of retainable phosphorus in the diet and amount of ffdm or ash in the radius; there is a very close relationship between amounts of ash and ffdm. At 1.4 g retainable phosphorus or less, a rather wide range is found in the concentration of ash of the ffdm (Figure 23); the same (Figure 24) is the case when the radius has less than 22.5 g ffdm. Other calculations showed a small positive effect in the amount of ffdm on width, length and volume; the correlation coefficient between fresh weight and volume was 0.95. No consequence of an effect of retainable phosphorus on the concentrations of phosphorus and calcium in the ash could be demonstrated.

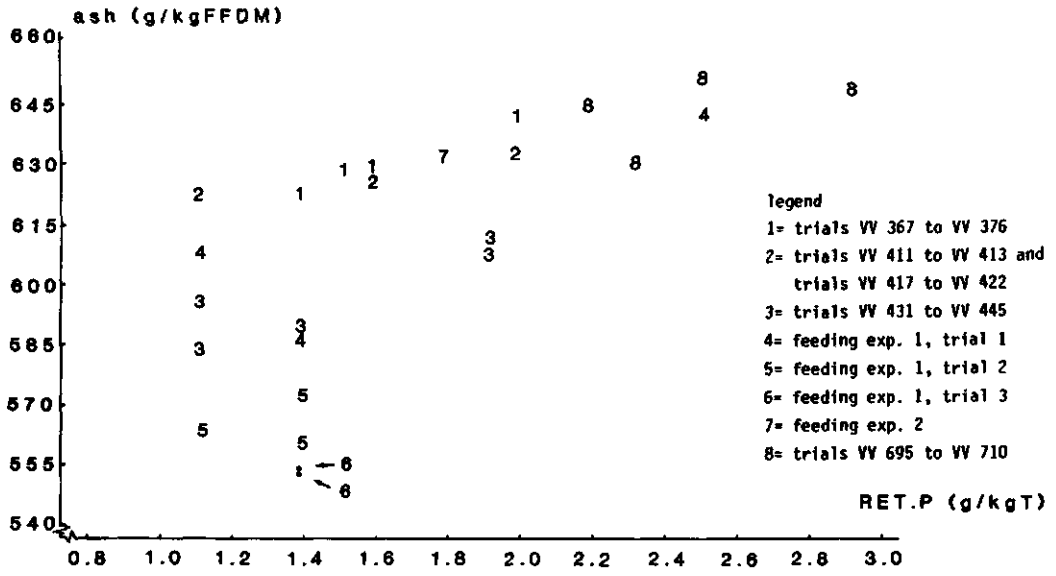

Figure 23 Relationship between dietary retainable P and ash concentration in FFDM of the radius

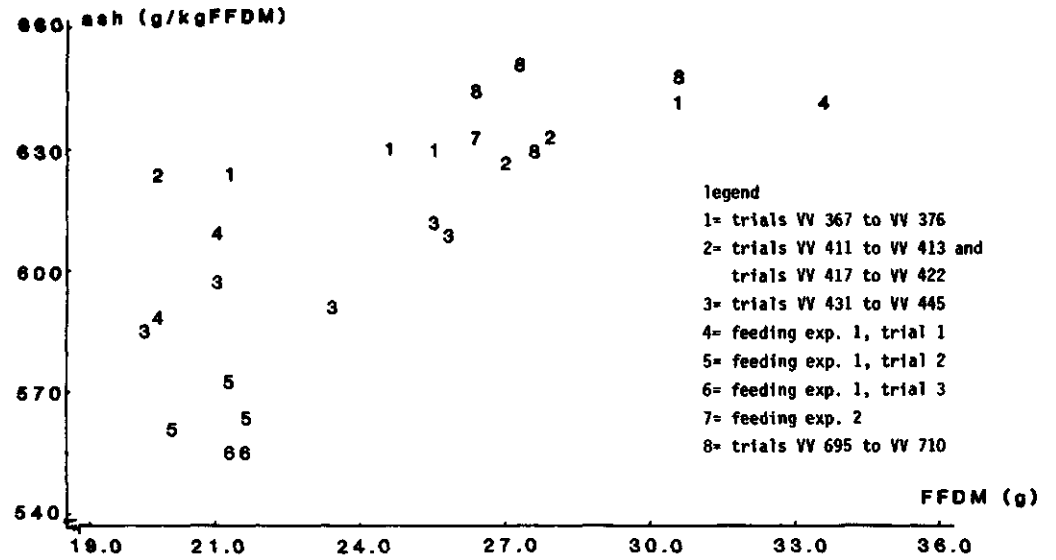

Figure 24 Relationship between amount of FFDM and its ash concentration of the radius

17.5.2.2. Relationship between amounts of ash, phosphorus and calcium in the radius and in the whole body

In two experiments, the amounts of ash, calcium and phosphorus in the radius could be compared with amounts in the whole body of the animal.
In the first experiment (for details see Chapter 8: first experiment) 26 animals were slaughtered at different live weights; the following equations could be calculated (Table 146).

Table 146. Relationship between quantities in the radius and in the whole body

equation	rsd	r	n
all animals			
total ash (g) in body = 159 + 152.5 ± 4.4 ash in radius (g)	138	0.99	26
total Ca (g) in body = 32 + 117.1 ± 3.8 Ca in radius (g)	44	0.99	26
total P (g) in body = 26 + 146.8 ± 4.1 P in radius (g)	23	0.99	26
animals more than 90 kg live weight			
total ash (g) in body = 477 + 134.7 ± 29.3 ash in radius (g)	181	0.82	12
total Ca (g) in body = 41 + 115.2 + 26.8 Ca in radius (g)	62	0.81	12
total P (g) in body = 94 + 125.9 ± 25.6 P in radius (g)	31	0.84	12

It can be seen from this table that there is a close relationship between the amount in the whole body with that in the radius when all animals are concerned. Nevertheless, the rsd's are fairly high, on average seven per cent of the mean. This relationship is less obvious when only animals of 90 kg and more are taken into account. In that case the coefficient of variation is again about seven per cent.
In the second experiment (for details see Chapter 8: fourth experiment), 15 animals were slaughtered at about 104 kg live weight. From the values obtained we got the following equations:

total ash(g) in body =1202 + 79.4 ± 22.5 ash in radius (g)	rsd =153	r =0.70
total Ca (g) in body = 311 + 70.0 ± 24.4 Ca in radius (g)	rsd = 58	r =0.62
total P (g) in body = 262 + 70.6 ± 24.2 P in radius (g)	rsd = 28	r =0.63

From these equations it is clear that the relationship is rather poor and that the residual standard deviation is of the same order as in the preceeding experiment.
It can be concluded that the amounts of ash, calcium and phosphorus in the whole body of pigs cannot be accurately estimated from the amounts found in the radius.

17.5.3. The fifth tail vertebra

In two experiments (trials VV 367 to VV 378: Chapter 12; and feeding experiment 1 trial 1: Chapter 16), besides the radius, the fifth tail vertebra was also removed and analysed in order to make a comparison between these two bones.
In the first experiment (for details see Table 77) it appeared that the ash concentration of the ffdm of the tail vertebra was on average 19 g/kg lower than that of the radius. Furthermore, the differences in ash concentration in the tail vertebra were greater between diets than those in the radius.

The correlation coefficient between the ash concentration of the radius and the fifth tail vertebra was 0.66 (n=30), and the following equation was calculated: ash (g/kg ffdm of radius) = 317 + 5.1 ± 1.1 ash (g/kg ffdm of tail vertebra); rsd = 11.
This does not show a high relationship between the two bones. Within a diet there was hardly any relationship. There were no significant correlations between the calcium and phosphorus concentrations in the ash of the radius and tail vertebra, but that of magnesium was significant (r = 0.87).
In the second experiment (Tables 130 and 131: Chapter 16),the concentration of ash of the ffdm in the radius was on average 40 g/kg higher than in the tail vertebra. Again in this experiment the differences in ash concentration in the tail vertebra tended to be greater between diets than those in the radius. This observation is in agreement with that of Friedel et al. (1973).
The relationship between these two bones was as follows: ash (g/kg ffdm radius) = 274 + 5.9 ± 0.8 ash (g/kg ffdm tail vertebra); rsd = 14 r = 0.80 n = 32. This again shows only a weak relationship between the two bones. Within the diets there were hardly any relationships. There were no significant correlations between the calcium and phosphorus concentrations in the ash of the radius and the tail vertebra but for magnesium r was 0.92.

17.6. CONCLUSIONS

Calculations regarding the errors due to sampling and analysis showed that for our experiments, with thoroughly mixed diets, the standard deviation for the phosphorus concentration in mixed diets supplemented with inorganic phosphorus was 0.18 g phosphorus per kg T.
Experiments with all diets showed no clear decrease in the absorption percentage of phosphorus at increasing live weights at a higher or lower phosphorus concentration in the diet. The higher the concentration of calcium in the diet, the more the decrease in the absorption percentage of phosphorus and calcium at increasing live weights.
A positive correlation coefficient was calculated between the digestibility of the dry matter and the absorption percentage of phosphorus. However, its variation in animals on metabolism crates was rather high and the use of the digestibility of dry matter as a covariable for each separate small experiment while estimating the absorption percentage of phosphorus cannot be recommended. Its use as a covariable for group-fed piglets looked promising, but it concerned only one experiment with sixteen diets.
It was shown that, when the amounts of ffdm or ash of the radius are used as indicators of the mineral content at slaughter weight, the residual standard deviation of the amount of phosphorus present in the body is about 30 g. Moreover, the prediction varies greatly from experiment to experiment so that it is doubtful whether differences in amounts of ash of radii between experiments supply enough information about differences in mineral supply. The fifth tail vertebra seems to be more sensitive than the radius as far as the concentration of ash in the fat-free dry matter is concerned. However, its relationship with that of the radius was not as high as expected (r = 0.66 to 0.80). The greater differences in ash concentration of the fifth tail vertebra might be explained by its more distal location in the body when compared with the radius.

Final discussion

(part three)

18. FINAL DISCUSSION

18.1. INTRODUCTION

In the preceeding chapters, the effects of diet composition and nutrient supply on the absorption and retention of phosphorus and of dietary phosphorus concentration on performance, gait score and bone mineralization have been described. In this chapter we will try to formulate the phosphorus requirements of slaughter pigs based on data from the literature and on our experiments. These requirements for phosphorus will be derived using the factorial approach for guaranteeing both an optimal and just sufficient supply of phosphorus. Requirements will be expressed as digestible phosphorus because of great differences in the digestibility of phosphorus between feedstuffs (Chapter 13). This also permits us to compare our recommended requirements with those of France and the Federal Republic of Germany who, unlike us, take faecal endogenous losses of phosphorus into account. When the phosphorus requirements of pigs are expressed in terms of digestible phosphorus, sufficient data on the content of digestible phosphorus in feeds should be available. Besides such data given in Chapter 13, results of experiments on the digestibility of phosphorus of many feedstuffs and feed phosphates, performed in 1985 and 1986, will soon be available.
The concentration of digestible phosphorus determines, to a large extent, the nutritional value of phosphorus from each feedstuff. It is only the specific effects of some feedstuffs and of compound feeds that are not covered completely in this way. These concern, amongst other things, the effects of dietary calcium concentration of added fat and of phytase-rich feedstuffs in a mixed diet.
With regard to added fat, we have seen (Chapter 10) that renderers' fats (the ones most commonly used in the Netherlands) do not affect phosphorus digestibility in a negative way. The effect of feedstuffs rich in phytase on the digestibility of phosphorus of a mixed diet is not yet precisely known, but a positive effect may be expected; this aspect needs more study. The desired level of calcium in relation to digestible phosphorus will be discussed in more detail in a separate section.

18.2. NET REQUIREMENT OF PHOSPHORUS FOR MAINTENANCE OF PIGS

The net requirement of phosphorus for maintenance includes inevitable endogenous losses of phosphorus which are excreted in the faeces and urine. Estimates for faecal endogenous losses of phosphorus were given in Chapter 2.8.2., which described how these losses depend on the supply of phosphorus in relation to the phosphorus requirement. At a low phosphorus supply (around minimal requirement), faecal endogenous loss of phosphorus was estimated to be about 5 mg/kg live weight/d but amounted to 15 mg/kg live weight/d on diets containing high levels of phosphorus (twice or more than the minimal requirement).
The amount of phosphorus excreted in the urine may not only originate from the maintenance metabolism, but may also come from production. The amount of phosphorus excreted in the urine at low dietary concentrations is low. In our experiments on pigs from 30 to 100 kg live weight (Chapters 12 and 13), the excretion of phosphorus in the urine varied from 20 to 40 mg per day on diets with a low concentration of phosphorus and a Ca/P ratio of the diet from 1.0 to 2.0. Twenty mg/d was found for pigs of 30 kg and 40 mg/d for those of 100 kg. Similar low amounts of phosphorus excreted in the urine are also quoted in several other studies (e.g. Grimbergen et al., 1985; Pointillart et al. 1985[a,b]). It is therefore surprising that some authors adopt much higher urinary losses of phosphorus; e.g. Guéguen and Perez

(1981) adopted 300 and 1 000 mg P/d for pigs of 30 and 100 kg respectively. These values might include the 'surplus' component of endogenous loss, corresponding to the excretion of phosphorus absorbed in excess of needs.

18.3. NET REQUIREMENT OF PHOSPHORUS FOR GROWTH OF PIGS

The net requirement of phosphorus for growth corresponds to the daily storage of phosphorus needed for optimal mineralization of the body weight gain. This requirement varies according to growth rate and also to the desired degree of bone mineralization. To a certain extent, the concentration of ash in the fat-free dry matter of bones of pigs increases almost linearly with the supply of phosphorus (Chapters 12, 14 and 16). With regard to slaughter pigs, it is certainly not necessary to obtain maximal mineralization. For breeding animals, which should achieve longevity, maximal mineralization of bones may be necessary.

Our calculations, using data from the literature (Chapter 4), showed that in slaughter pigs on average of 5.0 to 5.1 g phosphorus per kg live weight gain was retained. For these calculations, data were taken of animals which had received adequate concentrations of phosphorus and calcium in the diet (> 5.0 g/kg) and a Ca/P ratio of between 1.0 and 2.0. The mean concentrations of phosphorus in diets for pigs from 25 to 55 and from 56 to 110 kg live weight were 7.9 and 6.5 g/kg respectively. Also, experimental data were excluded when the growth rate was low, because of a low level of feeding (<2.5 times maintenance). Depending on the model adopted (i.e. the allometric function with only the linear, or both with the linear and the quadratic component, or the polynomial model with only the linear, or both with the linear and the quadratic component) there was a tendency at the lower live weights for somewhat more than 5.1 g phosphorus per kg body weight gain to be retained. Our experiments (Chapter 8) showed the same tendency (5.1 from 20 to 50 kg and 4.9 from 50 to 100 kg).

Although a mean figure of 5.1 g phosphorus per kg body weight gain may be adopted it may be necessary to diversify this figure. It was, for example, shown in Chapters 8 en 9 that this figure is also dependent on the composition of the weight gain. At the higher feeding level (100 versus 75 per cent of the C.V.B. feeding scheme), which almost totally resulted in a higher proportion of fat in the weight gain, the retention of phosphorus per kg weight gain decreased slightly from 5.2 to 4.9 g (Chapter 8.2). Also, at the higher energy supply (110 versus 85 per cent of the C.V.B. feeding scheme) and the same daily supply of phosphorus, which only resulted in a markedly daily increase of fat but not of protein retention, the daily phosphorus retention did not differ much (Chapter 8.4.), but the amount of phosphorus retained per kg weight gain was 4.3 and 5.2 respectively. Part of this difference can be explained by the higher supply of phosphorus per kg weight gain, but also by differences in fat retention. However, when a higher protein supply resulted in a higher protein retention, also between 0.20 to 0.30 g more phosphorus per kg gain was retained (Chapter 9.4.1.). This may also be the reason why boars or gilts retain more phosphorus per kg weight gain than barrows (Chapter 9.4.3.).

It may be clear that it is in fact necessary to know the protein and fat content of the weight gain in order to estimate the amount of phosphorus retained per kg weight gain. So, lack of knowledge concerning the composition of growth diminishes to some extent the accuracy of the estimation of the phosphorus requirement for growth of pigs. We suggest therefore diversifying the phosphorus requirement for production into one based on mean production rates and mean composition of the growth and another based on a high protein retention per kg growth.

For mean practical conditions we conclude that, based on data of slaughter experiments from the literature, those of our slaughter experiments (Chapter

8.2.) and balance experiments, the mean net requirement of phosphorus for growth (per kg live weight gain) is 5.05 g between 20 and 100 kg live weight. For animals with a leaner type of daily gain, the results of Chapters 8.2, 8.4 and 9.3 indicate that per kg live weight gain the net requirement of phosphorus for growth may be 0.2 to 0.3 g higher. Also, taking into account the increase in fat content with age, the following net requirements for growth are suggested (Table 147).

Table 147. Net requirements of P for growth (g/kg live weight gain)

	live weight (kg)				
	20	40	60	80	100
average conditions	5.15	5.10	5.05	5.00	4.95
high amount of protein in growth	5.40	5.35	5.35	5.30	5.25

In the literature, for 20 kg pigs higher retentions of phosphorus per kg growth are usually given than those presented in Table 147, but these figures are not supported by slaughter investigations. The high figures are mainly based on the work of Mudd et al. (1969[a]) and depend on a limited number of observations. The values in Table 147 for average conditions for pigs of 60 to 100 kg live weight are in agreement with those of A.R.C. (1981) but on average 0.6 g P/kg weight gain lower than given by Guéguen and Perez (1981). Our value for pigs of 40 kg live weight are 0.9 g P/kg lower than given by A.R.C. (1981) and Guéguen and Perez (1981). However, our calculations from data in the literature (Chapter 4) and those of our slaughter and balance experiments do not support the higher values given by these authors.

18.4. CALCULATIONS OF OPTIMAL REQUIREMENTS FOR DIGESTIBLE PHOSPHORUS OF SLAUGHTER PIGS

The data on the phosphorus requirement for maintenance and growth as presented in the preceeding sections allow us to estimate the phosphorus requirement of slaughter pigs from 20 to 110 kg live weight. As the requirement depends on the type of production (conventional or lean pigs) two cases are worked out. The first case is based on the current Dutch C.V.B. feeding scheme for a mean growth rate of 750 g/d and a feed conversion ratio of 3.1 (C.V.B., 1983). For the present calculations, this scheme has been changed somewhat because the feed intake from 80 kg live weight onwards, assumed according to this scheme, is too high. Therefore, the maximum feed intake was reduced from 3.3 to 3.1 kg/d. Because the growth rate was held the same in this scheme, the feed conversion ratio improved from 3.1 to 3.0. The second case concerns a very lean production with a mean growth rate of 900 g/d and a feed conversion ratio of 2.5. Such extremely good performances were, for instance, achieved in feeding trials on boars receiving diets with a high concentration of protein/lysine (Lenis and Metz, 1983). For this case, the higher retention of phosphorus per kg growth was adopted (Table 147). With regard to the endogenous losses of phosphorus, we assumed that these are twice the amount estimated in section 18.2., because the values presented there are minimal, and under more practical dietary phosphorus levels the endogenous losses are higher (Chapter 2.8.2.). Losses of phosphorus associated with growth are assumed to be included in endogenous losses of phosphorus.
The requirements are expressed in terms of apparently digestible phosphorus and not in truly digestible phosphorus. This is done because data on apparent digestibility of phosphorus of many feedstuffs and feed phosphates,

Table 148. Recommendations of apparent digestible P for slaughter pigs to achieve a high degree of bone mineralization

	C.V.B. scheme for mean growth rate = 750 g/d; FCR*=3.0						Scheme for mean growth rate = 900 g/d; FCR = 2.5					
live weight range (kg)	growth (g/d)	requirement (gP/d) maintenance[a]	growth[b]	total feed intake (gP/d)	(kg/d)	in feed[d] (g dig P/kg)	growth (g/d)	requirement (gP/d) maintenance[a]	growth[c]	total feed intake (gP/d)	(kg/d)	in feed (g dig P/kg)
20 to 30	495	0.29	2.54	2.83	1.1	2.6	595	0.29	3.20	3.49	1.1	3.2
30 to 40	620	0.40	3.17	3.57	1.5	2.4	745	0.40	4.00	4.40	1.5	2.9
40 to 50	725	0.50	3.69	4.19	1.9	2.2	870	0.50	4.65	5.15	1.9	2.7
50 to 60	805	0.60	4.08	4.68	2.3	2.0	965	0.60	5.17	5.77	2.3	2.5
60 to 70	855	0.71	4.31	5.02	2.65	1.9	1025	0.71	5.47	6.18	2.65	2.3
70 to 80	885	0.82	4.44	5.26	2.9	1.8	1060	0.82	5.63	6.45	2.9	2.2
80 to 90	890	0.92	4.44	5.36	3.0	1.8	1070	0.92	5.66	6.58	3.0	2.2
90 to 100	870	1.03	4.32	5.35	3.05	1.8	1045	1.03	5.50	6.53	3.05	2.1
100 to 110	825	1.13	4.07	5.20	3.10	1.7	990	1.13	5.18	6.31	3.10	2.0

* FCR = feed conversion ratio

a) because measurements on digestible P (dig P) are based on low P diets, the maintenance requirement for P is doubled.

b) based on mean conditions (Table 147)

c) based on a high amount of protein in growth (Table 147)

d) feed contains 9.05 MJ NE_f/kg

collected in 1985 and 1986, will be available soon. Moreover, accurate measurement of true digestibility is much more difficult than apparent digestibility.

The results of the calculations on the phosphorus requirement of slaughter pigs are presented in Table 148. This table shows that there is a gradual decrease in the concentration of digestible phosphorus in the diet at increasing live weights. The concentration of digestible phosphorus in diets for pigs with a high protein retention is on average 0.4 to 0.5 g/kg higher than for pigs with a mean growth rate of 750 g/d and a feed conversion ratio of 3.0. When our recommendations for digestible phosphorus are compared with those of other countries, which are based on available phosphorus (Table 18), we should first consider the following. It can be assumed that, at a faecal endogenous loss of 10 mg/kg live weight, the concentration of available phosphorus is on average 0.25 g/kg higher than that of digestible phosphorus. Furthermore, our recommendations are based on a NE_f concentration of 9.05 MJ/kg (=12.93 MJ ME/kg) and those of Table 18 on 12.55 MJ ME/kg. To compare the recommendations at the same level of dietary ME content (12.55 MJ ME/kg), then our recommendations must be divided by 1.03. Thus 2.0 g digestible phosphorus per kg at 12.93 MJ ME/kg are equivalent to 1.94 g digestible phosphorus per kg at 12.55 MJ ME/kg. So, for a fair comparison of our recommendations with those of Table 18 our values should be reduced by 0.20 g/kg. The recommendations of France and the German Federal Republic are based on a mean growth rate from 20 to 100 kg live weight of 750 and 740 g/d respectively and so apply to the average conditions of Table 147.

Based on these considerations we conclude that our values for the lean pigs are on average 0.1 g/kg lower than those of France, but 0.6 g/kg higher than those of the German Federal Republic. Our recommendations for pigs with a mean growth rate of 750 g/d and a feed conversion ratio of 3.0 are 0.5 g/kg lower and 0.2 g/kg higher than those of France and the German Federal Republic, respectively. So it is clear that the recommendations of France are higher than ours, mainly due to differences between 25 and 50 kg live weight, but that those of the German Federal Republic are lower than our recommended values.

In practice, the daily feed intake of pigs at the same live weight, as well as the growth rate, may deviate considerably from the values given in Table 148, reason to discuss this in more detail. When the feed intake is lower than that indicated in Table 148 and also results in a lower growth rate, then proportionally more feed (energy) is required for maintenance. Because the net requirement of phosphorus for maintenance is much lower than for growth, then the recommended values will certainly be sufficient, despite the fact that somewhat more phosphorus is retained per kg growth (higher protein content). When a lower feed intake results in the same growth rate, the feed conversion ratio is more favourable and less phosphorus is supplied per kg gain. In this case, the concentration of digestible phosphorus should be raised. This is actually demonstrated in Table 148 when the left part (feed conversion ratio of 3.0) is compared with the right part (feed conversion ratio of 2.5).

When the feed intake is higher than that indicated in Table 148 and results only in more fat retention and a slightly higher growth rate, then the concentration of digestible phosphorus in the diet can be somewhat lower (Chapter 8). When the feed intake is higher, resulting in a higher growth rate which is mainly due to protein retention, then a higher concentration of digestible phosphorus is necessary. This is actually represented in the right part of Table 148, where the amount of phosphorus per kg growth was raised (Table 147) and the feed conversion ratio is 2.5 instead of 3.0.

The concentrations of digestible phosphorus in the diets are based on a NE_f content of 9.05 MJ/kg so that at higher or lower NE_f concentrations in the

diets, not only the protein concentrations, but also the concentrations of digestible phosphorus must be corrected in proportion.
The dietary concentrations of digestible phosphorus as presented in Table 148 can be regarded as safe because a high degree of bone mineralization is achieved. Moreover, the losses of endogenous phosphorus were assumed to be at least twice as high as can be expected in the trials used for determining of the digestibility of phosphorus of feedstuffs. In the next section, we will discuss whether lower concentrations of digestible phosphorus are possible for slaughter pigs.

18.5. THE REQUIREMENT OF DIGESTIBLE PHOSPHORUS THAT IS JUST SUFFICIENT FOR SLAUGHTER PIGS

In Chapter 16 we have seen that low dietary concentrations of phosphorus did not increase the incidence of leg weakness when compared to a higher concentration; the same was observed in the literature (Chapter 5.5). Furthermore, it was found in Chapter 16, that the performance of slaughter pigs was hardly improved when a diet with 1.5 g digestible phosphorus + 0.75 g phosphorus from dicalcium phosphate per kg diet was compared with 1.5 g digestible phosphorus per kg diet. It was concluded in Chapter 16 that 2.2 g digestible phosphorus/kg diet containing 9.05 MJ NE_f is sufficient for slaughter pigs from 30 kg live weight onwards. Calculations using these feeding trials indicate that on the diets with 1.5 g digestible phosphorus/kg diet for all animals, on average 4.35 g digestible phosphorus per kg live weight increase was offered, while for the boars this amount was 4.14 g. These boars had a mean growth rate of 882 g/d and a feed conversion ratio of 2.66 for diets of 9.05 MJ NE_f/kg. Recent feeding trials at the I.V.V.O. institute indicate that from 41 to 110 kg live weight the performance of boars fed either 1.4 g or 2.1 g digestible phosphorus per kg diet were the same. On these diets (9.49 MJ NE_f/kg), the mean growth rate was 870 g/d and the mean feed conversion ratio was 2.8. This means that boars on the diet with 1.4 g digestible phosphorus/kg, received 3.9 g digestible phosphorus per kg weight increase.
The results of all our feeding trials suggest that with regard to growth rate and feed conversion ratio the concentration of digestible phosphorus in diets for slaughter pigs can be lower than those presented in Table 148 without having a negative effect on performance.
Another aspect which has to be discussed is whether a high degree of bone mineralization is necessary or not for slaughter pigs. It is well known that for optimal animal performance the high level of phosphorus required for maximal, or a high degree, of bone mineralization is not needed. It is our view that when optimal performance and a good score for gait is achieved, maximal or a high degree of bone mineralization is not necessary for slaughter pigs. The amounts of phosphorus needed per kg growth (Table 148) were based on experiments with high dietary concentrations of phosphorus so that it may be assumed that almost maximal bone mineralization was achieved. So, a choice must be made with regard to the amount of phosphorus per kg growth that is desirable.
Our feeding experiments (Chapter 16) indicate that even for boars with a mean growth rate of 882 g/d from 30 to 108 kg, 4.1 g digestible phosphorus offered per kg growth was almost sufficient, and recent experiments have shown that for boars from 41 kg onwards, 3.9 g digestible phosphorus offered per kg growth seemed to be sufficient. Therefore, it can be concluded that the phosphorus requirement for growth can be lower than that presented in Table 147. How much lower is not yet precisely known, but based on the same feeding trials it may be suggested that the net phosphorus requirements for growth per kg live weight from 50 kg onwards can be reduced by 0.5 g. The live weight of 50 kg is chosen because the

most intensive bone formation and mineralization occurs below 50 kg as can be concluded from the literature data and the results of Chapter 8.2. (Figure 16).
Another motive for lowering the estimate of phosphorus requirement to be recommended is to decrease our estimate of phosphorus required for maintenance. In our studies to determine the (apparent) digestibility of phosphorus, faecal endogenous losses are already included. Nevertheless, for the calculations presented in Table 148, we assumed 10 mg endogenous phosphorus loss in the faeces per kg live weight. Because of uncertainties about endogenous phosphorus losses, for safety reasons, we prefer not to reduce the correction of 10 mg to zero, but to 5 mg/kg/d. Furthermore, the loss of phosphorus in the urine can be taken as such and has not to be doubled, because a safety margin is already included in the faecal endogenous loss.
In Table 149 the results are presented of estimations of the phosphorus requirement of slaughter pigs based on an endogenous faecal loss of phosphorus of 5 mg per kg live weight, and a loss of phosphorus in the urine which increases from 20 mg/d at 20 kg live weight to 40 mg/d at 100 kg live weight and on a net phosphorus requirement for growth after 50 kg live weight which is 0.5 g less than adopted in Table 147 for a high level of bone mineralization. The requirements and recommendations of digestible phosphorus in the diets, as presented in Table 149, can be regarded as minimal recommendations for slaughter pigs. The recommendations in Table 149 for lean growth are on average 0.4 g/kg higher than those in the German Federal Republic but 0.3 g/kg lower than those in France. Our recommendations for a mean growth rate of 750 g/d and a feed conversion ratio of 3.0 are on average 0.8 and 0.1 g/kg lower than those in France and the German Federal Republic, respectively.

18.6. THE DESIRED CALCIUM LEVEL OF DIETS FOR SLAUGHTER PIGS

In the literature review and in our experiments (Chapters 2.6, 5.4 and 12) it has been shown that there are rather wide ranges of optimal Ca/P ratios of diets for the performance of slaughter pigs. This ratio should be at least be between 1.0 and 2.0 and in most research work it is shown that the best ratio may be between 1.2 and 1.4 to achieve the best utilization of phosphorus and performance of pigs. For the conversion of a Ca/P ratio into a Ca/digestible P ratio the following considerations were made:

a) From our experiments (Chapter 12) an optimum Ca/digestible P ratio could be calculated of between 3.0 to 3.5. Because of lack of sufficient experimental data (n=12) these figures have a rather weak basis;
b) The mean Ca/P ratio in the whole body of pigs is about 1.6. This suggests that the amount of digestible calcium should be close to 1.6 times that of digestible phosphorus. Assuming a digestibility of dietary calcium between 45 and 55 per cent (our experiments; Guéguen and Perez, 1981; A.R.C., 1981) then a Ca/digestible phosphorus ratio between 2.9 and 3.5 can be calculated;
c) A practical diet for slaughter pigs usually has a Ca/P ratio of 1.2 to 1.4. Based on our digestibility figures of phosphorus of the feedstuffs used, this leads to a Ca/digestible phosphorus ratio between 2.9 and 3.4.

From the three calculations it can be concluded that the Ca/digestible phosphorus ratio of diets for slaughter pigs should be between 2.9 and 3.5.

Table 149. Recommendations of apparent digestible P just sufficient for slaughter pigs

	C.V.B. scheme for mean growth rate = 750 g/d; FCR*=3.0						Scheme for mean growth rate = 900 g/d; FCR = 2.5					
live weight range (kg)	growth (g/d)	requirement (gP/d) maintenance	growth[a]	total feed intake (gP/d)	(kg/d)	in feed[c] (g dig P/kg)	growth (g/d)	requirement (gP/d) maintenance	growth[b]	total feed intake (gP/d)	(kg/d)	in feed (g dig P/kg)
20 to 30	495	0.15	2.54	2.69	1.1	2.4	595	0.15	3.20	3.35	1.1	3.0
30 to 40	620	0.20	3.17	3.37	1.5	2.2	745	0.20	4.00	4.20	1.5	2.8
40 to 50	725	0.25	3.69	3.94	1.9	2.1	870	0.25	4.65	4.90	1.9	2.6
50 to 60	805	0.30	3.67	3.97	2.3	1.7	965	0.30	4.68	4.98	2.3	2.2
60 to 70	855	0.36	3.88	4.24	2.65	1.6	1025	0.36	4.96	5.32	2.65	2.0
70 to 80	885	0.41	3.99	4.40	2.9	1.5	1060	0.41	5.10	5.51	2.9	1.9
80 to 90	890	0.46	3.99	4.45	3.0	1.5	1070	0.46	5.12	5.58	3.0	1.9
90 to 100	870	0.51	3.88	4.39	3.05	1.5	1045	0.51	4.98	5.49	3.05	1.8
100 to 110	825	0.57	3.66	4.23	3.10	1.4	990	0.57	4.69	5.26	3.1	1.7

* FCR = feed conversion ratio

a) based on mean conditions; from 50 kg live weight onwards requirement reduced by 0.5 g P/kg growth

b) based on a high amount of protein in growth; from 50 kg live weight onwards requirement reduced by 0.5 g P/kg growth

c) feed contains 9.05 MJ NE_f/kg

SUMMARY

In 1974 a research project was started at the I.V.V.O. institute in order to study various aspects of phosphorus feeding in pigs. There were several reasons for doing this:

1. The price of feed phosphates usually added to mixed feeds had increased enormously;
2. The considerable uncertainty concerning the recommendations of the phosphorus requirement for pigs due, for example, to the improved performance levels of modern pigs;
3. The use of more by-products instead of cereals in the feeds for pigs. There was at that time hardly any information available on the nutritive value of phosphorus in these by-products;
4. The possible relationship between the phosphorus supply and the frequency of leg weakness;
5. The increase in the number of animals per hectare of land, resulting in so much pig slurry and poultry manure being applied to fields in certain areas, that a high accumulation of phosphorus in the soil, together with leaching-out and run-off takes place. The effect is eutrophication of the water in ditches and other waterways.

The eutrophication is reason why, in the Netherlands, legislation will be enforced in 1987 in order to limit the amount of phosphorus in the manure which can be applied per hectare of land. Efforts are therefore being made to either prevent surplusses of phosphorus or to reduce them as much as possible. This can be achieved by lowering the standards, i.e. the recommendations concerning the quantities of phosphorus needed by pigs, and so the phosphorus content of the feed, which results in less phosphorus in the excreta. Reducing the standards, however, may affect the animals' production and metabolism. Phosphorus has many functions in the animal, and a lower dietary phosphorus level might lead to reduced performance.
The following aspects were studied in this thesis:

1. Phosphorus absorption and retention in pigs as related to diet composition and nutrient supply;
2. The effects of reduced phosphorus supply on performance and possibly on locomotory disturbances;
3. Defining the phosphorus requirements of slaughter pigs, and establishing standards for phosphorus which can be recommended for use in practice.

In Chapters 1 to 5 a review of the literature was discussed. Chapter 1 shows that the small intestine is the principal site for the absorption of phosphorus. Relatively minor quantities of phosphorus are absorbed in the large intestine.
The transport of phosphorus through the gut wall is an active process with sodium as the co-ion.
Various hormonal effects were described with regard to phosphorus absorption and retention. Vitamin D and its metabolites have important functions in phosphorus absorption and retention in pigs, but present knowledge is still poor.
The mechanisms in the regulation of the phosphorus homeostasis in the kidneys, also with regard to acid-base balance, are not well understood. With a low supply of phosphorus, excretion in the urine is negligible, but with a surplus of phosphorus or a shortage of calcium a large quantity of phosphorus will be excreted in the urine.
Chapter 2 deals with the effect of diet composition and supply on the absorption and retention of phosphorus in pigs. Phytate phosphorus must be

hydrolyzed by the enzyme phytase before the absorption of phosphorus from phytate can take place. In pigs, the stomach seems to be the principal place for the hydrolysis of phytate if the enzyme phytase (from seeds) is present. So, in feedstuffs with a lot of phytase activity (e.g. wheat), some of the phytate phosphorus is hydrolyzed and absorbed by the pig. A survey of results of studies on the digestibility of phosphorus showed that partly due to the variation in concentration of phytase and phytate, there is a large variation in the phosphorus absorption percentage between feedstuffs.

The faecal endogenous excretion of phosphorus in pigs amounted to 18 mg/kg live weight/d and seems to depend upon the amount of phosphorus supplied and required. With a supply of phosphorus just below the requirement, 5 mg P/kg/d, but under normal feeding conditions above the requirement, 10 mg/kg/d can be assumed.

Comparisons of the ability of inorganic phosphorus sources for supplying phosphorus to the pig showed considerable lack of standardization of methods and criteria.

A higher level of feeding tended to decrease the retention percentage of phosphorus slightly. Due to a stimulating effect of increased levels of dietary protein on growth rate, a higher absorption and retention of phosphorus might be observed. The addition of fat to diets had only a minor effect on absorption and retention. However, the number of experiments on pigs with regard to the effect of feeding level or supply of energy, protein or fat was limited. Fibre sometimes had a slightly negative effect on phosphorus absorption, but the results were conflicting with regard to what causes it.

The calcium concentration and the Ca/P ratio of the diet had a significant effect on phosphorus absorption and retention. From the available data it was calculated that an increase in dietary calcium concentration by 0.1 per cent, within the range of 0.10 to 1.50 per cent, resulted in a decrease in the absorption percentage of phosphorus by one percentage unit. No satisfactory relationship between dietary calcium and inorganic phosphorus concentrations could be derived to predict maximal phosphorus utilization.

No clear conclusion could be drawn concerning the effect of normal magnesium concentrations in the diet on phosphorus absorption. At higher levels of magnesium in the diet less phosphorus is excreted in the urine.

The effects of dietary sodium and potassium concentrations on phosphorus absorption and retention cannot be considered without also considering the acid-base balance. Experimental data on pigs are lacking, but research on chicks suggests that more attention should be paid to this acid-base aspect.

Essential trace elements and vitamins should be offered in sufficient quantities in order to prevent negative effects on phosphorus absorption and retention, often indirectly by retarded growth. Excessive amounts of iron, aluminium and fluorine, depress the absorption and retention of phosphorus.

The addition of antibiotics to pig diets results in minor or negligible positive effects on phosphorus absorption. The positive effects may be due to the stimulatory effect on growth rate.

Chapter 3 mainly deals with technological treatments of feeds and diets. Less recent investigations often showed a positive effect of (steam) pelleting on the absorption percentage of phosphorus, but in recent studies such a positive effect could not be demonstrated. Positive effects on phosphorus absorption of soaking the diet in water were observed in chicks. No conclusion could be drawn with regard to the effect of different environmental temperatures on phosphorus absorption and retention.

Chapter 4 deals with the amounts of phosphorus and calcium in the bodies of pigs and the factors involved, even in practical pig husbandry. Attention is paid to the live weight of the pigs, individual variation (coefficient

of variation: 8 to 9 per cent), the concentrations of phosphorus and calcium in the diet, also in relation to its feeding and energy level, and the breed.
The relationship between the amount of calcium and phosphorus in the body with, for example, live weight could best be estimated by relating the natural logarithm of the amount of minerals to the natural logarithm of live weight (Table 11). These calculations, showed an almost constant phosphorus retention per kg live weight gain of 5.1 g from 10 kg to 100 kg live weight, but there was a tendency towards higher values at lower live weights and lower ones at higher live weights. Except for newborn piglets, there was a close relationship between the amounts of calcium and phosphorus in the body: the Ca/P ratio was on average 1.62. There was also a close relationship between the amount of phosphorus and nitrogen in these slaughter experiments (average 210 g P/kg N). This close relationship can be helpful for establishing the phosphorus requirements of pigs.
The retention of phosphorus and calcium per kg live weight gain observed in balance experiments was about 20 per cent higher than when derived from slaughter experiments. Therefore, in retention studies very careful direct comparisons of both techniques are necessary to be sure of their accuracy.
A decline in the absorption and retention percentage of phosphorus and calcium in growing pigs with age can, to a large extent, be explained by the surplus amount of these minerals offered in relation to the requirement. Results with the balance experiments showed that up to about 55 kg live weight, there was a slight increase in the daily retention of phosphorus and calcium after which it remained fairly constant.
Chapter 5 deals with the background of the recommendations in use in several countries as to the phosphorus requirements of pigs. Recommendations on the total phosphorus requirement of pigs expressed as g/kg diet differed substantially between countries. Different values are also used for the content of digestible phosphorus of feedstuffs. Moreover, some recommendations concern optimal and others minimal phosphorus requirements. Optimal requirements may concern both optimal performance, bone strength, fertility and longevity or only some of these criteria.
Regression analyses of results of many feeding experiments showed that the conclusions drawn by the authors from their own results about the optimum phosphorus level in the diet can be criticized; they also usually included other considerations. It was also shown that the optimum phosphorus level depends on initial weight, sex and possibly breed of the animals, type of diet and level of feeding and on the criteria used in defining the optimum. Most information concerning the optimum phosphorus level is based on studies on diets of corn and soybean meal. The calculated inorganic phosphorus levels from the regression analyses based on the authors' optima for barrows and gilts agree well with the inorganic phosphorus levels given by N.R.C. (1979). Using our calculations, we could also derive optimum levels of inorganic phosphorus in such diets at several live weights of barrows and gilts together (Figure 9). The estimations of the optimum phosphorus levels for combinations other than barrows and gilts taken together, showed that those for boars and gilts above 30 kg live weight were somewhat higher. However, due to the limited number of observations above 30 kg it is difficult to indicate how great the differences are. For the usual diets in the Netherlands, the optimum level of inorganic phosphorus was at least 0.5 g/kg higher than that for diets of corn and soybean meal.
For a better comparison of the recommended phosphorus levels, the apparently digestible or available phosphorus per unit of ME should be used instead of total phosphorus or inorganic phosphorus per kg diet.
From the results of feeding experiments, it was concluded that the Ca/P ratio in the diet should be close to 1.25, although at higher phosphorus levels, when matched to phosphorus requirement, a higher Ca/P ratio does

not induce detrimental effects on a short term basis.
In Chapter 6 the experimental methods used in own experiments were described. These were aimed at presenting more information where the survey of the literature had shown this to be insufficient. Special attention was paid to diet composition and dietary supply of nutrients. In Chapters 7 to 17, results of these experiments, all but one with growing pigs, were given.
In Chapter 7, on duration of experiments, it was shown that in phosphorus and calcium balance studies, because of carry-over effects, much attention should be paid to an adequate length of the period of adaptation to a new diet. If there is only a small change in dietary concentration of these minerals, a period of 14 days will suffice. However, if there is a substantial change in their concentration (e.g. twice the concentration), then the adaptation period should be at least 21 days.
A collection period for faeces, from pigs on metabolism crates, of ten days was found preferable to that of five days, because the variance in absorption and retention percentages during a period of ten days was about half that of five days. This was also true for the variance in the digestibility of the dry matter; in the case of short collection periods variances are increased due to too great an influence of variation in the excretion of faeces from day to day.
In Chapter 8 on the effect of feeding level or energy supply, it was shown that when using levels of feeding according to the C.V.B. feeding scheme, generally applied in the Netherlands, or 25 to 33 per cent below this scheme, there was a tendency towards lower absorption and retention percentages of phosphorus at the higher levels of feeding. At the higher feeding level more phosphorus was retained daily, although less when expressed per kg live weight gain. As at the higher levels of feeding the additional supply of feed or energy mainly resulted in fat retention, it was concluded that when higher amounts of feeds are offered, it is not necessary to raise the concentration of phosphorus; somewhat lower levels of phosphorus might be possible.
A comparison of the retention of phosphorus by 14 pigs growing from 20 to 110 kg live weight, measured both by the balance technique and by the comparative slaughter technique, showed that an accurate estimation of the retention of phosphorus can be obtained by the balance technique. The estimated retention of phosphorus as determined with the balance technique was on average six per cent (25 $\pm$ 17 g P) higher.
The results of our balance experiments showed that the total amount of phosphorus in the bodies of pigs at 110 kg live weight can be fairly accurately predicted, provided that the phosphorus and calcium supplies are sufficient (at least 1.6 g digestible P and 4.0 g Ca/kg T) and that the daily allowance of feed and growth rate approach mean values found in practice. On average, 5.1 to 5.0 g phosphorus was retained per kg live weight gain.
In Chapter 9 on dietary protein/lysine levels, it was concluded that when a higher protein level in the diet results in a higher growth rate or nitrogen retention, there is also a tendency towards a higher retention of phosphorus per day. This can be explained by the high concentration of phosphorus in body protein (9 g P/kg dry fat-free muscle). For animals with a leaner type of daily gain it was concluded that per kg live weight gain the retention of phosphorus might be 0.2 to 0.3 g higher. It will be clear that in such a case, when the supply of phosphorus is low, it would be better to slightly raise the concentration of phosphorus in the diet.
Comparison of boars, barrows and gilts showed that above 60 kg live weight boars retain more phosphorus per day than barrows and gilts. This effect is mainly due to the higher nitrogen retention and growth rate of boars in that period. Therefore, the phosphorus requirement of boars above 60 kg

live weight will be somewhat higher than that of barrows and gilts.
It was shown that the P/N ratio in the bodies of pigs, contrary to expectation, is not completely constant but may be affected slightly by several factors such as the concentrations of phosphorus and protein in the diet, the level of energy intake and possibly the sex of the animal.
In Chapter 10 on fat supplementation, it was shown that fat added to the diet has no great effect on the absorption or retention of phosphorus if the fat has a fatty acid composition such as renderers' fat. The effect of fat is often confounded by effects caused by altered mineral content of the diet and also by the kind of fat used. Also, a minor effect on calcium absorption was observed. At high inclusion levels of fat, calcium absorption and retention can become suboptimal if these fats contain high concentrations of long chain saturated fatty acids, because insoluble calcium soaps are formed.
In Chapter 11 on the effect of fibre, it was shown that the inclusion of fibre originating mainly from grass meal, resulted in lower absorption and retention percentages for phosphorus. This effect might partly have been due to differences in daily live weight gain. Differences in phosphorus retention per kg weight gain were hardly noticeable when live weight was corrected for differences in gut-fill. The effect of fibre on absorption might be due both to an effect of fibre per se, and to differences in availability of phosphorus in the ingredients.
In Chapter 12 on the effect of dietary calcium concentration, it was concluded that a fairly reliable prediction of the optimum Ca/P ratio in a diet for maximum phosphorus utilization can be given, when the amount of digestible phosphorus offered is close to the minimum phosphorus requirement of the animal and when the calcium level in the diet is below 0.7 per cent. In these cases, the optimum Ca/P ratio is between 1.2 and 1.3 and an increase in dietary calcium by 0.1 per cent resulted in a decrease in the absorption percentage of P of about one percentage unit. Such an optimum Ca/P ratio was also found in feeding experiments in the literature. When the amount of available phosphorus exceeded requirement, a wide range in the optimum Ca/P ratios was found. Also, high calcium levels (0.9 per cent and higher) increased the variation in optimum Ca/P ratio.
The ratio of Ca to inorganic P, instead of the Ca/P ratio, did not improve the accuracy of the prediction of the optimum ratio. The optimum Ca/digestible P ratio varied between 3.0 and 3.5; the lower value for diets without supplementary phosphorus, the higher value for all diets including those with supplementary phosphorus. The Ca/digestible P ratio might give a better prediction, when digestible P is defined as truly digestible P; an optimum ratio of 3.0 was calculated for basal diets without supplementary inorganic phosphorus or for such diets plus supplementary phosphorus and phosphorus from animal origin (for the latter a digestibility of 90 per cent was used).
Chapter 13 deals with the absorption percentage of P from feedstuffs and mixed feeds. It was concluded in this chapter, from more than 30 digestion trials, that depending on the feedstuff, there are great differences in the absorption percentage of phosphorus. This may be due, for example, to the presence of phytases or to the phytate phosphorus concentration. Care was taken in these trials to ensure that the supply of phosphorus was below the requirement and that the Ca/P ratio of the ration was between 1.2 and 1.4. In most cases, the basal diet was barley or maize. It was calculated that the absorption percentage of phosphorus from phytate in mixed feeds varied from negligible to about 40 per cent. Due to lack of sufficient data it was not possible to show clearly whether the absorption percentage of phosphorus in feedstuffs from the same product group (e.g. maize) can be assumed to be equal. Furthermore, we do not yet have sufficient knowledge about whether, even within the same product, the absorption percentage of

phosphorus is about the same and, if this is not so, how the differences can be explained. More studies in this field are recommended.
In Chapter 14 results of phosphorus absorption and retention studies on growing pigs, receiving a basal diet supplemented with various inorganic phosphorus sources, were presented. It was concluded that to prove the existence of differences with regard to phosphorus metabolism between phosphorus sources fed, it is necessary to use a basal diet with a low concentration of phosphorus. If basal diets are composed of ordinary feedstuffs they contain so much phosphorus that the requirement for phosphorus is almost met. Moreover, in such basal diets intrinsic phosphorus plays too great a part and biases the results. This means that a semi-synthetic basal diet with a low concentration of phosphorus must be chosen.
Various phosphorus sources were also compared, using piglets from 5 to 10 weeks old. Several criteria were used. The highest coefficient of determination (R^2) was found when absorption percentages of phosphorus and amount of ash in the metatarsal bone were regressed on the phosphorus concentration in the diet. In contrast with the results from the literature, a low R^2 was obtained with bone breaking strength as a dependent variable. Possible causes of these differences were discussed. When various criteria were used the same ranking order of the phosphorus sources was not always obtained. There were substantial differences in phosphorus sources used, but samples of three batches of monocalcium phosphates from different factories hardly differed. Again, measurements using synthetic basal diets with a low phosphorus concentration were recommended.
In Chapter 15 on steam-pelleting and dietary copper concentration, it was shown that steam-pelleting improved the absorption and retention of phosphorus in diets, whether or not supplemented with inorganic phosphorus, when compared with non-pelleted diets. The difference was about three percentage units. The effect seemed to increase with live weight.
A reduction in the copper and zinc concentrations (as sulphates) in the diets of growing pigs had no negative effect on phosphorus retention; there might possibly be even a slightly positive effect.
The feeding experiments in Chapter 16 showed that when slaughter pigs from about 30 kg live weight onwards received diets with very low concentrations of calcium or phosphorus, signs of leg weakness were not observed any more frequently than when on diets with higher levels of these minerals. However, calcification of the bones was poorer and fractures are more likely to occur. Obstacles in the pen resulted in a worse score for gait.
The inclusion of two per cent NH_4Cl in the diet for pigs from 25 kg live weight onwards did not lead to dyschondroplasia. This is in contrast to findings in broiler chickens.
Adding 12 500 or 25 000 IU vitamin D_3 per kg to a diet containing 2 000 IU vitamin D_3 per kg which was rich in phytate phosphorus did not affect the absorption and retention of phosphorus or bone mineralization.
Diets with 1.5 g digestible phosphorus per kg tended to lead to a lower feed intake of pigs from 30 kg live weight onwards; therefore, a tendency towards lower growth rates was also observed. Improvements in performance were found at levels of 2.1 g digestible phosphorus per kg diet containing 8.70 MJ NE_f, but there was no further increase above this level.
Various calculations on most of the balance and feeding trials were presented in Chapter 17. The errors (standard deviations) of sampling and analysis of phosphorus in our mixed diets with supplementary phosphorus were 0.12 and 0.14 g P/kg dry matter respectively, those of mixed diets without supplementary phosphorus were 0.07 and 0.12 g/kg dry matter respectively. Because our diets were thoroughly mixed, it may be assumed that the error of sampling is, in practice, greater than with our diets.
For the diets and (low) phosphorus levels used, a decrease in the absorption percentage of phosphorus at increased live weights due to varying

phosphorus concentrations in the diets could not be demonstrated. However, the concentration of dietary calcium and, to some extent, the level of feeding certainly affected the decrease in the absorption percentage of phosphorus at higher live weights.

The absorption percentage of phosphorus showed a significant positive correlation with the digestibility of the dry matter ($r = 0.52$). However, the correlation in animals on metabolism crates was not very strong and the use of the digestibility of dry matter as a covariable for each separate small experiment, while estimating the absorption percentage of phosphorus, could not be recommended. Its use as a covariable for group-fed piglets was promising.

Mineral content of the animal at slaughter was also estimated from weight and composition of bones such as tail vertebra or radius. The fifth tail vertebra seemed to be somewhat more sensitive than the radius. Prediction of the amount of phosphorus in the whole bodies of pigs at slaughter weight, based on the fat-free dry matter or ash of the radius, had a large standard deviation of 30 g within an experiment. Between experiments, predictions still had a lower precision. Obviously, such data hardly supply any accurate information on mineral supply and utilization.

In the final discussion of Chapter 18, phosphorus requirements of slaughter pigs were formulated. These requirements were derived with the factorial approach for guaranteeing both an optimal and a supply of phosphorus that is just sufficient (Tables 148 and 149). Requirements are expressed as digestible phosphorus. A guide line as to how digestibility data of feedstuffs and feed phosphates could best be measured was given in Chapters 13 and 14. It was also suggested that the Ca/digestible P ratio of diets for slaughter pigs should be between 2.9 and 3.5.

SAMENVATTING

In 1974 werd een onderzoekproject op het I.V.V.O. gestart met als doel diverse aspecten van de fosforhuishouding bij varkens te bestuderen. Als reden hiervoor kunnen de volgende ontwikkelingen genoemd worden:

1. de aanzienlijke prijsstijging van voederfosfaten;
2. de onduidelijkheid in de te hanteren fosfornormen voor varkens, onder andere door de sterk verbeterde groeiprestaties van varkens van diverse gebruikskruisingen;
3. de opname van meer bijprodukten in plaats van granen in de mengvoeders voor varkens. Van deze bijprodukten was nauwelijks kennis voorhanden van de nutritionele waarde van het aanwezige fosfor (P);
4. een mogelijk verband tussen een tekort aan fosfor in het voeder en het optreden van beengebreken bij varkens als gevolg van de ontwikkelingen genoemd onder 2) en 3);
5. het milieuverontreinigend aspect van fosfor. Door het sterk toegenomen aantal dieren wordt in sommige delen van Nederland zoveel drijfmest van varkens en pluimvee per ha toegediend, dat accumulatie van fosfor in de bodem plaatsvindt. Als gevolg van uitspoeling en afspoeling van fosfor ontstaat eutrofiëring van het grond- en oppervlaktewater.

Eutrofiëring van het grond- en oppervlaktewater is aanleiding voor de Nederlandse overheid om in 1987 via wettelijke maatregelen de toe te dienen hoeveelheid drijfmest/ha aan banden te leggen door de daarin aanwezige hoeveelheid P als maatstaf te nemen.
Vooral de laatste reden is een extra aanleiding geweest allerlei mogelijkheden te onderzoeken om het overschot aan fosfor zoveel mogelijk terug te dringen. Dit kan o.a. door de benutting van P door het dier te verhogen of door de behoeftenormen voor fosfor te verlagen, waardoor het fosforgehalte in het voeder omlaag kan en er minder fosfor in mest en urine komt. Het is echter niet duidelijk of de P-normen wel verlaagd kunnen worden, omdat P een belangrijke rol speelt in allerlei levensprocessen en veel P in het bot wordt vastgelegd; een verlaging van het P-gehalte in het voeder zou dan ook wel eens tot slechtere mestprestaties van het dier kunnen leiden.
De volgende aspecten zijn in dit proefschrift nader bestudeerd:

1. het effect van de samenstelling van het voeder en de voedervoorziening op de absorptie en retentie van P in het varken;
2. het effect van een verlaagd P-gehalte in het voeder op de mestresultaten en op het mogelijk optreden van beengebreken;
3. het vaststellen van de P-behoefte voor slachtvarkens en het geven van een aanbeveling voor P-normen.

In de hoofdstukken 1 tot en met 5 is een overzicht van de literatuur gegeven. In hoofdstuk 1 is allereerst beschreven dat de dunne darm de belangrijkste plaats is waar absorptie van P plaatsvindt; in de dikke darm wordt slechts weinig P geabsorbeerd. Transport van P door de darmwand is een actief proces, waarbij natrium als co-ion fungeert. Vervolgens zijn de effecten van diverse hormonen op de absorptie en retentie van P behandeld. Vitamine D en de metabolieten ervan hebben veel invloed op de P-absorptie en -retentie, maar het is nog niet duidelijk hoe die processen gereguleerd worden. Dit is ook het geval bij de regulatie van de P-homeostase door de nieren, waarbij het zuur-base evenwicht een duidelijke rol speelt. Bij een krappe voorziening van P is de uitscheiding van P met de urine verwaarloosbaar klein, maar bij een overschot aan P of een tekort aan calcium wordt een aanzienlijke hoeveelheid P met de urine uitgescheiden.

In hoofdstuk 2 wordt het effect van voedersamenstelling en -voorziening op de absorptie en retentie van P bij varkens behandeld. Wanneer P in het voeder aanwezig is als fytaat, moet het enzym fytase fytaat eerst hydrolyseren (waardoor inositol en vrij fosfaat ontstaat), alvorens absorptie van P door de darmwand kan plaatsvinden. Bij varkens lijkt de maag de belangrijkste plaats voor hydrolyse van fytaat als tenminste het enzym fytase (afkomstig van zaden) aanwezig is. Van voedermiddelen met veel fytase activiteit (zoals tarwe), kan een deel van het fytaat gehydrolyseerd en de vrijgekomen P door het varken benut worden. Een overzicht van proeven, waarin de verteerbaarheid of beschikbaarheid van P in veevoeders is bepaald, laat zien dat er een grote variatie in verteerbaarheid/beschikbaarheid gevonden wordt, hetgeen voor een deel verklaard kan worden door verschillende fytase activiteit en het gehalte aan fytaat.
De endogene uitscheiding van P in de mest kan sterk variëren (van 1 tot 18 mg/kg lichaamsgewicht/d) en lijkt afhankelijk te zijn van de hoeveelheid toegediende P ten opzichte van de behoefte. Wanneer iets onder de P-behoefte gevoederd wordt kan een uitscheiding van 5 mg P/kg/d aangenomen worden, maar onder praktijkomstandigheden waarbij in het algemeen boven de behoefte gevoederd wordt, één van 10 mg P/kg/d.
Vergelijking van de nutritieve waarde van P in diverse voederfosfaten wordt bemoeilijkt door onvoldoende uniformiteit in standaardisatie van methoden en criteria.
Bij een hoger voederniveau lijkt het retentie% van P iets af te nemen. Wanneer als gevolg van een hoger eiwitgehalte in het voeder de groeisnelheid verhoogd wordt neemt meestal ook de absorptie en retentie van P toe. De opname van voedervet in het mengvoeder heeft vrijwel geen effect op de P-absorptie en -retentie. Er zijn echter maar weinig proeven met varkens in de literatuur beschreven omtrent het effect van voederniveau of de voorziening van energie, eiwit of vet op de P-huishouding.
Ruwe celstof heeft soms een klein negatief effect op de P-absorptie, maar er zijn tegenstrijdige verklaringen voor wat hiervoor verantwoordelijk is.
De hoeveelheid calcium (Ca) en de Ca/P-verhouding in het voeder hebben een duidelijk effect op de P-absorptie en -retentie. Op basis van de beschikbare gegevens is uitgerekend dat bij een toename van het Ca-gehalte in het voeder met 0,1%, in de range van 0,1 tot 1,5%, het absorptie% van P met één eenheid afneemt. Als gevolg van een tekort aan Ca neemt, afhankelijk van het P-gehalte in het voeder, het retentie% van P toe bij een stijging van het Ca-gehalte in het voeder tot 0,5 à 0,9%. Het is niet gelukt om een bevredigende waarde te berekenen voor de verhouding Ca/anorganisch P in het voeder om een maximale P-benutting te voorspellen.
Er lijkt geen duidelijk effect te zijn van het gehalte aan magnesium in het voeder op de P-absorptie; wel neemt de P-uitscheiding met de urine af bij een hoger magnesium gehalte.
Het effect van natrium en kalium in het voeder op de P-absorptie en -retentie kan alleen in samenhang met de zuur-base balans van het dier beschouwd worden. Er zijn hierover vrijwel geen proeven met varkens gedaan, maar onderzoekresultaten bij kuikens laten zien dat meer aandacht geschonken dient te worden aan het zuur-base evenwicht bij varkens.
Essentiële spoorelementen en vitamines moeten in voldoende mate verstrekt worden, om negatieve effecten op de P-absorptie en -retentie te voorkomen; dit kan waarschijnlijk verklaard worden door een indirect effect als gevolg van de tragere groeisnelheid. Het toevoegen van antibiotica aan varkensvoeders heeft geen of een klein positief effect op de P-absorptie; het positieve effect hangt samen met een iets betere groei.
In hoofdstuk 3 is het effect van technologische behandelingen van voeders op de P-absorptie en -retentie beschreven. Hoewel ouder onderzoek meestal een duidelijk positief effect van het met stoom pelleteren van voeder op de P-absorptie aantoonde, wordt in recenter onderzoek geen duidelijk positief

effect aangetoond. Bij kuikens is een positief effect op de P-retentie waargenomen wanneer het voeder enige tijd is voorgeweekt in water.
In hoofdstuk 4 wordt ingegaan op de hoeveelheid P en Ca in het lichaam van varkens en op de factoren die hierop invloed uitoefenen, zoals het lichaamsgewicht, individuele diervariatie (een variatie coefficient van 8 à 9%), het gehalte aan P en Ca in het voeder, het voeder- of energieniveau en het ras.
De hoeveelheid P en Ca in het dier kan het best geschat worden wanneer de (natuurlijke) logaritme van de hoeveelheid van deze mineralen gerelateerd wordt aan de (natuurlijke) logaritme van bijv. het levend gewicht (Tabel 11). Deze berekeningen toonden aan dat de retentie aan P per kg levend gewicht toename vrijwel constant was nl. 5,1 g van 10 tot 100 kg levend gewicht. Er was een kleine tendens tot een hogere waarde bij een laag en een lagere waarde bij een hoog lichaamsgewicht. De Ca/P verhouding in het dier vanaf 5 kg lichaamsgewicht is ongeveer 1,62, varieert maar weinig en kan als controle dienen voor de juiste uitvoering van onderzoek naar de retentie van Ca en P. Alleen bij pasgeboren biggen is die verhouding circa 1,77. Er is ook een nauw verband berekend tussen de hoeveelheid P en N in het dier (gemiddeld 210 g P/kg N).
De P en Ca retentie, vastgesteld met behulp van balansproeven, blijkt per kg gewichtstoename ongeveer 20% hoger te zijn dan bij slachtproeven. Dit verschil kan o.a. verklaard worden door de proefuitvoering (voederniveau), onzekerheid omtrent de groeisnelheid bij balansproeven en fouten gemaakt bij de verzameling en analyse van monsters van (vetrijke) karkassen. Daarom wordt aanbevolen, voor het verkrijgen van een goed inzicht in de nauwkeurigheid van de gemeten retentie van P en Ca, een direkte vergelijking te maken tussen de balans- en de vergelijkende slachttechniek.
Een afname van het absorptie- en retentiepercentage van P en Ca bij toenemend gewicht van slachtvarkens kan voor een belangrijk deel verklaard worden door de toenemende overmaat aan deze mineralen t.o.v. de behoefte. Resultaten van de balansproeven gaven een geleidelijke toename van de retentie aan P en Ca per dag aan tot ongeveer 55 kg lichaamsgewicht, waarna deze vrij constant bleef.
In hoofdstuk 5 wordt de achtergrond van de P-behoeftenormen voor varkens gegeven, zoals die in diverse landen gelden. P-normen uitgedrukt in g P/kg voeder vertonen grote verschillen tussen de landen, wat voor een deel verklaard kan worden door verschil in het gehalte aan verteerbaar- (of beschikbaar-) P van veevoedergrondstoffen. Bovendien gaat het bij sommige ervan om optimale normen, bij andere om minimale normen. Bij optimale normen is met diverse aspecten rekening gehouden zoals optimale groei en voederconversie, maximale botsterkte, vruchtbaarheid en levensduur of een aantal hiervan.
Regressie analyse van de resultaten (groei en voederconversie) van veel voederproeven toonde aan dat veel onderzoekers bij het trekken van conclusies over het optimale P-gehalte in het voeder, uit de eigen proefresultaten nog meer criteria dan alleen groei en voederconversie gebruikt hebben. Met behulp van regressie analysetechniek is tevens aangetoond dat het optimale P-gehalte in het voeder afhangt van het gewicht, sexe en misschien ras, het soort voeder en voederniveau en van andere criteria die niet in de regressie analyse zijn meegenomen, zoals bot-asgehalte en botsterkte.
De meeste gegevens voor het berekenen van het optimale P-gehalte zijn afkomstig van voeders die vrijwel alleen mais en sojaschroot bevatten. Het optimale anorganisch P-gehalte in het voeder, berekend met behulp van regressie analysetechniek, en gebaseerd op het optimum P-gehalte voor borgen en zeugen, zoals dat is aangegeven door de onderzoekers, kwam goed overeen met de normen zoals die in de N.R.C. tabel (1979) zijn aangegeven.

Met behulp van onze berekeningen konden optimale anorganisch P-gehalten in

dergelijke voeders berekend worden voor verschillende gewichten van gemengd gemeste borgen en zeugen (Figuur 9). De berekeningen laten zien dat het optimum voor gemengd gemeste beren en zeugen, na 30 kg lichaamsgewicht, wat hoger is dan voor gemengd gemeste borgen en zeugen; door het geringe aantal waarnemingen is echter niet aan te geven hoeveel dat precies is. Voor voedersamenstellingen, zoals gangbaar in Nederland, is het optimale anorganisch-P-gehalte ten minste 0,5 g/kg hoger dan voor voeders gebaseerd op mais en sojaschroot.
Om de P-normen voor varkens tussen diverse landen beter te kunnen vergelijken wordt aanbevolen het gehalte aan verteerbaar- of beschikbaar-P per eenheid ME (beschikbare energie) te nemen in plaats van het gehalte aan P of anorganisch-P per kg voeder.
Op basis van de uitkomsten van voederproeven kan geconcludeerd worden dat de Ca/P verhouding in het voeder in de buurt van 1,25:1 moet liggen, hoewel bij een duidelijke overmaat aan P een hogere Ca/P verhouding in het voeder op korte termijn geen duidelijke stoornissen tot gevolg heeft.
In hoofdstuk 6 wordt de proefmethodiek van de eigen proeven beschreven. Met deze proeven is getracht meer inzicht te verkrijgen in die aspecten waar de literatuur onvoldoende houvast bood. Veel aandacht is geschonken aan de voedersamenstelling en de voedervoorziening. In de hoofdstukken 7 tot en met 17 zijn de resultaten van de eigen proeven beschreven die op één na allemaal met slachtvarkens van ca. 30 tot 110 kg zijn gedaan.
In hoofdstuk 7 is, voor dieren gehuisvest op stofwisselingskooien, ingegaan op de duur van de aanpassings- en verzamelperiode (van mest en urine). Het blijkt dat als gevolg van de overgang van het ene op het andere voeder met een geheel ander P- en Ca-gehalte er een duidelijke nawerking is. Daarom moet de aanpassingsperiode ten minste 14 dagen zijn bij een geringe wijziging van het P- en Ca-gehalte in het voeder; bij een grote verandering is het raadzaam ten minste 21 dagen aan te houden.
Een verzamelperiode voor mest van tien dagen was beter dan vijf dagen omdat de variantie van het absorptie- en retentie% gedurende een periode van tien dagen ongeveer de helft was van die van vijf dagen. Dit gold ook voor de verteerbaarheid van de droge stof; bij korte verzamelperioden is de invloed van de variatie in uitscheiding van mest van dag tot dag te groot.
In hoofdstuk 8 is het effect van voeder- en energieniveau beschreven. Het bleek dat wanneer volgens het C.V.B.-schema voor energie werd gevoederd of 25 tot 33% onder dit schema, er een tendens was naar een lager absorptie- en retentie% voor P bij de hogere voederniveaus. Wel was de dagelijkse P retentie hoger bij het hogere voederniveau, maar minder P werd vastgelegd per kg toename in gewicht. Bij de hogere voederniveaus leidde de extra hoeveelheid voeder voornamelijk tot vetaanzet. Daarom is de conclusie getrokken dat wanneer een hoger voederniveau of extra energie voornamelijk leidt tot extra vetaanzet het gehalte aan P in het voeder niet verhoogd behoeft te worden; een lager gehalte aan P is misschien wel mogelijk.
De retentie aan P van 14 varkens tussen 20 en 110 kg levend gewicht werd geschat zowel met behulp van de balans- als met de vergelijkende slachttechniek. De resultaten laten zien dat de schattingen volgens beide technieken goed met elkaar overeenkomen; die van de balanstechniek was gemiddeld 6% (25 $\pm$ 17 g P) hoger.
De resultaten van alle balansproeven tezamen laten zien dat de hoeveelheid P in varkens van 110 kg levend gewicht goed geschat kan worden, mits er voldoende P en Ca verstrekt is (ten minste 1,6 g verteerbaar P en 4,0 g Ca/kg voeder droge stof) en de voedervoorziening en groeisnelheid van de dieren overeenkomen met die van de praktische varkenshouderij. Er wordt van 20 tot 110 kg gemiddeld 5,1 tot 5,0 g P per kg levend gewicht aangezet.

In hoofdstuk 9 wordt het effect van eiwit/lysine behandeld. Er kan geconcludeerd worden dat wanneer een hoger eiwitgehalte in het voeder leidt tot een hogere groeisnelheid of eiwitretentie, er ook een tendens is naar een hogere P-retentie per dag. Dit kan verklaard worden door het hoge P-gehalte in vlees (eiwit bevat ca. 9 g P/kg vetvrij materiaal). Uit onze proeven kon berekend worden dat varkens die per dag een hogere eiwitaanzet hebben een 0,2 tot 0,3 hogere retentie van P per kg groei hebben. Wanneer in zo'n situatie de P-voorziening minimaal is moet het P-gehalte in het voeder dus enigszins verhoogd worden. Wanneer beren, borgen en zeugen met elkaar vergeleken worden dan blijkt dat beren boven 60 kg meer P per dag aanzetten dan borgen en zeugen. Dit kan vooral verklaard worden door de hogere eiwitaanzet en groei bij beren in die periode. Daarom is de P-behoefte bij beren boven 60 kg iets groter dan die van borgen en zeugen.
Uit onze proeven blijkt dat de P/N verhouding in het varken niet zo constant is als gedacht. Deze verhouding wordt enigszins beïnvloed door het gehalte aan P en eiwit in het voeder, het energieniveau en waarschijnlijk door de sexe van het dier.
In hoofdstuk 10 is het effect van toegevoegd vet beschreven. Het blijkt dat vet toegevoegd aan het voeder geen noemenswaard effect had op de absorptie en retentie van P, wanneer het vet een vetzuurpatroon heeft wat veel lijkt op dat van destructievet. Het effect van vet op de P-huishouding is een gecombineerd effect van veranderde mineralen gehaltes in het voeder en het type vet. Er was ook meestal geen waarneembaar effect op de Ca-absorptie, maar bij een hoog gehalte aan vet met veel verzadigde vetzuren met lange koolstofketens kan de Ca-absorptie en -retentie dalen door de vorming van onoplosbare calciumzepen.
In hoofdstuk 11 is het effect van ruwe celstof beschreven. Veel grasmeel in het voeder leidde tot een lager absorptie- en retentie% van P, hetgeen waarschijnlijk deels verklaard kan worden door de lagere groeisnelheid van varkens die grasmeel in het voeder kregen. Er was nl. geen verschil in aanzet van P per kg groei wanneer de groei gecorrigeerd wordt voor verschil in maag-darmvulling. Het effect van ruwe celstof op de P-absorptie is verder mogelijk niet alleen afkomstig van ruwe celstof maar ook van verschillen in P-beschikbaarheid van de grondstoffen in de voeders.
In hoofdstuk 12 wordt het effect van het calciumgehalte in het voeder behandeld. Op grond van de verkregen resultaten wordt geconcludeerd dat er een betrouwbare schatting van een optimale Ca/P verhouding in het voeder gemaakt kan worden om een maximale P-benutting te verkrijgen, indien de verstrekte hoeveelheid verteerbaar-P dicht bij de minimum P-behoefte is en bij een Ca-gehalte in het voeder onder de 0,7%. In die situatie is de optimale Ca/P verhouding 1,2 à 1,3 en een toename van 0,1% Ca in het voeder leidde tot een afname van het P-absorptie% met één percentage-eenheid, hetgeen ook in de literatuurstudie werd gevonden. Wanneer de P-voorziening de behoefte duidelijk overschrijdt en bij Ca-gehaltes in het voeder boven 0,9%, is de variatie in optimale Ca/P verhouding groot en kan geen duidelijke uitspraak worden gedaan over de gewenste Ca/P verhouding. Wanneer in plaats van Ca/P de Ca/anorganisch P-verhouding wordt gehanteerd neemt de nauwkeurigheid voor het schatten van een optimum verhouding wat af.
De optimale Ca/verteerbaar-P verhouding varieerde tussen 3,0 en 3,5. Bij voeders zonder toegevoegd anorganisch-P is deze verhouding 3,0, maar nam toe tot 3,5 wanneer ook voeders inbegrepen werden waaraan wel anorganisch-P was toegevoegd. Het lijkt er op dat een nog betere voorspelling mogelijk is wanneer in plaats van (schijnbaar) verteerbaar-P waar verteerbaar-P genomen wordt, maar hiervoor zijn diverse aannames nodig.

In hoofdstuk 13 staat de verteerbaarheid van P uit grondstoffen en mengvoeders centraal. Het blijkt uit circa 30 verteringsproeven met grondstoffen dat er grote verschillen in P-verteerbaarheid zijn. De P-verteerbaarheid van mais en van mais afgeleide bijprodukten is laag (ca. 20%), terwijl die van gerst en sojaschroot veel hoger is (ca. 40%). Dit verschil kan o.a. verklaard worden uit de aanwezigheid van het enzym fytase en mogelijk de vorm waarin fytaat voorkomt. Bij de verteringsproeven is er voor gezorgd dat de P-voorziening onder de P-behoefte lag en dat de Ca/P verhouding in het rantsoen tussen de 1,2 en 1,4 was. In de meeste verteringsproven is het basisvoeder mais of gerst geweest.
Er zijn meer proeven nodig om vast te kunnen stellen of de verteerbaarheid van P bij eenzelfde produktgroep (bijv. mais) steeds vrijwel gelijk is en hoe eventuele verschillen verklaard kunnen worden.
Hoofdstuk 14 gaat over de waarde van voederfosfaten in de varkensvoeding. Uit de eerste proeven komt naar voren dat om verschillen in voederfosfaten aan te tonen met behulp van absorptie en retentie van P een basisvoeder nodig is, dat een laag gehalte aan P bevat: een basisvoeder bestaande uit vaak in de praktijk gebruikte grondstoffen, bevat al zoveel P dat de behoefte bijna gedekt wordt. Dit vergroot de proeffout aanzienlijk. Daarom wordt een semisynthetisch basisvoeder met een laag gehalte aan P aanbevolen.
Vervolgens zijn diverse P-bronnen met elkaar vergeleken in een proef met biggen van 5 tot 10 weken oud, waarbij een groot aantal criteria is gebruikt. Het best kan de waarde van een P-bron voor varkens geschat worden aan de hand van het P-absorptie% en de hoeveelheid as in de middenvoetsbeentjes. De breeksterkte van de middenvoetsbeentjes gaf een veel minder nauwkeurige schatting dan in de literatuur vermeld is. De diverse criteria geven niet altijd dezelfde rangorde van de waarde van de gebruikte P-bronnen.
Er waren duidelijke verschillen in de onderzochte P-bronnen, maar de drie monocalcium fosfaten, afkomstig van drie verschillende producenten, bleken weinig van elkaar te verschillen in waarde als P-bron.
In hoofdstuk 15 is aangegeven dat het P-absorptie% iets toenam (3 eenheden) wanneer voeders (in meelvorm) met stoom werden gepelleteerd.
Een verlaging van het gehalte aan koper en zink (als sulfaat) in het voeder had geen negatief effect op de P-retentie; er was zelfs een gering positief effect waarneembaar.
In hoofdstuk 16 zijn de resultaten van diverse voederproeven beschreven. Bij slachtvarkens vanaf 30 kg, die voeders kregen met een erg laag gehalte aan Ca en P, zijn niet meer gevallen van beengebreken waargenomen dan bij voeders met een hoger gehalte aan Ca en P. De botmineralisatie is echter onvoldoende en beenbreuk komt eerder voor. Spoorbielzen in het hok leidden tot een lagere beoordeling voor de kwaliteit van het beenwerk.
De opname van 2% ammoniumchloride in het voeder voor varkens vanaf 25 kg heeft niet tot dyschondroplasia (een afwijking aan de uiteinden van de beenderen van de poten) geleid, dit in tegenstelling tot resultaten bij mestkuikens.
Toevoeging van 12.500 of 25.000 IE (internationale eenheden) vitamine D_3 aan een voeder dat reeds 2.000 IE vitamine D_3/kg en veel fytaat-P bevatte, gaf geen verandering in P-absorptie en -retentie en botmineralisatie bij varkens van 30 tot 100 kg.
Voeders met 1,5 g verteerbaar-P/kg gaven een tendens naar een iets lagere voederopname bij varkens vanaf 30 kg; daardoor was de groeisnelheid ook iets lager. Op voeders met 2,1 g verteerbaar P/kg nam de groeisnelheid iets toe, maar bij een hoger gehalte aan verteerbaar-P was er geen verdere verbetering in de mestresultaten.

In hoofdstuk 17 zijn resultaten beschreven van diverse berekeningen uitgevoerd met uitkomsten afkomstig van veel van onze balans- en voederproeven. De standaardafwijking van de bemonsterings- en analysefout voor P in de mengvoeders met toegevoegd anorganisch-P van ons onderzoek waren resp. 0,12 en 0,14 g P/kg droge stof en die van mengvoeders zonder toegevoegd anorganisch-P 0,07 resp. 0,12 g P/kg droge stof. In onze proeven zijn de voeders intensief gemengd, zodat verondersteld mag worden dat de bemonsteringsfout in de praktijk groter is.
Bij de door ons gebruikte voeders met lage P-gehaltes werd een afname in P-absorptie% bij het zwaarder worden van een varken (40 tot 100 kg) niet aangetoond. Wel had het Ca-gehalte in het voeder en enigszins het voederniveau invloed op die afname.
Er was een duidelijk positief verband tussen de verteerbaarheid van de droge stof en het absorptie% van P. Omdat in een aantal proeven met individuele dieren op stofwisselingskooien dit verband niet altijd even duidelijk aanwezig was, wordt ontraden in dergelijke proeven zonder meer de verteerbaarheid van droge stof als covariabele te gebruiken voor correctie van het P-absorptie%. In de proef met groepen biggen, waarin diverse P-bronnen met elkaar vergeleken zijn, lijkt het gebruik van de verteerbaarheid van droge stof als covariabele perspectief te bieden.
De hoeveelheid P en Ca in het varken is ook geschat uit de hoeveelheid as en het asgehalte in enkele botten als radius (spaakbeen) en staartwervel. De (vijfde) staartwervel lijkt wat gevoeliger voor verschillen in mineralenvoorziening dan de radius. Het schatten van de hoeveelheid P in varkens bij het geslacht gewicht op basis van de hoeveelheid vetvrije droge stof of as in de radius had binnen de proef een standaardafwijking van 30 g; tussen proeven was de schatting nog veel onnauwkeuriger.
In hoofdstuk 18 zijn op basis van voorgaande resultaten P-normen voor slachtvarkens geformuleerd. Deze normen werden afgeleid met behulp van de factoriële methode, waarbij rekening is gehouden met de hoeveelheid P die nodig is voor onderhoud en voor groei (Tabel 147). In deze normen is eveneens rekening gehouden met de samenstelling van de groei (normale of eiwitrijke), terwijl tevens voorstellen zijn gedaan voor optimale P-normen (voor vrijwel maximale botmineralisatie) en voor P-normen die juist voldoende zijn voor slachtvarkens (Tabel 148 en 149). Deze normen zijn uitgedrukt in verteerbaar P; in de hoofdstukken 13 en 14 is een richtlijn vermeld voor het bepalen van het gehalte van een voeder daaraan. Het is gewenst dat de Ca/verteerbaar P verhouding in het voeder voor slachtvarkens tussen 2,9 en 3,5 ligt.

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A P P E N D I C E S

Appendix 1. Assumed phoshorus and phytate phoshorus content in feedstuffs (g/kg; Simons et al., 1981; Chapters 2.8 and 5.3.)

feedstuff	phoshorus	phytate P	feedstuff	phoshorus	phytate P
barley	3.3	2.1	cottonseed meal	8.0	5.6
oats	3.3	2.0	groundnut meal	6.4	4.2
sorghum	2.7	1.9	soybean meal solv. extr. (44)	6.5	3.9
millet	3.2	2.3	soybean meal solv. extr. (50)	7.8	4.7
maize	2.5	1.6	isolated soy-protein	0.1	0
wheat	3.3	2.4	blood meal	1.6	0
rice	2.6	1.3	bone meal	88.0	0
peas	4.1	2.0	casein	4.0	0
beans	3.9	1.8	white fish meal	37.0	0
wheat middlings	10.9	8.1	fish meal	23.0	0
wheat bran	11.8	8.7	herring meal (Norw.)	19.0	0
maize gluten feed	8.5	5.6	herring meal (Danish)	20.6	0
wheat gluten	1.3	1.0	blood fibrin	0.9	0
cane molasses	0.7	0	tankage	39.7	0
tapioca	1.0	0.4	meat and bone meal	54.7	0
potato flakes	2.1	0	whey powder	6.6	0
rape	7.4	5.2	feather meal	1.8	0
coconut meal	5.5	2.9	grass meal	4.0	0.2
linseed meal	8.9	5.3	lucerne meal	2.7	0.3
linseed expeller	8.0	4.8			

Appendix 2. Amount of faecal loss of endogenous P in pigs (Chapter 2.8.2.)

Ca (% in T) of diet	P	number of observations	weight (kg)	intake of P (mg/d)	technique[a]	remarks	faecal endogenous P (mg/d)	(mg/kg/d)	reference
0.44	0.22	7	±25	2250	i.p. 40 mCi	without addition of Pi	88	2.9	Cupák et al.(1972)
0.98	0.70	5	±25	7000	"	dicalcium phosphate added	53	1.8	"
0.98	0.70	6	±25	7050	"	sodium polyphosphate added	63	2.1	"
0.98	0.58	6	±25	5810	"	superphosphate added	176	5.9	"
0.40	0.29	4	±80	4701	i.m. 4.4 mCi		184	2.3	Vemmer and Oslage(1973
0.53	0.39	4	75	3943	i.m. 4.0 mCi	0.28% P from Ca phytate	170	2.3	"
1.08	0.58	4	55	11600	s.c. 1-3 mCi		320	5.8	Brüggeman et al.(1962)
0.49	0.33	2	29	3300	"		41	1.4	"
0.49	0.33	2	68	6600	"		170	2.5	"
0.49	0.33	2	15	1765	"		37	2.5	"
0.82	0.33	4	79	6700	"		256	3.2	"
0.82	0.33	1	25	3350	"		36	1.4	"
0.82	0.67	1	20	3342	"	0.33% P from Ca phytate	435	21.8	"
0.13	0.22	1	40	2250	"		190	4.8	"
0.23	0.25	1	41	2250	"		190	4.6	"
0.06	0.12	1	28	1200	"	0.05% P from Ca phytate	80	2.9	"
0.12	0.17	1	29	1700	"	0.10% P " "	90	3.1	"
0.23	0.27	1	29	2700	"	0.20% P " "	150	5.2	"
0.33	0.37	1	30	3700	"	0.30% P " "	170	5.7	"
0.82	0.33	1	18	1790	"		23	1.3	"
1.08	0.58	2	30	8700	"		440	14.7	"
0	0	2	144	0	mineral free diet		600	4.1	Molnar et al.(1966/67)
0	0	2	178	0	"		510	3.0	"
0.67	0.63	7	230	21940	i.m.1.3-9.9mCi	pregnant sows	1296	5.6	Gütte et al. (1961)
0	0	2	144	0	i.m. 11 mCi	P free diet	570	4.0	Lantsch et al. (1965)
0.90	0.60	3	186	22000	i.m. 11 mCi, intake: i.v. 10-18mCi	21-23 g/P/d	1320	7.1	"
*	*	10	± 200	16577	i.p. 40 Ci	pregnant sows	560	2.8	Procházka and Jambor(1978)
*	*	6	± 200	32830	i.p. 40 Ci	lactating sows	738	3.7	"
0.67	0.63	8	196	21940	i.m. 3 mCi	lactating sows	1116	5.7	Gütte et al. (1961)
0.83	0.64	2	38-100	*	i.m. 4 mCi	same diet from 38-100kg	*	5.6	Vemmer (1982)
0.47	0.30	2	39-102	*	i.m. 4 mCi	same diet from 39-102kg	*	4.8	"
1.01	0.83	4	14	4465	i.m. 16.7 mBq		*	16.6	Partridge (1981)
0.92	0.69	4	35	8815	i.m. 16.7 mBq		*	17.6	"

[a] i.p. = intra peritoneal; i.m. = intra muscular; i.v. = intra veneous; s.c. = subcuteneous; mCi = milli Curie; mBq = milli Becquerel

* value not given

Appendix 3. *Absorption of total P and phytate P; detailed data of diets containing two feedstuffs and no supplemented P* (Chapter 2.8.3.)

Diet	in diet (g/kg dm) Ca	P	phytate P as % of total P	method	n	live weight (kg)	absorption% of total P	absorption% of phytate P phytate1	phytate2	phytate3	reference
barley + soybean meal	4.9	3.3	52	5	6	13-72	38	-20	-14	2	Brüggemann et al. (1962)
"	8.0	4.1	60 +[1]	1	4	50	30	-17	- 3	2	King (1980)
corn + soybean meal	⋆[2]	3.9	60 +	1	7	55	32	-13	0	6	Harmon et al. (1970[a])
"	⋆	3.9	60 +	1	7	15	39	- 2	11	16	"
"	3.2	2.9	60 +	1	3	30	36	1	12	20	Vipperman et al. (1974)
"	5.9	2.9	60 +	1	3	30	15	-13	-22	-14	"
"	8.8	2.9	60 +	1	3	30	16	-29	-18	-10	"
"	6.8	3.4	55	1	4	25	30	-21	- 6	1	Bayley et al. (1975[a])
" pellets	6.8	3.6	55	1	4	25	41	- 8	8	15	"
"	9.5	3.3	50	1	4	25	43	- 4	12	20	"
" pellets	11.2	3.9	50	1	4	25	44	-18	5	12	"
"	10.0	3.9	61 +	1	4	25	19	-31	-19	-12	Bayley and Thomson (1969)
" pellets	10.0	3.9	61 +	1	4	25	29	-15	- 3	3	"
"	5.9	3.7	68	1	4	43	22	-16	- 6	1	Pointillart et al. (1985[b])
"	5.9	3.7	68	1	4	52	26	-10	0	7	"
sorghum + soybean meal	5.8	4.0	60 +	1	6	45	36	- 7	6	13	Moser (1980)
corn + rapeseed meal	6.0	5.4	81	1	4	39	34	19	24	27	Pointillart et al. (1985[b])
"	6.0	5.4	81	1	4	46	13	- 7	- 2	1	"

1) + : value not available and is estimated

2) ⋆ : value not available

3) method 1 = digestibility exp. direct
2 = " " indirect
3 = slope ratio technique on bone ash with $NaH_2PO_4.H_2O$ as a reference
4 = " " " " breaking strength with $NaH_2PO_4.H_2O$ as a reference
5 = digestibility exp. with labelled P direct
6 = " " " " indirect
7 = slope ratio technique on digestibility of P

4) phytate 1 = 100% of inorganic P is absorbed
phytate 2 = 80% " " "
phytate 3 = as phytate 2 but also 5 mg P end/kg body weight

Appendix 4. Absorption of total P and phytate P; detailed data of feedstuffs (for explanation see Appendix 3; Chapter 2.8.3.)

Feedstuff	in feedstuff (g/kg T) Ca	P	phytate P	method[3]	n	live weight (kg)	absorption% of total P	absorption% of phytate P[4] phytate 1	phytate 2	phytate 3	reference
alfalfa meal	14.1	3.4	0 +[1]	4	5	15-42	100	100	100	104	Cromwell et al. (1983)
barley (Vanguard)	*[2]	3.8	2.5 +	4	5	16-34	31	- 6	5	10	Stober et al. (1979)
"	*	6.1	2.6	5	4	80	59	4	31	40	Vemmer and Oslage (1973)
"	0.5	3.3	2.1	1	2	52	51	24	35	51	Weiser (1912)
"	0.9	4.8	3.1	1	5	37	34	-24	- 7	4	Weigand and Kirchgessner (1980)
"	*	*	*	2	*	45	18	-26	-16	- 8	Besecker et al. (1967)
"	*	3.2	2.1 +	2	4	50	16	-27	-17	- 8	Calvert et al. (1978)
"	0.9	4.8	3.1	1	5	37	42	- 1	14	21	Weigand and Kirchgessner (1980)
corn	*	*	*	4	5	15-36	29	- 8	3	9	Huang and Allee (1981)
"	*	3.2	2.1 +	4	5	15-36	16	-27	-17	-11	Miracle et al. (1977)
" dried	*	3.7	2.4 +	4	4	15-36	10	-36	-26	-21	Ross et al. (1983)
" most + acid	*	3.7	2.4 +	4	4	15-37	58	36	47	52	"
" pelleted	*	3.7	2.4 +	4	4	15-36	12	-33	-23	-18	"
" reconstituted	*	3.7	2.4 +	4	4	15-37	25	-14	- 3	2	"
" dried	*	3.0	2.0 +	4	4	15-32	18	-24	-14	- 8	"
" moist + acid	*	3.0	2.0 +	4	4	15-32	48	21	32	37	"
" moist	*	3.0	2.0 +	4	4	15-31	40	9	19	25	"
" reconstituted	*	3.0	2.0 +	4	4	15-31	26	-12	- 2	4	"
"	*	3.2	2.1 +	4	5	16-36	9	-38	-28	-22	Stober et al. (1979)
"	0.1	3.1	2.0	1	4	50	30	- 5	5	19	Weiser (1912)
"	*	3.3	2.2 +	1	5	50	12	-35	-24	-14	Calvert et al. (1978)
"	*	3.8	2.7	1	4	27	29	- 1	8	13	Pointillart et al. (1984)
" moist	*	3.9	2.6 +	8	8	16-26	41	11	21	25	Boyd et al. (1981)
cotton seed	*	12.7	8.9 +	4	6	15-28	0	-43	-34	-33	Stober et al. (1980[a])
"	*	*	*	4	5	15-36	42	17	26	27	Huang and Allee (1981)
milo	*	*	*	4	5	15-36	25	- 7	1	7	Huang and Allee (1981)
oats	*	*	*	4	5	15-36	36	- 7	7	12	Huang and Allee (1981)
"	*	3.9	2.3 +	4	6	15-34	23	-28	-15	-10	Stober et al. (1980[b])
palm kernel cake	2.2	7.8	4.7 +	4	8	12-29	11	-48	-35	-33	Hew et al. (1982)
peanut meal	2.0	6.7	4.4 +	4	8	12-29	12	-33	-23	-21	Hew et al. (1982)
peanut hulls	2.6	1.0	0.6 +	7	6	80	-20	-100	-86	-53	Lindemann et al. (1984)
rice bran	0.7	16.7	8.4 +	4	8	12-29	25	-50	-30	-29	Hew et al. (1982)

Appendix 4. continued

Feedstuff	in feedstuff (g/kg T) Ca	P	phytate P	method[3]	n	live weight(kg)	absorption% of total P	absorption% of phytate P[4] phytate 1	phytate 2	phytate 3	reference
sorghum dried	*	*	*	4	9	15-35	19	-16	- 7	-1	Trotter and Allee (1979[a])
" moist + acid	*	*	*	4	9	15-35	42	17	26	32	"
" moist	*	*	*	4	9	15-35	43	19	27	33	"
"	*	*	*	2	8	40	3	-36	-28	-20	Tonroy et al. (1973)
soybean meal	*	*	*	4	5	15-35	17	-38	-25	-22	Cromwell (1980)
"	*	*	*	2	6	40	27	-22	- 8	- 5	Tonroy et al. (1973)
"	*	*	*	4	5	15-36	36	- 7	7	10	Huang and Allee (1981)
" 44XP	*	6.7	4.0 +	4	6	12-33	38	- 3	10	13	Ross et al. (1982)
" 48XP	*	7.6	4.6 +	4	6	12-32	22	-30	-17	-14	"
" dehulled	*	7.5	4.5 +	4	5	15-36	18	-37	-23	-21	Miracle et al. (1977)
wheat	*	*	*	4	5	15-35	40	19	26	30	Cromwell (1980)
"	*	*	*	4	5	15-36	51	34	41	45	Huang and Allee (1981)
"	*	4.4	3.3 +	4	5	15-36	51	34	41	45	Miracle et al. (1977)
"	*	4.1	2.7	1	4	28	46	19	29	35	Pointillart et al. (1984)
" soft red winter	*	4.7	3.5 +	4	6	13-33	51	34	41	45	Cromwell et al. (1985)
wheat bran	*	*	*	6	16	30-50	36	14	21	23	Guéguen et al. (1968)
"	*	13.4	9.9 +	4	6	15-34	35	12	19	20	Stober et al. (1980[b])
wheat middlings	*	*	*	7	*	20	52	35	42	43	Erickson et al. (1979)
"	*	10.7	7.9 +	4	6	15-34	34	10	18	19	Stober et al. (1980[b])
wheat pollard	1.7	10.3	7.6 +	4	8	12-29	55	39	46	48	Hew et al. (1982)
wheat offal	*	11.2	9.6	1	14	26	52	38	44	48	Frape et al. (1979)

Appendix 5. Results of experiments to assess value of P sources (Chapter 2.8.4.)

diet	weight (kg)	number pigs/ tr.mt.	number of observ.	Ca% in diet	P% total in diet	P% added	criteria[5]	mean gr (kg/d)	mean fc	mean fi (kg/d)	ranking order[1, 2]	references
corn,soy,tankage	28	7 or 2	7 or 2	1.19	0.85	-	^{32}P abs%	*	*	0.9	Cha,Def,DCP*,SoP*,NRP	Ammerman et al.(1963)
"	"	"	"	"	"	-	^{32}P ret%	*	*	0.9	Cha,DCP,Def,SoP*,NRP	"
corn, soy	30-90	6	1	0.8/0.7[3]	0.6/0.5	0.16	gr,fc	0.81	3.7	2.9	DCP,SoP*	Aldinger et al. (1959)
corn, soy	5-*[4]	*	*	0.8,0.6	0.6,0.5	*	gr,fc,fi,BA	*	*	*	FiM,DCP*	Blance and Young (1969)
"	5-*	*	*	0.8	0.5	*	gr,fc,fi,BA	*	*	*	FiM,DCP*	"
"	7-22	72	9	*	*	0.33	gr	*	*	*	DCP=MAP	Borggreve and v.d. Kerk (1978)
"	7-22	72	9	*	*	0.33	fc	*	*	*	MAP,DCP*	"
corn,soy, feather meal	7-91	*	*	0.58	0.29	*	gr,fc,fi	*	*	*	DCP=Def=Cur	Chamberlain and Griffin (1963)
"	"	*	*	0.70	0.35	*	gr,fc,fi	*	*	*	DCP=Def=Cur	"
corn, soy	15-40	24	6	*	*	0.1,0.2	gr,fc,fi,BS,BA	0.60	2.44	1.5	MBM=DCP	Cromwell et al. (1976)
"	15-96	18	6	*	*	0.10,0.15 0.20,0.25	gr,fc,fi, BS,BA	0.72	3.12	2.3	MBM=DCP	"
wheat, blood meal	25	6	6	0.98	0.75	0.50	^{32}P ret%	*	*	*	SPP,DCP,Sup	Cupák et al. (1972)
corn, soy	9-38	12	1	*	0.35,0.45,0.55	*	gr	0.51	2.16	1.10	MSP,DCP,Def	Futrell et al. (1969)
"	9-38	12	1	*	0.35,0.45,0.55	*	fc	0.51	2.16	1.10	MSP,Def,DCP	"
"	9-35	12	1	*	0.35,0.45,0.55	*	BA	0.51	2.16	1.10	MSP=Def=DCP	"
corn,soy	35-90	10	12	0.85	0.30,0.50,0.70	0, 0.1,0.2	gr,fc,fi,BA	0.52	3.7	1.9	DCP,SoP*	Harmon et al. (1970[b])
"	27-90	10	12	0.85	0.30,0.50,0.70	0,0.1,0.2	gr,fc,fi,BA	0.52	3.7	1.9	DCP,SoP*	"
corn, soy	28-90	20	2	0.72	0.45,0.60	*	gr,fc,fi,BS,BA	*	*	*	DCP=Def	Harmon et al. (1974)
"	11-90	15	3	0.72	0.42,0.54,0.66	0.12,0.24,0.36	gr,fc,fi	*	*	*	DCP=Def	"
barley, soy	17-102	36	3	0.75	0.4,0.6,0.8	0, 0.2,0.4	gr	0.76	3.3	2.5	MSP=Def,STP=DCP	Newman and Elliot (1976)
"	"	"	"	"	"	"	fc	"	"	"	DCP,MSP,Def,STP	"
barley, soy	19-99	47	1	0.7	0.6	0.25	gr	0.76	3.8	2.9	MSP,Def	"
"	"	"	"	"	"	"	fc	"	"	"	Def,MSP	"
barley, soy	20-99	18	3	0.75,1.10	0.5,0.75	0.16,0.41	gr	0.68	3.6	2.4	MSP=Def	"
"	"	"	"	"	"	"	fc	"	"	"	MSP,Def	"
corn, soy	20-*	55	11	*	*	*	gr,fc	0.77	3.2	2.4	TCP,DCP*	Noland et al. (1964)
corn, soy	20-91	12	2	0.65	0.65	0.31	gr,BA	0.71	2.9	2.2	DCP,Def,TCP	Noland et al. (1971)
"	"	"	"	"	"	"	fc	"	"	"	Def,TCP,DCP	"
synthetic	19-90	6	6	0.90	0.30,0.45,0.60	0.12,0.27,0.42	gr,BA	0.80	3.3	2.6	DCP,SoP	Plumlee et al. (1958)
"	"	"	"	"	"	"	fc	"	"	"	DCP=SoP	"
synthetic	18-57	6	6	0.90	0.30	0.12	gr	0.63	2.9	1.8	Cur,MCP=BoM,SoP=DCP,Def	"
"	"	"	"	"	"	"	fc	"	"	"	SoP,MCP,BoM,Cur,Def,DCP	"
"	"	"	"	"	"	"	BA	"	"	"	BoM,MCP,Def,Cur,DCP,SoP	"
synthetic	16-50	6	6	0.82	0.28	0.24	gr,fc	0.59	2.7	1.6	DCP,MCP,SoP*	"
synthetic	12-47	6	6	0.65	0.28	0.24	gr	0.58	2.3	1.4	DCP,BoM,MCP,Cur,SoP*	"
"	"	"	"	"	"	"	fc	"	"	"	Cur,DCP=MCP,BoM,SoP*	"

Appendix 5. continued

diet	weight (kg)	number pigs/ tr.mt.	number of observ.	Ca% in diet	P% total in diet	P% added	criteria[5]	mean gr (kg/d)	mean fc	mean fi (kg/d)	ranking order	reference
synthetic	12-47	6	6	0.65	0.28	0.24	BA	0.58	2.3	1.4	MCP,DCP,Cur,BoM,SoP*	Plumlee et al. (1958)
synthetic	9-42	6	6	0.65	0.30	0.26	gr	0.48	2.54	1.22	FPA, DCP	"
"	"	"	"	"	"	"	fc	"	"	"	DCP,FPA	"
corn, soy	15-88	12	1	0.65	0.45	0.15	gr	0.70	3.4	2.4	FPA,DCP	"
"	"	"	"	"	"	"	fc	"	"	"	DCP,FPA	"
wheat,barley corn, blood	20	3to20	3to20	0.98	0.75	0.25	^{32}P abs%	-	-	1.5	DSP,SPP,Sup,DCP,TCP	Procházka et al. (1972)
"	"	"	"	"	"	"	^{32}P in bone	-	-	1.5	Sup,DCP,SPP,DSP,TCP	"
*	5-20	19	19	*	*	0.35	gr,fc	0.34	1.63	0.56	Hos,DCP	Rosin (1972)
*	"	10	10	*	*	"	BA	"	"	"	Hos,DCP	"
corn, soy	5-20	15	2	*	0.35,0.45	0.1,0.2	gr,fc	*	*	*	DCP,BoM,Def	Van Zante et al. (1967)
synthetic	16-42	3	1	0.55	0.45	0.25	gr,fc	0.44	3.34	1.47	Sup1150°C,Sup250°C,DCP	Wicke (1972)
"	"	"	"	"	"	"	BA ,BS	"	"	"	DCP,Sup250,Sup1150	"
*	45	*	*	0.70	0.50	-	^{32}Pabs%, ^{32}Pret%	-	-	-	DSP,DSP+Ca,NRP	Guéguen and Rerât (1965)
corn, soy	11-91	16	4	0.70	0.50	0.15,0.30	gr,fc,fi	0.72	3.16	2.27	BoM,DCP,SoP*	Chapman et al. (1954)
"	"	"	"	"	"	"	BS	"	"	"	BoM,DCP*,SoP	"
"	"	"	"	"	"	"	BA	"	"	"	SoP,BoM*,DCP	"
*	20-100	*	*	*	*	*	*	*	*	*	MSP,MCP,Hos,DSP,TSP, DCP,TCP	Günther (1973)
barley, soy skimmilk	6-20	18	18	0.91	0.75	0.32	^{32}Pabs%,gr,fc,BA	0.40	1.50	0.60	DCP=Def	Partridge (1981)
milo, soy	25-95	10	10	0.80	0.80,0.49	0.38	gr,fc	0.72	3.18	2.29	BoM=MAP,MgP*	Kromka et al. (1979)
*	15-35	14	14	*	*	*	BS	*	*	*	DCP,MSP,BoM	Huang and Allee (1981)
corn, soy	12-102	30	3	0.65	0.41,0.51,0.61	0.10,0.20,0.30	gr,fc,fi	0.73	3.01	2.15	Def=DCP	Hagemeier et al. (1981)
"	"	"	"	"	"	"	BA,BS	"	"	"	Def,DCP	"
corn, soy	22-94	8	8	0.75	0.60	0.40	gr,fc,fi,BA,BS	0.79	3.40	2.69	Def=APP	Clawson and Armstrong (1981)
sorghum, soy	20-100	40	4	var.	0.40,0.50	0.10,0.20	gr,fc,fi	0.66	3.24	2.17	DCP=APP	Tunmire et al. (1983)
"	"	"	"	"	"	"	BA,BS	"	"	"	DCP,APP	"
barley, soy	24-75	10	10	0.73	0.54	0.18	gr,fc,BA	0.68	3.63	2.47	DCP=BoM=Def	King (1980)
"	"	"	"	"	"	"	fi	"	"	"	Def,BoM=DCP	"
"	"	"	"	"	"	"	Pabs%	"	"	"	BoM,DCP=Def	"
barley, soy	20-50	18	18	0.81	0.61	0.19	^{32}Pabs%,gr,fc,BA	0.56	1.45	2.62	DCP=Def	Partridge (1981)
semi synth.	30-50	6	6	0.49	0.13-0.29	0, 0.08,0.16	Pabs%	*	*	*	MCP,DCP.2H_2O,DCP,oH_2O	Grimbergen et al. (1985)
"	"	"	"	"	"	"	"	*	*	*	MCP,DCP.2H_2O,DCP,oH_2O	"
practical	8-33	26	2	1.40	0.87	*	gr,fc,BA	0.54	2.14	1.16	DCP,TCP	Latimier et al. (1982)
"	7-32	39	3	1.13	0.85	*	gr	0.50	2.10	1.05	TCP,DCP	"
"	"	"	"	"	"	"	fc,BA	"	"	"	DCP,TCP	"
corn, soy	22-97	96	3?	*	*	*	gr,fc,fi	0.77	3.09	2.37	DCP,DFP	Peo et al. (1984)
corn, soy	21-94	16	16	0.6/0.5	0.5/0.4	0.17/0.08	gr,fc,fi	0.78	3.18	2.47	DRP=APP	Clawson and Southern (1985)
"	22-94	8	8	"	"	"	gr,fc,fi	0.77	3.28	2.51	DRP=APP,NRP,TSuP	"
"	24-94	8	8	0.8	0.6	0.27	gr,fc,fi	0.83	3.24	2.68	APP=DRP=TSuP,NRP	"
corn, soy	24-108	48	*	0.72/0.60	0.6/0.48	*	gr,fc,fi,BS	*	*	*	DCP=DFP	Kornegay et al. (1984)

Appendix 5 continued.

1) the P source with the highest effect is given first, marked with * gives a significantly lower effect than the preceeding one.
2) legend of P sources
3) change to lower concentration during experiment
4) value not given
5) gr=growth rate; fc=feed conversion ratio; fi=feed intake; BS=breaking strength; BA=bone ash percentage

			Ca%	P%
APP	= ammonium polyphosphate	$(NH_4)_3\ P_3O_9$	-	32
BoM	= bonemeal	-	32	14
Cha	= chloroapatite	$Ca_{10}(PO_4)_6Cl_2$	36	17
Cur	= Curacao Island phosphate	mainly $Ca_{10}(PO_4)_6F_2$ and $Ca_{10}(PO_4)_6(OH)_2$	35	15
DCP	= dicalcium phosphate	$CaHPO_4.2H_2O$	23	18
Def	= defluorinated phosphate	several possibilities	35	14
DSP	= disodium phosphate	$Na_2HPO_4.12H_2O$	-	9
FiM	= fishmeal	-	4	3
Hos	= Hostaphos	Ca, Mg, Na H_2PO_4	9	17
MAP	= monoammonium phosphate	$NH_4H_2PO_4$	-	27
MBM	= meat and bonemeal	-	12	3
MCP	= monocalcium phosphate	$Ca(H_2PO_4)_2.H_2O$)	16	25
MgP	= magnesium phosphate	-	28	19
MSP	= monosodium phosphate	$NaH_2PO_4.2H_2O$	-	20
NRP	= natural rock phosphate	$FeAlPO_4$	-	13
PPA	= phosphoric acid	H_3PO_4	-	28
SOP	= soft phosphate	$Ca_5(PO_4)_3F$	36	15
SPP	= sodium pyrophosphate	$Na_4P_2O_7$	-	23
STP	= sodium tripolyphosphate	$Na_5P_3O_{10}$	-	25
Sup	= Superphosphate	$Ca(H_2PO_4)_2$	36	15
Sup 250°C	= " at 250°C	"	36	15
Sup 1150°C	= " at 1150°C	"	36	15
TCP	= tricalcium phosphate	$Ca_3(PO_4)_2$	39	20
TSP	= trisodium phosphate	Na_3PO_4	-	17
TSup	= triple Superphosphate	-	14	21

Remark: The P sources had not in all experiments the same composition, moreover is not known how many H_2O molecules were present as crystalline water.

Appendix 6a. P and Ca retention per day and per kg live weight gain (mean and sd) reliable data and the Ca and P concentrations in diets* (Chapter 4.4.2.)

live weight range (kg)	5-9	10-14	15-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-110
live weight (kg)	9	11	15±1	26±2	34±2	43±2	56±3	63±3	75±4	83±2	96±5
Ca% in T diet	0.84	0.84	0.98±0.12	0.99±0.37	1.04±0.29	0.80±0.27	0.91±0.32	0.74±0.13	0.74±0.12	0.76±0.11	0.62±0.18
P% in T diet	0.63	0.63	0.80±0.12	0.63±0.12	0.78±0.13	0.71±0.11	0.67±0.08	0.61±0.14	0.48±0.14	0.63±0.15	0.43±0.17
Ca retention (g/d)	2.6 ±0.2	3.0 ±0.8	3.9 ±0.2	4.7 ±1.5	5.2 ±1.1	5.4 ±1.6	6.4 ±1.7	6.2 ±1.8	8.4 ±0.9	6.6 ±1.2	7.4 ± 1.6
P retention (g/d)	1.7 ±0.1	2.2 ±0.6	2.4 ±0.5	2.4 ±1.0	3.0 ±0.6	3.3 ±0.9	4.2 ±1.0	3.8 ±1.0	4.4 ±1.0	4.0 ±0.6	4.4 ± 1.3
Ca/P retention	1.52±0.07	1.39±0.08	1.53±0.05	2.06±0.88	1.73±0.17	1.66±0.24	1.53±0.33	1.58±0.10	1.70±0.10	1.66±0.21	1.70±0.15
growth (kg/d)	0.26±0.02	0.27±0.03	0.39±0.06	0.52±0.13	0.52±0.06	0.61±0.09	0.64±0.09	0.69±0.12	0.79±0.09	0.66±0.09	0.81±0.10
Ca retention (g/kg growth)	10.2 ±0.5	11.2 ±2.6	9.6 ±0.4	8.4 ±3.6	10.1 ±1.7	8.8 ±2.0	10.3 ±3.1	8.9 ±1.1	10.2 ±0.6	10.1 ±1.4	9.1 ±1.1
P retention (g/kg growth)	6.8 ±0.7	8.2 ±2.0	6.1 ±0.6	5.6 ±0.5	5.8 ±0.7	5.3 ±1.0	6.7 ±1.8	5.5 ±0.7	5.7 ±0.8	6.0 ±0.8	5.4 ±1.0
n (for Ca n is sometimes lower)	77	76	34	24	67	21	39	14	11	23	8

* data were taken when Pi % in T diet was ≥ 0.15%, Ca% in T diet ≥ 0.45%, level of feeding ≥ 628 kJ $NE_f/W^{3/4}$, Ca/P ratio of retention from 1.0 to 2.2

Appendix 6b. P and Ca retention per day and per kg live weight gain (mean and sd) of all balance experiments and the Ca and P concentrations in the diets* (Chapter 4.4.2)

live weight range (kg)	5-9	10-14	15-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-109
n	77	80	34	127	141	73	88	55	11	43	24	14
live weight (kg)	9	11±1	15	25±1	32±2	44±2	54±3	64±4	75±4	82±2	91±2	100±1
Ca% in T diet	0.84	0.85±0.04	0.98±0.12	0.94±0.21	0.92±0.26	0.75±0.25	0.93±0.33	0.78±0.18	0.74±0.12	0.76±0.10	0.74±0.17	0.83±0.11
P% in T diet	0.63	0.65±0.11	0.80±0.12	0.60±0.16	0.73±0.13	0.60±0.16	0.66±0.12	0.67±0.12	0.48±0.14	0.63±0.12	0.65±0.18	0.49±0.07
P retention (g/d)	1.7 ±0.1	2.2 ±0.6	2.4 ±0.5	2.5 ±1.2	3.6 ±1.4	3.3±1.2	4.0 ±1.2	5.8 ±2.6	4.4 ±1.0	4.8 ±1.1	7.9 ±4.8	9.1 ±2.3
Ca retention (g/d)	2.6 ±0.2	3.0 ±0.8	3.9 ±0.2	3.7 ±1.0	5.1 ±1.4	4.6 ±2.2	6.8 ±1.6	7.2 ±2.1	8.4 ±0.9	7.3 ±1.2	9.5 ±3.6	9.4±2.8
Ca/P retention	1.52±0.07	1.38±0.08	1.53±0.05	1.98±1.17	1.47±0.37	1.38±0.38	1.66±0.61	1.32±0.32	1.70±0.10	1.52±0.22	1.44±0.66	1.07±0.31
n	77	80	34	58	117	49	86	55	10	42	24	2
growth (kg/d)	0.26±0.02	0.26±0.04	0.39±0.06	0.42±0.10	0.50±0.08	0.61±0.09	0.63±0.10	0.70±0.09	0.79±0.09	0.72±0.09	0.60±0.14	0.82±0.12
P retention (g/kg growth)	6.8 ±0.6	8.2 ±2.0	6.2 ±0.6	6.2 ±1.0	7.5 ±4.0	6.5 ±2.2	6.4 ±2.0	8.2 ±3.6	5.7 ±0.8	6.7 ±1.0	13.4±7.2	-
Ca retention (g/kg growth)	10.2 ±0.5	11.3 ±2.5	9.6 ±0.4	9.0 ±2.6	10.5±3.9	9.6±4.8	11.6 ±5.2	10.2±0.6	10.2±0.6	10.1±1.2	16.1±6.1	-

* data were taken when Pi % in T diet was < 0.15%, Ca% in T diet < 0.45%, level of feeding < 628 kJ $NE_f/W^{3/4}$

Appendix 7. Variation in amount of Ca and P in the live weight groups of pigs (mean and sd) (Chapter 4.4.3.)

number of observations	live weight (kg)	amount (g) Ca	amount (g) P		reference
6	7 ± 2	58 ± 16	36 ± 10	individual	Spray and Widdowson (1950)
11	11 ± 1	91 ± 10	59 ± 5	groups of 5 pigs	Müller and Kirchgessner (1974)
12	15 ± 1	145 ± 29	87 ± 15	individual	Mudd et al. (1969[a])
5	16 ± 2	99 ± 8	60 ± 5	groups of 10 pigs	Günther et al. (1967/1968)
6	16 ± 2	115 ± 19	73 ± 10	individual	Rymarz et al. (1982)
7	17 ± 4	150 ± 36	95 ± 20	individual	Blair et al. (1963)
5	18 ± 2	132 ± 7	83 ± 6	individual	Rymarz et al. (1982)
4	20	179 ± 21	112 ± 12	groups of 5 pigs	Günther and Rosin (1970)
6	20 ± 1	163 ± 7	106 ± 6	individual	Stoy (1983)
7	25 ± 1	193 ± 10	116 ± 7	individual	Oslage (1964)
4	25 ± 2	214 ± 13	133 ± 10	individual	Moinizadeh (1975)
6	28 ± 2	235 ± 37	145 ± 18	individual	Rymarz et al. (1982)
3	31 ± 1	240 ± 3	147 ± 2	groups of 2, 3 and 4 pigs	Weniger and Funk (1953[b])
4	40 ± 1	316 ± 19	194 ± 12	groups of 3 pigs	Weniger and Funk (1953[b])
4	40 ± 1	305 ± 26	200 ± 15	individual	Oslage (1964)
3	41	394 ± 33	236 ± 13	groups of 6 pigs	Mudd et al. (1969[b])
4	45 ± 3	365 ± 28	220 ± 19	individual	Rymarz et al. (1982)
4	48 ± 4	392 ± 16	240 ± 13	individual	Rymarz et al. (1982)
4	50	415 ± 34	259 ± 21	groups of 5 pigs	Günther and Rosin (1970)
4	53 ± 3	463 ± 38	280 ± 23	individual	Rymarz et al. (1982)
6	61 ± 1	450 ± 36	293 ± 19	individual	Oslage (1964)
4	68 ± 3	580 ± 44	338 ± 21	individual	Rymarz et al. (1982)
4	69 ± 6	530 ± 52	316 ± 67	individual	Rymarz et al. (1982)
4	74 ± 5	622 ± 35	383 ± 31	individual	Rymarz et al. (1982)
20	85 ± 3	738 ± 44	456 ± 28	groups of 4 pigs	Nielsen (1972)
4	86 ± 4	702 ± 50	411 ± 21	individual	Rymarz et al. (1982)
4	88 ± 4	738 ± 67	437 ± 29	individual	Rymarz et al. (1982)
6	91 ± 2	632 ± 14	402 ± 12	individual	Oslage (1964)
4	95 ± 4	872 ± 35	492 ± 13	individual	Rymarz et al. (1982)
4	99 ± 2	965 ±154	564 ± 68	individual	Moinizadeh (1975)
4	99 ± 2	889 ± 10	542 ± 7	individual	Moinizadeh (1975)

Appendix 7. continued

number of observations	live weight (kg)	amount (g) Ca	amount (g) P		reference
4	98 ± 2	842 ± 82	511 ± 40	individual	Moinizadeh (1975)
4	99 ± 2	806 ± 58	497 ± 31	individual	Moinizadeh (1975)
4	99 ± 2	792 ± 10	486 ± 7	individual	Moinizadeh (1975)
4	100	697 ±100	428 ± 61	groups of 8 or 16 pigs	Weniger and Funk (1953[b])
4	100	836 ±118	512 ± 70	groups of 5 pigs	Günther and Rosin (1970)
4	100 ± 8	910 ± 35	522 ± 11	individual	Rymarz et al. (1982)
6	98 ± 2	895 ± 64	535 ± 17	individual	Stoy (1983)
6	98 ± 2	795 ± 52	482 ± 30	individual	Stoy (1983)
6	100 ± 1	937 ± 49	585 ± 25	individual	Stoy (1983)
6	99 ± 2	864 ±102	538 ± 50	individual	Stoy (1983)
6	100 ± 2	879 ± 64	538 ± 29	individual	Stoy (1983)
6	100 ± 2	821 ±100	483 ± 56	individual	Stoy (1983)
6	100 ± 3	892 ± 59	533 ± 25	individual	Stoy (1983)
6	102 ± 3	954 ± 65	570 ± 35	individual	Stoy (1983)
5	101 ± 2	821 ± 79	508 ± 43	individual	Stoy (1983)
6	100 ± 4	876 ± 71	534 ± 31	individual	Stoy (1983)
4	103 ± 2	831 ± 67	469 ± 30	individual	Rymarz et al. (1982)
4	107 ± 2	998 ± 84	573 ± 41	individual	Rymarz et al. (1982)
29	110 ± 1	767 ± 66	485 ± 40	individual	Oslage (1964)
12	130 ± 3	961 ±137	581 ± 69	individual	Weniger and Funk (1953[b])

Appendix 8. Data from slaughter experiments

n	Sex[a]	age (d)	live weight	EBW	dry weight (g)	N (g)	fat (g)	ash (g)	Ca (g)	P (g)	rel[b]	reference
15	3	1	1.0	*	*	*	*	*	10.1	5.7	0	Günther et al. (1966/67)
3	3	1	1.0	*	202	21.9	27	39	10.8	6.3	0	Weniger and Funk (1953[a,b])
6	3	1	1.2	1.2	216	*	13	*	14.2	7.2	0	Mudd et al (1969[a])
1	3	1	1.2	*	*	22.1	*	*	12.9	7.7	0	Freese (1958)
4	3	1	1.3	*	259	26.2	19	49	13.0	8.0	0	Berge and Indrebø (1954)
6	3	1	1.2	*	*	19.5	*	*	13.2	7.7	0	Lenkeit (1957)
6	3	1	1.3	*	275	24.9	16	56	19.6	9.3	0	Becker et al (1979)
8	3	1	1.5	1.5	263	*	14	*	16.1	9.0	0	Mudd et al. (1969[a])
3	3	1	1.5	1.4	*	27.8	18	60	16.7	9.3	0	Manners and McCrea (1963[b])
3	3	1	1.5	*	*	*	*	*	17.0	10.0	0	Blair et al (1963)
16	3	1	1.5	*	*	*	80	*	14.2	8.1	0	Spray and Widdowson (1950)
3	2	2	1.8	1.7	*	37.9	40	67	17.9	10.8	0	Manners and McCrea (1963[b])
3	3	7	3.2	3.0	*	69.9	306	94	24.1	16.3	0	Manners and McCrea (1963[b])
7	3	7	2.3	*	606	51.5	207	63	16.0	12.0	0	Berge and Indrebø (1954)
2	3	11	2.5	*	*	53.3	*	*	28.2	13.1	0	Freese (1958)
3	3	14	5.6	5.3	*	123.2	796	161	41.7	28.1	0	Manners and McCrea (1963)
10	3	14	3.9	3.7	1028	91.1	329	104	25.7	17.8	0	Muller and Kirchgessner (1974)
3	3	14	3.9	*	1200	87.5	532	98	23.0	20.0	0	Berge and Indrebø (1954)
1	3	20	5.7	*	*	131.6	*	*	58.7	29.1	0	Freese (1958)
3	3	21	5.1	*	1551	112.8	690	142	35.0	25.0	0	Berge and Indrebo (1954)
10	3	21	6.0	*	*	*	1200	*	44.0	28.0	0	Spray and Widdowson (1950)
6	3	21	7.4	*	2490	154.6	1314	*	58.3	35.8	0	Spray and Widdowson (1950)
10	3	21	7.8	*	2226	183.8	789	210	62.8	36.8	0	Becker (1976)
11	3	21	6.0	*	*	*	*	*	40.7	25.4	0	Günther et al (1966/67)
3	3	28	5.9	*	1841	135.5	799	160	47.0	30.0	0	Berge and Indrebø (1954)
3	4	28	9.9	9.6	*	228.3	1763	324	87.6	56.3	0	Manners and McCrea (1963[b])
5	3	29	6.7	*	*	163.3	*	*	78.1	37.0	0	Freese (1958)
2	3	42	8.8	*	2930	204.2	1382	255	70.0	44.0	0	Berge and Indrebø (1954)
60	3	40	11.0	10.4	3052	283.4	934	333	89.1	57.4	0	Muller and Kirchgessner (1974)
24	3	*	11.3	*	*	*	*	*	76.8	46.1	1	Blair and Benzie (1964)
3	3	56	14.7	*	4983	336.3	2264	470	132.0	74.0	0	Berge and Indrebø (1954)
12	3	56	15.3	14.5	4316	*	1676	*	145.5	87.0	0	Mudd et al (1969[a])
11	2	77	17.1	15.4	4781	359.1	2098	439	122.7	77.6	0	Rymarz et al. (1982)
7	3	56	17.4	*	*	*	*	*	150.0	94.8	0	Blair et al. (1963)
50	3	56	16.4	*	*	*	*	*	98.8	59.6	1	Günther et al. (1967/68)
5	3	61	19.3	*	*	481.3	*	*	169.0	106.0	0	Mollgaard (1955)

Appendix 8: continued

4	3	56	12.0	*	*	*	1600	*	104.0	66.0	0	Spray and Widdowson (1950)
20	3	65	20.0	*	*	*	*	*	179.0	112.5	0	Günther and Rosin (1970)
2	3	*	20.1	19.1	6004	*	2429	*	181.3	108.7	0	Mudd et al (1969[a])
8	3	75	24.9	21.8	5984	598.8	1412	742	214.0	133.0	0	Moinizadeh (1975)
7	1	89	25.2	22.7	8076	567.1	3684	*	193.0	116.4	0	Oslage (1964)
6	2	91	28.3	25.8	8026	665.6	3050	816	235.0	145.0	0	Rymarz et al. (1982)
3	3	112	33.0	*	*	*	4400	*	220.0	157.0	0	Spray and Widdowson (1950)
6	3	*	23.0	*	*	*	*	*	211.3	127.5	0	Mudd et al. (1969[b])
9	3	*	31.3	*	12154	588.1	7564	914	240.3	147.4	0	Weniger and Funk (1953[a,b])
2	3	*	36.0	34.2	11373	*	4519	*	385.3	225.2	0	Mudd et al. (1969[a])
4	1	116	40.0	36.8	13137	964.3	6260	*	305.5	200.1	0	Oslage (1964)
9	3	*	39.8	*	15167	787.2	9036	1181	325.1	199.5	0	Weniger and Funk (1953[a,b])
18	3	*	41.0	*	*	*	*	*	393.8	236.0	0	Mudd et al. (1969[b])
8	2	126	46.2	43.2	16836	1090.4	8735	1286	378.5	230.0	0	Rymarz et al. (1982)
20	3	120	50.0	*	*	*	*	*	415.2	258.8	0	Günther and Rosin (1970)
4	2	126	53.1	49.5	18070	1296.0	8360	1610	463.0	280.0	0	Rymarz et al. (1982)
2	3	*	55.0	52.3	17962	*	7658	*	549.0	322.0	0	Mudd et al. (1969[a])
12	2	154	70.4	65.8	27157	1657.6	14807	1990	577.3	345.7	0	Rymarz et al. (1982)
2	3	168	76.0	*	*	*	16700	*	664.0	415.0	0	Spray and Widdowson (1950)
6	1	144	60.6	55.6	23800	1374.0	13771	*	450.3	292.6	0	Oslage (1964)
80	3	*	85.0	80.8	33936	2231.6	17341	2613	738.4	456.1	0	Nielsen (1972)
12	2	182	89.6	84.7	38322	2112.0	22590	2532	770.7	446.7	0	Rymarz et al. (1982)
6	1	183	91.2	85.4	41910	1965.2	27444	*	632.2	402.0	0	Oslage (1964)
2	3	*	90.6	86.1	36213	*	20195	*	791.0	451.6	0	Mudd et al. (1969[a])
39	3	192	98.7	92.0	38504	2489.0	20373	3011	832.2	509.2	0	Moinizadeh (1975)
40	3	*	100.0	*	*	*	*	*	736.1	451.7	0	Weniger and Funk (1953[a,b])
20	3	182	100.0	*	*	*	*	*	836.2	512.2	0	Günther and Rosin (1970)
12	2	210	110.3	105.1	47150	393.6	29237	2953	913.0	521.3	0	Rymarz et al (1982)
29	3	208	110.3	105.1	54585	2360.9	36876	*	767.0	485.0	0	Oslage (1964)
12	3	*	130.0	124.3	*	*	48873	*	961.0	581.0	1	Weniger and Funk (1953[a,b])

a:1 = barrow, 2 = gilts, 3 = barrows and gilts, 4 = boars
b:1 = not used for further calculations

Appendix 9. Relationship between live weight (W), empty body weight (EBW), fat-free body weight (FFW), fat-free empty body weight (FFEBW), nitrogen weight (NW) and phosphorus and calcium (W, EBW, FFW, FFEBW in kg; NW, Ca and P in g) (Chapter 4.4.3.)

equation number	equation	significance of the variables linear	square	R^2	rsd[a]
1	$Ca = -3.43 + 8.90\ W - 0.0077\ W^2$	***	ns	0.980	2.3
2	$Ca = -4.09 + 9.54\ EBW - 0.0100\ EBW^2$	***	ns	0.981	2.3
3	$Ca = -4.57 + 9.54\ FFW + 0.0215\ FFW^2$	***	*	0.989	2.0
4	$Ca = -5.63 + 10.41\ FFEBW + 0.0238\ FFEBW^2$	***	*	0.991	1.9
5	$Ca = 0.23 + 0.362\ NW - 0.000008\ NW^2$	***	ns	0.990	0.8
6	$P = -1.90 + 5.59\ W - 0.0057\ W^2$	***	**	0.991	0.9
7	$P = -2.31 + 5.88\ EBW - 0.007\ EBW^2$	***	**	0.992	0.9
8	$P = -0.33 + 5.77\ FFW + 0.0125\ FFW^2$	***	**	0.994	0.9
9	$P = -1.02 + 6.31\ FFEBW + 0.0135\ FFEBW^2$	***	**	0.996	0.8
10	$P = -0.03 + 0.2256\ NW - 0.000008\ NW^2$	***	*	0.997	0.3

a) to calculate the rsd at a given W except for NW: $rsd_W = rsd\sqrt{W^{3/2}}$

and for $rsd_{NW} = rsd\sqrt{W}$

Appendix 10a. Data of feeding experiments used for regression analyses (Chapter

B	FWT	S	NH	NU	D	NEf	L	P_b	FYT	R	M	C	PD	P_1	GR_1	FC_1	FI_1	P_2	GR_2	FC_2	FI
8	26	3	12	1	1	9.82	1	3.6	2.3	2	0	0	4.8	3.6	0.29	*	*	4.1	0.41	*	
16	100	3	15	3	1	9.85	1	3.6	2.2	3	0	0	5.1	3.6	*	*	*	4.1	*	*	
10	30	3	100	4	1	9.83	1	3.5	2.2	1	0	0	6.0	6.0	*	*	*	8.0	*	*	
35	61	3	77	7	1	10.05	1	3.1	1.9	1	0	0	5.0	5.0	*	*	*	6.0	*	*	
61	104	3	77	7	1	10.10	1	3.0	1.9	1	0	0	4.1	4.1	*	*	*	5.0	*	*	
25	90	2	12	3	1	9.85	1	3.5	2.2	3	0	0	5.0	3.5	0.60	3.52	1.69	4.4	0.75	2.98	2.9
25	90	2	12	3	1	9.85	1	3.5	2.2	3	0	0	5.0	3.5	0.71	3.04	2.32	4.4	0.76	2.96	2.9
25	60	3	12	3	1	9.90	1	3.1	2.0	3	0	0	4.7	3.1	0.59	3.29	1.94	4.7	0.90	2.65	2.4
25	60	3	12	3	1	9.90	1	3.1	2.0	3	0	0	4.7	3.1	0.72	2.43	1.75	4.7	0.91	2.42	2.2
25	60	3	12	3	1	9.90	1	3.4	2.2	3	0	0	4.6	3.4	0.63	2.96	1.87	4.6	0.85	2.79	2.3
25	60	3	12	3	1	9.90	1	3.4	2.2	3	0	0	4.6	3.4	0.58	3.12	1.83	4.6	0.84	2.37	2.0
25	90	4	16	4	1	9.90	1	3.5	2.2	2	0	0	4.6	3.5	0.63	3.48	2.20	4.1	0.73	3.36	2.4
25	90	2	24	3	1	9.90	1	3.3	2.1	3	0	0	4.5	4.5	0.76	3.25	2.47	6.2	0.77	3.31	2.9
25	90	4	24	3	1	9.90	1	3.3	2.1	3	0	0	5.4	4.5	0.80	3.10	2.47	6.2	0.88	3.05	2.8
15	33	3	24	3	1	9.96	1	3.2	1.9	3	0	0	5.0	4.0	0.50	2.50	1.24	5.0	0.55	2.33	1.2
25	51	3	14	2	1	9.94	1	3.2	2.0	1	0	0	4.5	4.5	0.77	2.50	1.95	5.5	0.76	2.69	2.0
22	49	3	12	2	1	9.94	1	3.2	2.0	1	0	0	4.5	4.5	0.70	2.50	1.78	5.5	0.74	2.38	1.7
65	100	3	20	2	1	10.10	1	2.9	1.8	1	0	0	4.4	3.5	0.73	3.45	2.54	4.4	0.82	3.33	2.7
65	100	3	20	2	1	10.10	1	2.9	1.8	1	0	0	4.4	3.5	0.81	4.35	2.81	4.4	0.67	3.85	2.8
60	100	3	20	2	1	10.10	1	2.9	1.8	2	0	0	4.4	3.5	0.69	3.70	2.59	4.4	0.79	3.57	2.8
60	100	3	20	2	1	10.10	1	2.9	1.8	2	0	0	4.4	3.5	0.67	4.17	2.79	4.4	0.84	3.70	3.1
4	10	3	20	2	5	10.49	1	1.2	0.6	1	0	0	4.2	2.4	0.16	2.38	0.36	3.6	0.17	2.30	0.3
4	13	3	24	3	4	10.13	1	2.7	1.8	1	0	0	4.4	4.0	0.25	1.71	0.43	4.4	0.29	1.63	0.4
13	86	3	24	3	1	9.90	1	3.2	2.0	1	0	0	4.4	4.0	0.66	3.03	2.00	4.4	0.71	3.09	2.2
3	18	3	6	6	5	10.73	1	1.4	*	3	0	0	5.0	5.0	*	*	*	6.0	*	*	*
3	18	3	11	11	5	10.73	1	1.4	*	1	0	0	7.3	1.4	0.30	2.00	0.57	4.4	0.38	1.80	0.6
3	18	3	16	16	5	10.73	1	1.4	*	1	0	0	7.3	2.8	0.35	1.80	0.61	4.4	0.37	1.90	0.6
21	91	1	20	4	1	9.83	1	3.4	2.2	3	0	1	5.1	3.4	0.70	3.55	2.47	4.5	0.77	3.43	2.6
21	91	2	20	4	1	9.83	1	3.4	2.2	3	0	1	5.1	3.4	0.60	3.64	2.18	4.5	0.70	3.31	2.3
19	93	3	16	4	1	9.83	1	3.4	2.2	3	0	1	5.0	3.8	0.68	3.46	2.36	5.0	0.78	3.15	2.4
19	93	3	32	4	1	9.83	1	3.4	2.2	3	0	1	5.0	5.0	0.81	3.22	2.61	6.3	0.80	3.24	2.5
17	93	3	80	16	1	9.96	1	3.4	2.1	2	0	1	5.0	5.0	0.78	3.16	2.40	6.5	0.75	3.12	2.3
14	95	3	15	3	4	9.45	1	4.1	2.7	2	0	1	6.1	5.1	0.73	3.44	2.51	5.6	0.74	3.38	2.4
28	100	4	24	8	1	9.85	1	3.3	2.0	3	0	1	6.3	5.3	0.86	2.76	2.36	6.3	0.91	2.72	2.4
13	96	3	20	4	1	9.99	1	3.2	2.0	3	0	1	4.7	4.2	0.75	*	*	4.7	0.79	*	*
13	96	3	20	4	1	9.80	1	3.2	2.1	3	0	1	4.7	4.2	0.71	*	*	4.7	0.77	*	*
13	96	3	20	4	2	9.45	1	4.1	2.9	3	0	1	5.1	5.1	0.80	*	*	5.6	0.80	*	*
9	17	1	12	12	1	9.88	1	3.3	2.0	1	1	0	4.4	4.4	0.28	2.96	0.66	8.6	0.27	2.48	0.6
17	86	1	9	9	1	9.88	1	3.3	2.0	1	2	0	4.4	4.4	0.76	2.29	1.73	8.6	0.81	2.36	1.9
9	117	1	6	6	1	9.89	1	3.3	2.0	1	3	0	4.4	4.4	0.73	2.78	2.02	8.6	0.70	3.02	2.1
9	17	2	12	12	1	9.88	1	3.3	2.0	1	1	0	4.4	4.4	0.25	2.64	0.59	8.6	0.29	2.60	0.7
17	86	2	9	9	1	9.88	1	3.3	2.0	1	2	0	4.4	4.4	0.79	2.31	1.82	8.6	0.80	2.27	1.8
9	117	2	6	6	1	9.88	1	3.3	2.0	1	3	0	4.4	4.4	0.86	2.76	1.81	8.6	0.69	2.88	2.0
9	17	4	12	12	1	9.88	1	3.3	2.0	1	1	0	4.4	4.4	0.31	2.30	0.67	8.6	0.31	2.34	0.6
17	86	4	9	9	1	9.88	1	3.3	2.0	1	2	0	4.4	4.4	0.81	2.30	1.86	8.6	0.82	2.25	1.8
9	117	4	6	6	1	9.89	1	3.3	2.0	1	3	0	4.4	4.4	0.78	2.61	2.03	8.6	0.77	2.64	2.0
22	90	3	24	24	3	9.23	2	3.3	2.4	3	0	1	5.0	3.5	0.58	3.19	1.85	5.0	0.64	3.05	1.9
19	52	3	96	12	1	9.74	1	3.5	2.2	1	0	0	6.0	5.0	0.71	2.72	1.93	7.0	0.76	2.66	2.0
52	93	3	72	12	1	10.08	1	3.0	1.9	1	0	0	4.0	4.0	0.80	2.98	3.70	5.0	0.80	2.98	3.7
52	93	3	72	12	1	9.92	1	3.3	2.1	1	0	0	4.0	4.0	0.80	2.98	3.70	5.0	0.80	2.98	3.7
20	50	3	28	7	4	10.99	2	3.5	2.5	2	0	0	3.9	3.5	0.53	2.76	1.46	3.9	0.54	2.70	1.4
10	20	3	96	12	3	9.70	1	4.0	1.9	1	1	0	6.0	6.0	0.42	1.76	0.74	8.0	0.40	1.75	0.7
20	35	3	96	12	1	9.81	1	3.3	2.1	1	2	0	6.0	6.0	0.59	2.37	1.40	8.0	0.59	2.30	1.3
35	60	3	96	12	1	9.92	1	3.2	2.0	1	4	0	6.0	5.0	0.86	2.88	1.90	6.0	0.68	2.89	1.8
60	104	3	96	12	1	10.08	1	3.0	1.9	1	5	0	4.1	4.1	0.78	3.82	2.82	5.0	0.76	3.71	2.8
22	90	3	8	1	2	8.92	1	3.7	2.3	1	0	0	5.0	4.0	0.70	3.22	2.25	5.0	0.72	3.21	2.3
23	100	4	42	42	4	9.06	2	4.6	2.3	2	0	0	5.5	5.5	0.84	2.80	2.34	7.5	0.82	2.86	2.3
21	101	4	16	16	4	9.06	2	4.7	2.4	2	0	0	6.0	6.0	0.71	2.72	1.93	10.0	0.70	2.82	1.9
22	100	2	16	16	4	9.08	2	4.5	2.3	1	0	0	6.0	6.0	0.71	2.89	2.06	10.6	0.71	2.84	2.0

GR_3	FC_3	FI_3	P_4	GR_4	FC_4	FI_4	P_5	GR_5	FC_5	FI_5	REFERENCE
0.46	*	*	*	*	*	*	*	*	*	*	ABRAMS et al. (1975)
*	*	*	5.1	*	*	*	5.6	*	*	*	ALLEE et al. (1975)
*	*	*	*	*	*	*	*	*	*	*	ARTHUR et al. (1980)
*	*	*	*	*	*	*	*	*	*	*	ARTHUR et al. (1980)
*	*	*	*	*	*	*	*	*	*	*	ARTHUR et al. (1980)
0.77	3.01	2.55	5.6	0.78	3.06	2.57	*	*	*	*	BAYLEY and THOMSON (1969)
0.84	2.59	3.23	5.6	0.83	2.71	3.06	*	*	*	*	BAYLEY and THOMSON (1969)
*	*	*	*	*	*	*	*	*	*	*	BAYLEY et al. (1975a)
*	*	*	*	*	*	*	*	*	*	*	BAYLEY et al. (1975a)
*	*	*	*	*	*	*	*	*	*	*	BAYLEY et al. (1975a)
*	*	*	*	*	*	*	*	*	*	*	BAYLEY et al. (1975a)
0.82	2.93	2.41	5.1	0.82	3.07	2.52	*	*	*	*	BAYLEY et al. (1975b)
0.79	3.16	2.49	8.5	0.79	3.22	2.49	*	*	*	*	BAYLEY et al. (1975b)
0.83	2.74	2.29	8.5	0.88	2.84	2.44	*	*	*	*	BAYLEY et al. (1975b)
*	*	*	*	*	*	*	*	*	*	*	CHAPPLE et al. (1979a)
*	*	*	*	*	*	*	*	*	*	*	CHAPPLE et al. (1979a)
*	*	*	*	*	*	*	*	*	*	*	CHAPPLE et al. (1979a)
*	*	*	*	*	*	*	*	*	*	*	CHAPPLE et al. (1979b)
*	*	*	*	*	*	*	*	*	*	*	CHAPPLE et al. (1979b)
0.78	3.57	2.80	*	*	*	*	*	*	*	*	CHAPPLE et al. (1979b)
0.85	3.70	3.12	*	*	*	*	*	*	*	*	CHAPPLE et al. (1979b)
0.13	2.68	0.34	6.0	0.15	2.44	0.37	7.2	0.15	2.41	0.35	COMBS et al. (1962)
0.29	1.68	0.48	*	*	*	*	*	*	*	*	COMBS et al. (1962)
0.72	3.14	2.26	*	*	*	*	*	*	*	*	COMBS et al. (1962)
*	*	*	8.0	*	*	*	*	*	*	*	COALSON et al. (1970)
0.42	1.70	0.70	10.5	0.40	2.00	0.78	*	*	*	*	COALSON et al. (1972)
0.40	1.80	0.69	7.3	0.42	1.60	0.70	*	*	*	*	COALSON et al. (1972)
0.82	3.42	2.79	*	*	*	*	*	*	*	*	CROMWELL et al. (1970)
0.74	3.29	2.45	*	*	*	*	*	*	*	*	CROMWELL et al. (1970)
0.78	3.20	2.50	7.5	0.78	3.10	2.41	*	*	*	*	CROMWELL et al. (1970)
0.82	3.24	2.65	*	*	*	*	*	*	*	*	CROMWELL et al. (1970)
*	*	*	*	*	*	*	*	*	*	*	CROMWELL et al. (1972a)
0.77	3.32	2.55	*	*	*	*	*	*	*	*	CROMWELL et al. (1974)
0.87	2.71	2.36	8.3	0.90	2.70	2.42	9.3	0.90	2.70	2.43	CROMWELL et al. (1979)
0.79	*	*	*	*	*	*	*	*	*	*	CROMWELL et al. (1972b)
0.78	*	*	*	*	*	*	*	*	*	*	CROMWELL et al. (1972b)
0.80	*	*	*	*	*	*	*	*	*	*	CROMWELL et al. (1972b)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
*	*	*	*	*	*	*	*	*	*	*	CRENSHAW et al. (1981)
0.59	3.28	1.90	*	*	*	*	*	*	*	*	DUIGE et al. (1975)
*	*	*	*	*	*	*	*	*	*	*	FAMMATRE et al. (1977)
*	*	*	*	*	*	*	*	*	*	*	FAMMATRE et al. (1977)
*	*	*	*	*	*	*	*	*	*	*	FAMMATRE et al. (1977)
*	*	*	*	*	*	*	*	*	*	*	FRAPE et al. (1979)
*	*	*	*	*	*	*	*	*	*	*	GUTIERREZ (1979)
*	*	*	*	*	*	*	*	*	*	*	GUTIERREZ (1979)
*	*	*	*	*	*	*	*	*	*	*	GUTIERREZ (1979)
*	*	*	*	*	*	*	*	*	*	*	GUTIERREZ (1979)
*	*	*	*	*	*	*	*	*	*	*	HARMON et al. (1970b)
*	*	*	*	*	*	*	*	*	*	*	HANSSEN and GRONDALEN (1979)
*	*	*	*	*	*	*	*	*	*	*	HANSSEN and GRONDALEN (1979)
*	*	*	*	*	*	*	*	*	*	*	HANSSEN and GRONDALEN (1979)

Appendix 10a. Data of feeding experiments used for regression analyses (Chapter 5.

B	FWT	S	NH	NO	D	Nef	L	P_b	FYT	R	M	C	PD	P_1	GR_1	FC_1	FI_1	P_2	GR_2	FC_2	FI_2
12	102	3	30	3	1	9.94	1	3.1	2.0	3	0	0	4.6	3.1	0.62	3.19	1.62	4.0	0.73	2.95	2.15
7	21	1	10	10	1	9.84	1	3.9	2.4	3	0	0	6.3	3.9	0.37	1.83	0.67	4.7	0.44	1.63	0.71
29	118	4	6	3	1	10.03	1	3.1	1.9	1	0	0	4.5	4.5	0.80	3.20	2.56	6.0	0.80	3.20	2.56
7	18	4	72	3	1	9.73	1	3.7	2.3	1	1	0	6.0	5.0	*	*	*	7.0	*	*	*
18	109	4	72	3	1	9.83	1	3.5	2.2	1	2	0	5.0	5.0	*	*	*	7.0	*	*	*
30	48	3	18	18	4	9.20	2	4.3	2.7	1	1	0	6.0	4.3	0.59	2.65	1.50	5.0	0.59	2.60	1.53
30	108	3	18	18	4	9.20	2	4.3	2.7	1	2	0	5.0	4.3	0.75	3.09	2.31	5.0	0.78	2.98	2.31
24	75	5	10	10	2	8.78	2	3.6	2.2	3	0	0	3.6	3.6	0.61	3.68	1.94	5.4	0.64	3.61	1.94
24	75	5	10	10	2	8.78	1	3.6	2.2	3	0	0	3.6	3.6	0.69	3.68	2.54	5.4	0.73	3.61	2.65
12	82	3	30	6	1	9.82	1	3.3	2.0	3	0	3	5.2	5.2	0.70	3.03	2.10	7.3	0.72	3.17	2.27
38	91	3	30	6	1	10.02	1	3.0	1.9	3	0	3	4.4	4.4	0.83	3.15	2.61	6.0	0.82	3.27	2.67
54	91	3	20	4	1	10.16	1	2.8	1.8	3	0	1	4.1	4.1	0.78	2.98	2.33	5.6	0.79	3.25	2.55
21	45	4	28	7	1	9.88	1	3.2	2.0	1	1	0	5.9	5.2	0.62	2.54	1.47	6.5	0.65	2.33	1.46
45	117	4	28	7	1	10.07	1	3.0	1.9	1	2	0	5.2	4.1	0.70	3.47	2.35	5.2	0.69	3.36	2.29
21	117	4	28	7	1	9.88	1	3.2	2.0	1	3	1	5.2	5.2	0.66	3.13	1.99	6.5	0.66	3.04	1.97
35	95	3	16	2	1	10.03	1	3.2	2.0	1	0	0	4.0	4.0	0.73	3.13	2.30	6.5	0.78	3.13	2.46
22	95	3	12	2	1	10.07	1	3.0	1.9	3	0	0	5.0	3.0	0.64	3.45	2.18	4.0	0.67	3.33	2.25
8	20	3	90	9	1	9.74	1	3.5	2.2	1	0	0	6.0	5.0	0.31	1.98	0.62	6.0	0.33	2.04	0.66
8	20	3	90	9	1	9.62	1	3.8	2.4	1	0	0	6.0	5.0	0.34	1.86	0.64	6.0	0.38	1.80	0.69
7	20	3	3	3	1	9.84	1	3.9	2.4	3	0	0	6.0	5.0	*	*	*	6.0	*	*	*
17	46	3	96	8	3	8.72	1	3.3	2.0	3	1	0	5.0	3.3	0.62	2.77	1.69	4.0	0.66	2.74	1.78
46	100	3	96	8	3	8.77	1	3.3	2.0	3	2	0	4.2	3.3	0.78	3.75	2.84	3.5	0.82	3.79	3.07
17	100	3	96	8	3	8.72	1	3.3	2.0	3	3	1	5.0	3.3	0.71	3.43	2.40	4.0	0.75	3.42	2.56
19	58	3	47	1	2	8.87	1	3.5	2.2	3	1	0	4.7	3.5	0.59	3.32	2.00	6.0	0.71	3.02	2.14
58	99	3	47	1	2	8.89	1	3.5	2.2	3	2	0	4.2	3.5	0.81	4.38	3.38	5.0	0.81	4.52	3.70
19	99	3	47	1	2	8.87	1	3.5	2.2	3	3	1	4.7	3.5	0.69	3.91	2.68	6.0	0.76	3.77	2.86
20	53	3	36	3	3	8.75	1	3.8	2.2	1	1	0	4.8	4.8	0.63	3.04	2.02	7.6	0.66	3.00	1.97
53	99	3	36	3	3	8.77	1	3.6	2.1	1	2	0	4.0	4.0	0.73	3.97	2.85	6.0	0.67	4.17	2.73
20	99	3	36	3	3	8.75	1	3.8	2.2	1	3	1	4.8	4.8	0.70	3.57	2.48	7.6	0.66	3.67	2.41
19	58	3	80	2	2	8.87	1	3.5	2.2	3	1	0	4.8	3.5	0.70	3.60	2.50	6.0	0.74	3.13	2.34
58	99	3	80	2	2	8.89	1	3.5	2.2	3	2	0	4.3	3.5	0.80	4.68	3.63	5.0	0.88	4.07	3.52
19	99	3	80	2	2	8.87	1	3.5	2.2	3	3	0	4.8	3.5	0.76	4.24	3.14	6.0	0.82	3.73	3.05
20	90	1	10	10	2	8.94	2	4.0	2.5	1	0	0	4.0	4.0	0.66	2.81	1.86	6.0	0.66	2.83	1.87
8	42	4	32	4	1	9.72	1	3.4	2.1	1	1	0	5.0	5.0	0.55	2.08	1.17	7.5	0.58	2.16	1.23
42	92	4	16	2	1	9.72	1	3.4	2.1	1	2	0	5.0	5.0	0.89	2.76	2.45	7.5	0.90	2.70	2.43
8	92	4	16	2	1	9.72	1	3.4	2.1	1	3	0	5.0	5.0	0.72	2.48	1.81	7.5	0.74	2.57	1.83
22	95	4	20	2	1	9.72	1	3.4	2.1	1	0	0	5.0	5.0	0.74	3.09	2.32	10.0	0.72	3.27	2.31
31	102	4	90	2	1	9.72	1	3.4	2.1	1	0	0	5.0	5.0	0.90	2.60	2.33	7.5	0.90	2.58	2.33
7	93	2	96	12	1	9.74	1	3.3	2.1	1	0	0	6.4	5.1	0.65	2.86	1.87	7.7	0.67	2.95	1.95
16	95	3	10	2	1	9.77	1	3.4	2.1	3	0	0	5.5	3.0	0.52	3.93	2.04	4.0	0.63	3.27	2.06
14	96	3	56	14	1	9.77	1	3.4	2.1	1	0	0	5.0	5.0	0.75	2.96	2.22	10.0	0.75	3.12	2.33
22	80	3	16	2	1	9.67	1	3.1	2.0	3	0	0	5.1	3.1	0.54	3.70	2.00	5.1	0.70	3.53	2.47
30	90	3	16	2	1	9.67	1	3.1	2.0	3	0	0	5.0	4.0	0.69	3.45	2.38	5.0	0.68	3.33	2.26
30	90	3	16	2	1	9.67	1	3.1	2.0	3	0	0	5.0	4.0	0.69	3.70	2.55	5.0	0.69	3.33	2.30
17	105	1	8	4	2	9.31	1	3.4	2.3	1	0	0	4.9	3.4	0.81	2.99	2.41	3.9	0.80	3.06	2.44
18	105	1	8	4	2	9.31	1	3.5	2.3	1	0	0	4.9	3.5	0.83	3.10	2.53	4.0	0.82	3.02	2.33
17	105	1	8	4	1	10.23	1	3.0	2.0	1	0	0	4.8	3.0	0.71	2.67	1.90	3.5	0.76	2.70	2.06
18	105	1	8	4	1	10.23	1	3.1	2.0	1	0	0	4.5	3.1	0.66	2.82	1.86	3.5	0.75	2.73	2.04
23	67	3	30	30	4	8.64	1	4.6	2.4	2	1	0	5.2	5.2	0.87	*	*	7.8	0.89	*	*
23	103	3	30	30	4	8.64	2	4.6	2.4	2	2	0	5.2	5.2	0.78	3.28	2.56	7.8	0.77	3.34	2.57
7	19	3	48	6	4	9.55	1	4.2	2.0	1	0	0	6.0	4.9	0.36	1.91	0.69	7.1	0.38	1.86	0.71
7	19	3	70	10	4	9.55	1	4.2	2.0	2	0	0	8.6	7.1	0.39	1.64	0.64	10.1	0.41	1.62	0.66
14	45	3	8	2	3	9.77	1	3.5	2.6	3	0	0	5.0	3.5	0.47	2.98	1.40	5.0	0.54	2.47	1.32
14	45	3	8	2	3	10.29	1	2.5	2.0	3	0	0	5.0	3.5	0.47	2.76	1.27	5.0	0.54	2.62	1.42
35	120	1	20	2	4	9.55	2	3.9	2.5	3	0	0	5.5	5.5	0.71	3.40	2.41	11.0	0.65	3.70	2.41
16	93	3	24	6	1	9.99	1	3.2	2.0	1	0	0	5.0	5.0	0.72	3.16	2.28	8.6	0.73	3.17	2.32
14	96	3	32	8	1	9.99	1	2.3	2.0	1	0	0	6.0	5.0	0.69	3.16	2.18	10.0	0.75	3.19	2.39
18	60	3	24	3	1	9.84	1	3.3	2.0	1	0	0	6.0	5.0	0.68	2.54	1.73	7.0	0.69	2.57	1.77
18	60	3	24	3	1	9.53	1	4.0	2.4	1	0	0	6.0	5.0	0.66	2.62	1.79	7.0	0.71	2.57	1.83
25	95	1	12	12	1	9.68	1	3.6	2.4	1	0	0	5.0	5.0	*	*	*	7.5	*	*	*
8	20	3	24	4	1	9.79	1	3.7	2.3	1	0	0	6.0	5.7	0.41	1.84	0.75	5.7	0.42	1.90	0.80
8	20	3	24	4	1	9.67	1	4.1	2.5	1	0	0	6.2	4.8	0.41	1.74	0.71	6.2	0.42	1.68	0.71
9	21	3	24	4	1	9.72	1	3.5	2.1	3	0	0	6.3	5.5	0.40	1.84	0.74	7.1	0.43	1.80	0.78

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GR_3	FC_3	FI_3	P_4	GR_4	FC_4	FI_4	P_5	GR_5	FC_5	FI_5	REFERENCE
0.76	3.00	2.28	6.0	0.76	3.00	2.27	*	*	*	*	HAGEMEIER et al. (1981)
0.49	1.43	0.70	6.3	0.55	1.32	0.72	7.1	0.56	1.37	0.76	HARROLD et al. (1981)
0.80	3.20	2.56	9.0	0.80	3.20	2.56	10.5	0.80	3.20	2.56	HINES et al. (1979)
*	*	*	*	*	*	*	*	*	*	*	HICKMAN and MAHAN (1980)
*	*	*	*	*	*	*	*	*	*	*	HICKMAN and MAHAN (1980)
0.61	2.48	1.51	7.0	0.59	2.57	1.52	*	*	*	*	KEMPEN van et al. (1976)
0.77	2.99	2.31	7.0	0.77	3.01	2.32	*	*	*	*	KEMPEN van et al. (1976)
*	*	*	*	*	*	*	*	*	*	*	KING (1980)
*	*	*	*	*	*	*	*	*	*	*	KING (1980)
*	*	*	*	*	*	*	*	*	*	*	KORNEGAY (1973)
*	*	*	*	*	*	*	*	*	*	*	KORNEGAY (1973)
*	*	*	*	*	*	*	*	*	*	*	KORNEGAY (1973)
0.60	2.52	1.43	*	*	*	*	*	*	*	*	KORNEGAY and THOMAS (1981)
0.70	3.49	2.38	*	*	*	*	*	*	*	*	KORNEGAY and THOMAS (1981)
0.66	3.13	1.99	*	*	*	*	*	*	*	*	KORNEGAY and THOMAS (1981)
0.79	3.13	2.51	*	*	*	*	*	*	*	*	LIBAL et al. (1969)
0.69	3.57	2.39	6.0	0.72	3.45	2.49	7.0	0.70	3.45	2.42	LIBAL et al. (1969)
0.33	1.94	0.64	8.0	0.34	1.84	0.62	9.0	0.35	1.94	0.67	MAHAN et al. (1980)
0.37	1.79	0.66	8.0	0.38	1.87	0.70	9.0	0.37	1.85	0.68	MAHAN et al. (1980)
*	*	*	8.0	*	*	*	9.0	*	*	*	MAHAN (1981)
0.70	2.50	1.73	8.0	0.70	2.51	1.73	*	*	*	*	NEWMAN and ELLIOTT (1976)
0.81	3.65	2.90	6.5	0.83	3.60	2.98	*	*	*	*	NEWMAN and ELLIOTT (1976)
0.76	3.25	2.46	8.0	0.78	3.21	2.48	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
*	*	*	*	*	*	*	*	*	*	*	NEWMAN and ELLIOTT (1976)
0.67	2.80	1.88	10.0	0.66	2.83	1.88	*	*	*	*	NIELSEN et al. (1971)
0.55	2.10	1.16	*	*	*	*	*	*	*	*	NIMMO et al. (1980a)
0.89	2.70	2.40	*	*	*	*	*	*	*	*	NIMMO et al. (1980a)
0.72	2.50	1.78	*	*	*	*	*	*	*	*	NIMMO et al. (1980a)
*	*	*	*	*	*	*	*	*	*	*	NIMMO et al. (1980b)
0.90	2.74	2.47	*	*	*	*	*	*	*	*	NIMMO et al. (1980b)
*	*	*	*	*	*	*	*	*	*	*	NIMMO et al. (1981)
0.69	3.33	2.30	6.0	0.69	3.24	2.22	7.0	0.71	3.37	2.40	PARKER et al. (1974)
*	*	*	*	*	*	*	*	*	*	*	PARKER et al. (1975)
0.71	3.49	2.48	*	*	*	*	*	*	*	*	PEO et al. (1975)
*	*	*	*	*	*	*	*	*	*	*	PEO et al. (1975)
*	*	*	*	*	*	*	*	*	*	*	PEO et al. (1975)
0.81	3.04	2.42	4.9	0.83	2.95	2.48	5.4	0.78	3.15	2.44	PETERSEN and VEMMER (1981)
0.78	2.91	2.29	4.9	0.81	3.01	2.32	5.4	0.80	2.99	2.38	PETERSEN and VEMMER (1981)
0.82	2.89	2.37	4.5	0.85	2.99	2.54	5.0	0.82	2.96	2.43	PETERSEN and VEMMER (1981)
0.78	2.69	2.10	4.5	0.81	2.64	2.17	5.0	0.83	2.74	2.24	PETERSEN and VEMMER (1981)
0.90	*	*	*	*	*	*	*	*	*	*	PFIRTER et al. (1979)
0.79	3.29	2.59	*	*	*	*	*	*	*	*	PFIRTER et al. (1979)
*	*	*	*	*	*	*	*	*	*	*	PFIRTER et al. (1979)
*	*	*	*	*	*	*	*	*	*	*	PFIRTER et al. (1979)
0.52	2.64	1.36	*	*	*	*	*	*	*	*	PIERCE et al. (1976)
0.52	2.22	1.16	*	*	*	*	*	*	*	*	PIERCE et al. (1976)
*	*	*	*	*	*	*	*	*	*	*	POPPE et al. (1973)
*	*	*	*	*	*	*	*	*	*	*	PRINCE et al. (1974)
*	*	*	*	*	*	*	*	*	*	*	PRINCE et al. (1974)
0.71	2.53	1.82	*	*	*	*	*	*	*	*	REINHART et al. (1976)
0.71	2.53	1.81	*	*	*	*	*	*	*	*	REINHART et al. (1976)
*	*	*	*	*	*	*	*	*	*	*	SCHROEDER et al. (1974)
0.41	1.87	0.75	*	*	*	*	*	*	*	*	SCHIEFELBEIN (1979)
0.47	1.70	0.81	*	*	*	*	*	*	*	*	SCHIEFELBEIN (1979)
0.41	1.89	0.78	*	*	*	*	*	*	*	*	SCHIEFELBEIN (1979)

Appendix 10a. Data of feeding experiments used for regression analyses (Chapter 5

B	FWT	S	NA	NU	D	NEf	L	P_b	FYT	R	M	C	PD	P_1	GR_1	FC_1	FI_1	P_2	GR_2	FC_2	FI_
9	21	3	24	4	1	9.56	1	3.8	2.3	3	0	0	9.2	5.1	0.41	1.72	0.71	8.4	0.43	1.72	0.74
9	19	3	16	4	1	9.72	1	3.5	2.2	1	0	0	6.8	5.5	0.35	2.29	0.81	8.2	0.37	1.79	0.66
9	19	3	16	4	1	9.50	1	3.9	2.4	1	0	0	9.0	5.9	0.41	1.71	0.69	8.0	0.41	1.61	0.66
27	91	3	7	7	1	10.06	1	3.2	2.0	2	0	0	4.5	4.5	0.63	3.22	2.09	6.5	0.62	3.27	2.15
15	70	3	10	10	3	8.82	2	3.9	2.2	3	0	0	3.9	3.9	0.52	2.90	1.51	6.1	0.52	2.90	1.51
23	76	3	8	8	3	8.82	2	3.9	2.2	3	0	0	3.9	3.9	0.59	3.01	1.76	4.7	0.59	3.01	1.76
27	91	3	15	1	1	10.06	1	3.2	2.0	2	0	0	4.6	3.9	0.75	2.87	2.15	4.1	0.79	2.84	2.24
25	95	4	6	6	1	9.68	1	3.6	2.4	1	0	0	5.0	5.0	*	*	*	7.5	*	*	*
25	95	4	6	6	1	9.68	1	3.6	2.4	1	0	0	5.5	4.0	*	*	*	5.5	*	*	*
50	104	1	24	6	1	10.07	1	3.1	2.0	3	0	0	4.1	3.1	0.76	3.84	2.88	4.1	0.78	3.60	2.79
50	104	2	24	6	1	10.07	1	3.1	2.0	3	0	0	5.1	3.1	0.76	3.84	2.88	4.1	0.78	3.60	2.79
25	45	3	48	12	1	9.88	1	3.2	2.0	1	1	0	5.2	4.0	0.73	2.76	2.02	5.2	0.79	2.49	1.97
45	103	3	48	12	1	10.07	1	3.1	2.0	1	2	0	4.2	3.1	0.69	3.76	2.57	4.2	0.80	3.40	2.72
25	103	3	48	12	1	9.88	1	3.2	2.0	1	3	1	5.2	4.0	0.70	3.18	2.42	5.2	0.80	3.14	2.51
25	45	5	48	12	1	9.88	1	3.2	2.0	1	1	0	5.6	3.8	0.71	2.61	1.86	5.0	0.73	2.31	1.68
45	107	5	48	12	1	10.07	1	3.0	1.9	1	2	0	4.5	3.0	0.80	3.44	2.74	4.0	0.88	3.14	2.79
25	107	5	48	12	1	9.88	1	3.2	2.0	1	3	1	5.6	3.8	0.75	3.36	2.52	5.0	0.81	3.10	2.52
36	86	3	48	8	1	9.88	1	3.1	2.0	1	0	1	5.0	5.0	0.79	3.10	2.45	6.2	0.78	3.16	2.46
43	102	3	9	3	1	9.74	1	3.3	2.2	1	0	0	4.0	3.3	0.88	3.57	3.13	4.0	*	3.51	3.16
48	105	3	27	9	1	9.74	1	3.3	2.2	1	0	0	4.5	3.3	0.72	3.28	2.35	4.5	0.81	3.03	2.45
41	100	3	27	9	1	9.74	1	3.3	2.2	1	0	0	4.5	3.3	0.75	3.19	2.37	4.5	0.87	2.94	2.56
20	100	3	40	2	1	9.66	1	3.4	2.3	1	0	1	3.9	3.9	0.66	3.25	2.16	5.0	0.66	3.24	2.15
20	100	3	40	2	1	9.71	1	3.4	2.3	1	0	1	3.9	3.9	0.67	3.20	2.17	5.0	0.67	2.27	2.19
27	110	3	20	20	4	8.91	2	3.8	2.0	1	0	1	4.8	4.1	0.71	2.39	1.69	5.6	0.70	2.40	1.69

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GR_3	FC_3	FI_3	P_4	GR_4	FC_4	FI_4	P_5	GR_5	FC_5	FI_5	REFERENCE
0.45	1.65	0.71	*	*	*	*	*	*	*	*	SCHIEFELBEIN (1979)
0.40	1.96	0.77	*	*	*	*	*	*	*	*	SCHIEFELBEIN (1979)
0.42	1.55	0.65	*	*	*	*	*	*	*	*	SCHIEFELBEIN (1979)
*	*	*	*	*	*	*	*	*	*	*	STOCKLAND and BLAYLOCK (1973)
*	*	*	*	*	*	*	*	*	*	*	STONE and McINTOSH (1977)
0.59	3.01	1.76	6.2	0.59	3.01	1.76	*	*	*	*	STONE and McINTOSH (1977)
0.88	2.67	2.35	5.4	0.79	2.83	2.24	6.4	0.78	2.80	2.18	STOCKLAND and BLAYLOCK (1973)
*	*	*	*	*	*	*	*	*	*	*	TANKSLEY (1977)
*	*	*	8.5	*	*	*	10.0	*	*	*	TANKSLEY (1977)
0.78	3.58	2.74	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.80	3.58	2.74	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.82	2.54	2.10	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.80	3.46	2.74	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.82	3.20	2.59	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.78	2.32	1.80	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.89	3.10	2.75	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.84	3.06	2.54	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.78	3.10	2.42	*	*	*	*	*	*	*	*	THOMAS and KORNEGAY (1981)
0.85	3.51	3.00	*	*	*	*	*	*	*	*	TROTTER and ALLEE (1980)
*	*	*	*	*	*	*	*	*	*	*	TROTTER and ALLEE (1980)
*	*	*	*	*	*	*	*	*	*	*	TROTTER and ALLEE (1980)
*	*	*	*	*	*	*	*	*	*	*	TUNMIRE et al. (1983)
*	*	*	*	*	*	*	*	*	*	*	TUNMIRE et al. (1983)
0.70	2.40	1.68	10.4	0.72	2.36	1.70	13.5	0.69	2.40	1.66	VEMMER et al. (1973)

Appendix 10b. Explanation of abbreviations used in Appendix 10a

B - initial weight (kg)
FWT - final weight (kg)
S = Sex; 1 = barrows; 2 = gilts, 3 = barrows + gilts, 4 = boars, 5 = boars + gilts
NA - number of animals in experiment per treatment
NO = number of observations per treatment
D = type of diet;
1 = corn + soybean meal or sorghum + soybean meal
2 = barley + soybean meal or wheat + soybean meal
3 = other diets with a maximum of 3 ingredients
4 = diets with more than 3 ingredients
5 = synthetic diets
NE_f = net energy of fattening for pigs (MJ/kg diet)
L = Level of feeding; 1 = ad libitum, 2 = restricted
P-b - P content in diet without supplementation of inorganic P
FYT - phytate P content in diet
R - Ca/P ratio; 1 = constant, 2 = variable, 3 = Ca is constant
M - experimental period divided in M observations
C - during experimental period C times changed to a lower P content
PO - optimal P content according to author
P-1 = P content in diet at level 1 etc.
GR-1 - growth rate (kg/d) at level 1 etc.
FC-1 - feed conversion ratio at level 1 etc.
FI-1 - feed intake (kg/d) at level 1 etc.

Appendix 11. Number of the observations of the feeding trials specified according to initial weight, type of diet, level of feeding and sex (for explanation see Appendix 10b) (Chapter 5.3.)

initial weight (B) kg	type of diet					level of feeding		sex				
	1	2	3	4	5	1	2	1	2	3	4	5
B≤ 5	0	0	0	1	4	5	0	0	0	5	0	0
5<B≤10	18	0	1	2	0	21	0	2	2	14	3	0
10<B≤15	8	1	3	1	0	12	1	0	0	13	0	0
15<B≤20	18	5	2	1	0	24	2	6	1	17	2	0
20<B≤25	22	3	2	5	0	25	7	2	5	14	8	3
25<B≤30	6	0	0	3	0	6	3	0	0	7	2	0
30<B≤35	4	0	0	1	0	4	1	1	0	3	1	0
35<B≤40	2	0	0	0	0	2	0	0	0	2	0	0
40<B≤45	6	0	0	0	0	6	0	0	0	3	2	1
45<B≤50	3	0	1	0	0	4	0	1	1	2	0	0
50<B≤55	3	0	1	0	0	4	0	0	0	4	0	0
55<B≤60	3	2	0	0	0	5	0	0	0	5	0	0
60<B≤65	3	0	0	0	0	3	0	0	0	3	0	0
total	96	11	10	14	4	121	14	12	9	92	18	4

Appendix 12a. Results of regression analysis on growth rate (Chapter 5.3.3.2.)

Model used to calculate the expected growth rate:

$E\ (\underline{\text{growth rate}}_k) =$

$c_o + c_1 Pi + c_2\ Pi^2 + c_3 B + c_4 B^2 + c_5 B.Pi + c_6 B^2.Pi + c_7 B.\ Pi^2 + c_8 B^2.Pi^2 +$

$Level_k + \underline{e},\ var\ (\underline{e}|B) = \sigma^2 B^{-1}$

$Growth\ rate_k$: growth rate at Level of feeding $_k$, k = 1, 2

$Level\ of\ feeding_k$: contribution of Level of feeding k (1 = ad libitum; 2 = restricted)

Estimations of the coefficients

	estimations	se
constant	0.15914	0.19217
c_1	1.64305	1.16191
c_2	-2.95382	1.52845
c_3	0.03155	0.01291
c_4	-0.00047	0.00019
c_5	-0.10590	0.08091
c_6	0.00226	0.00128
c_7	0.23467	0.11461
c_8	-0.00510	0.00200
Level of feeding 1	0	0
Level of feeding 2	-0.06107	0.02705

Appendix 12b. Regression analysis on feed conversion ratio (Chapter 5.3.3.2.)

Model used to calculate the expected feed conversion ratio:

$E\ (\underline{\text{feed conversion}}_j) = c_o + c_1 Pi + c_2 Pi^2 + c_3\ B + c_4 B.Pi + type\ of\ diet_j +$

$\underline{e},\ var\ (\underline{e}|B) = o^2 B^{-1}$

$Feed\ conversion_j$: feed conversion at type of $diet_j$, j = 1, 2, 3, 4, 5

Estimates of the coefficients

	estimations	se
constant	3.56313	0.24480
c_1	-6.40788	1.15364
c_2	5.90729	1.09941
c_3	0.00541	0.00563
c_4	0.06378	0.02039
type of diet 1	0	0
" 2	0.50473	0.11673
" 3	0.21483	0.12550
" 4	-0.12248	0.12646
" 5	-0.38925	0.57037

Appendix 13. Mineral concentrations in feedstuffs used for the experiments (g/kg)

Trials	ingredient	T	Ca	Mg	P
VV367 to VV378	grass meal pellets	894	12.3	-	3.1
"	barley	823	0.4	-	3.3
"	soybean meal solv. extr.	857	2.9	-	6.2
"	milo	843	0.4	-	3.5
"	corn	856	0.1	-	2.4
"	oat husk meal	875	1.2	-	1.1
VV411 to VV422	tapioca	853	2.3	-	0.9
"	milo	853	0.1	-	2.3
"	grass meal pellets	916	8.7	-	3.3
"	corn	857	0.1	-	2.5
"	barley	832	0.6	-	3.5
"	wheat middlings	874	1.1	-	12.2
"	wheat	839	0.3	-	3.2
"	soybean meal solv. extr.	864	2.8	-	5.5
VV431 to VV445	wheat middlings	859	1.2	4.1	10.9
"	corn	850	0.1	1.0	2.3
"	barley	833	0.5	1.0	3.0
"	grass meal pellets	914	5.5	1.3	4.0
"	soybean meal solv. extr.	878	2.6	2.6	5.7
"	milo	863	0.1	1.1	2.3
"	wheat	848	0.4	1.2	3.7
VV572 to VV583	maize gluten feed	863	0.3	2.0	5.1
"	wheat middlings	832	1.1	3.8	10.0
"	rice bran solv. extr.	908	2.2	8.2	16.1
"	wheat bran	840	1.0	4.9	11.5
"	coconut expeller	843	1.0	3.0	5.0
"	grass meal pellets	904	18.7	2.2	1.8
"	soybean meal solv. extr.	850	2.6	2.5	5.1
"	maltsprouts	956	1.4	1.3	4.6
VV588,	tapioca	-	2.6	-	-
feeding exp.3,	wheat middlings	-	1.1	-	10.4
trial 1	soybean meal solv. extr.	-	3.0	-	5.8
"	grass meal pellets	-	11.1	-	3.0
VV597 to VV608,	tapioca	-	2.9	0.9	1.0
feeding exp.3,	soybean meal solv. extr.	-	2.9	2.6	6.1
trial 2	wheat middlings	-	0.9	3.5	11.4
first batch	grass meal pellets	-	6.1	-	3.6
feeding exp.3,	wheat middlings	-	1.2	-	9.8
trial 2,	grass meal pellets	-	13.6	-	2.6
second batch	soybean meal solv. extr.	-	2.6	-	6.4
	tapioca	-	2.4	-	0.9
VV614 and	citrus pulp	-	14.9	-	1.3
feeding exp. 3,	tapioca	-	2.8	-	1.0
trial 3	wheat middlings	-	1.0	-	10.1
first batch	soybean meal solv. extr. (XF <3.5%)	-	2.5	-	7.0
	hominy feed	-	0.4	-	5.4
	maize gluten feed	-	0.2	-	3.9
feeding exp.3,	maize gluten feed	-	0.2	-	4.9
trial 3	hominy feed	-	0.4	-	5.3
second batch	wheat middlings	-	0.8	-	12.5
	soybean meal solv. extr. (XF<3.5%)	-	2.4	-	6.6
	citrus pulp	-	14.5	-	0.9
	tapioca	-	0.5	-	1.1
	hominy feed	-	0.6	-	5.8

VV680,	grass meal pellets	-	8.2	2.2	2.8
feeding exp.3	soybean meal solv. extr.	-	2.2	2.8	6.2
trials 4 and 5	citrus pulp	-	12.7	-	0.9
	wheat bran	-	1.4	-	12.4
	tapioca	-	1.2	-	1.0
VV735	barley	866	1.2	1.3	3.9
"	hominy feed	899	1.2	3.9	8.4
"	maize gluten feed	876	1.7	3.6	7.6
"	sunflower meal solv. extr.	880	3.3	4.9	7.9
"	linseed meal solv. extr.	900	3.7	5.1	5.9
VV740, VV743	hominy feed USA	878	0.1	-	7.5
and feeding	tapioca chips	857	0.9	-	0.6
exp. 2	soybean meal solv.extr.(XF <3.5%)	850	2.8	-	6.6
"	wheat middlings	844	0.9	-	10.4
"	linseed expeller	860	3.6	-	7.3
"	maize	856	0.1	-	2.6
VV749,	citruspulp	898	15.0	1.2	0.9
feeding exp.3	tapioca	865	1.6	1.0	0.7
trial 6	wheat middlings	847	0.9	3.1	9.7
"	rice bran (<3% husks)	875	7.2	6.1	14.4
"	maize gluten feed (XP <21%)	880	0.6	3.7	8.4
"	hominy feed USA	892	0.7	2.5	4.9
"	coconut expeller	938	1.2	3.1	5.5
"	soybean meal solv.extr.(XF >7%)	877	3.1	2.6	5.9
VV769	maize	859	0.8	-	3.3
"	wheat middlings	868	1.3	3.5	10.3
"	rice bran	877	5.0	-	11.4
"	citruspulp	868	11.6	1.6	1.6
"	groundnut expeller	911	2.0	-	6.2
LV06 to LV09	soybean meal extr. (3.5-7.0%)	858	2.7	-	6.5
"	wheat middlings	862	1.4	-	12.4
"	rice bran (<3% husks)	900	2.3	-	14.4
"	rice bran solv. extr.	889	1.3	-	17.2
"	linseed expeller	924	3.3	-	7.2
"	citrus pulp	888	12.7	-	0.9
"	tapioca (57.5-62.5% starch)	845	2.3	-	1.0
"	maize gluten feed (< 21% XP)	905	1.2	-	8.5
LV25 to LV28	soybean meal extr. (Brasil)	880	2.9	-	6.3
"	grass meal (12.3% DXP)	932	6.2	-	2.6
"	potato protein dried	849	0.5	-	3.2
"	maize gluten feed (19% DXP)	874	0.4	-	6.8
"	tapioca (66% starch)	856	3.7	-	1.1
"	citrus pulp	885	13.8	-	1.0
"	linseed meal extr.	896	3.8	-	8.8
"	hominy feed solv. extr.	889	0.9	-	5.8
LV29 to LV32	hominy chop USA	901	0.5	-	7.4
"	wheat middlings	854	1.0	-	10.6
"	citrus pulp	894	13.4	-	0.9
"	soybean meal extr. (>7% XF)	885	5.2	-	5.9
"	rice bran (<3% husks)	875	7.2	-	14.4
"	groundnut expeller	947	1.2	-	5.6

Appendix 14. Composition of premixes used in the digestion, balance and feeding trials (mg/kg)

	VV478 to VV480	VV481 to VV483	VV566 to VV583 VV597 to VV608 VV622, VV588 feeding exp. 3 trials1,2	VV656 to VV675 VV614, VV680 feeding exp. 3 trials3,4,5	LV06 to LV09	LV25 to LV32	VV740, VV743, VV749 feeding exp. 2 feeding exp. 3 trial 6	VV730 to VV738 VV744 VV752 to VV802	piglet trial see Chapter 14.3.	other trials than mentioned before
Coppersulphate $CuSO_4.5H_2O$	-	400	500	440	40	40	440	40	700	800
Iron sulphate $FeSO_4.7H_2O$	430	430	430	430	430	430	430	430	1500	430
Zinc sulphate $ZnSO_4.H_2O$	215	335	-	-	-	155	150	155	300	455
Zincoxyde ZnO	-	-	75	75	75	-	-	-	-	-
Manganeseoxyde MnO	105	105	50	50	50	50	50	50	50	105
Cobaltsulphate $CoSO_4$	14	14	-	-	-	-	-	-	-	14
Potassiumiodide KJ	2	2	2	2	2	2	2	2	2	2
Magnesiumoxide MgO	52	52	-	-	-	-	-	-	-	52
Sodiumselenite Na_2SeO_3	-	-	0.15	0.15	0.15	0.15	0.15	0.15	0.30	-
Vitamin A 500 IU/mg	2.8	2.8	-	-	-	-	-	-	-	2.8
Vitamin AD_3 500/170 IU/mg	10.3	10.3	-	-	-	-	-	-	-	10.3
Vitamin AD_3 500 100 IU/mg	-	-	16	16	16	16	16	16	20	-
Vitamin B1 (thiamin)	0.7	0.7	-	-	-	-	-	-	2	0.7
Vitamin B2 (riboflavin)	3.4	3.4	4	4	4	4	4	4	7.5	3.4
Vitamin B3 (pantothenic acid)	8.2	8.2	8	8	8	8	8	8	3	8.2
Vitamin B4 (cholinechloride)	112	112	240	100	100	125	125	125	-	112
Vitamin B5 (niacin)	29	29	20	20	20	20	20	20	20	29
Vitamin B6 (pyridoxine)	0.7	0.7	-	-	-	10	-	-	2	0.7
Vitamin B12 (cyanocobalamin)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	-	0.02

Appendix 14. continued

Folic acid	0.3	0.3	-	-	-	-	-	-	-	0.3
Vitamin K_3	-	-	-	-	-	-	-	-	8	-
Vitamin E	4.3	4.3	8	8	8	8	8	8	20	4.3
Zinc bacitracine 10%	200	200	-	-	-	-	-	-	-	200
Nitrovin 30% / Tylan premix	-	-	33	-	-	-	-	-	160	-
Santoquin	-	-	125	125	125	125	125	125	-	-
Biotin 2%	-	-	-	-	-	-	-	-	3	-
Antioxydant	-	-	-	-	-	-	-	-	60	-

Remark: a) in VV597 to VV608 and VV 672 to VV675 1.0 and 0.9 g extra vitamin E respectively was added per kg added fat
b) the concentrations of vitamins were adjusted to 100 per cent purity if not indicated otherwise
c) in VV744 5.5 MgSO4 per kg maize kernels was added
d) the composition of the premix for trials VV 358 to 360 and VV395 to VV410 is not known.

Appendix 15. Results of the balance trials during the preliminary experiments described in Chapter 7

Trial		weight	growth	% in T		intake (g/d)			d_T	absorption %		retention %		retention (g/d)		
VV	n	(kg)	(g/d)	Ca	P	T	Ca	P	(%)	Ca	P	Ca	P	Ca	P	N
342, 328 to330	9	84	533	0.64	0.43	2099	14.24	9.01	78.0	52	39	38	35	5.93	3.51	-
	sd	6	79	-	-	75	0.37	0.47	1.7	3.4	3.8	3.4	3.8	0.44	0.44	-
343	3	90	383	0.26	0.45	2167	6.02	9.68	79.0	49	42	47	24	2.81	2.28	-
	sd	3	49	-	-	-	-	-	0.9	2.2	3.1	2.6	2.3	0.16	0.23	-
358	3	38	550	0.97	0.84	1244	12.34	10.48	81.1	39	42	37	28	4.58	2.98	14.0
359	3	67	730	1.15	0.91	1854	21.71	16.79	79.1	31	32	30	24	6.54	4.12	19.2
360	3	97	790	1.26	0.94	2318	29.73	21.85	79.4	31	33	30	26	8.96	5.68	19.7

Appendix 16. Results of the balance trials[a] of the first experiment described in Chapter 8 on effect of feeding trial

Trial VV	n	weight (kg)	growth (g/d)	% in T		intake (g/d)				d_T (%)	absorption %		retention %		retention (g/d)		
				Ca	P	T	Ca	P	N		Ca	P	Ca	P	Ca	P	N
566	3	43	631	0.71	0.58	1619	11.73	9.41	54.3	79.1	40	38	39	36	4.55	3.34	20.8
567	2	71	741	0.71	0.58	2200	15.93	12.76	72.6	80.4	40	36	39	32	6.23	4.03	21.1
568	2	99	616	0.71	0.58	2577	18.73	14.97	86.0	81.5	35	34	33	28	6.27	4.17	20.2
569	3	42	565	0.71	0.58	1321	9.58	7.68	44.3	80.5	48	42	46	40	4.43	3.11	18.9
570	3	65	558	0.71	0.58	1746	12.65	10.12	57.6	81.4	43	40	40	34	5.12	3.46	17.8
571	2	88	518	0.71	0.58	2066	15.01	12.00	68.9	81.2	34	34	32	26	4.87	3.06	18.0

a: animals in trials VV 566 to VV 568 were fed at a high level of feeding; those in trials VV 569 to VV 571 received 80 per cent of the amount fed at the high level of feeding.

Appendix 17. Results of the slaughter investigations of the first experiment described in Chapter 8

animal no.	level of feeding	age (days in exp.)	live weight (kg)	empty body weight (kg)	dry weight (g)	nitrogen (g)	fat (g)	ash (g)	Ca (g)	P (g)
26	high	13	32.4	27.3	9234	728	3716	871	224.7	148.0
27	low	13	27.6	24.0	7910	676	2662	876	245.2	150.0
18	high	13	34.9	29.2	9974	789	4171	1051	287.0	181.5
13	low	13	35.9	30.9	10386	786	4435	933	254.9	164.7
32	high	27	49.7	42.7	15010	1112	6547	1377	364.9	236.2
35	low	27	41.0	36.4	12417	1036	4507	1286	353.2	224.8
3	high	41	56.1	47.2	18544	1223	8711	1656	450.6	280.0
5	low	41	46.9	40.8	15763	1059	7249	1501	422.2	254.5
9	high	69	71.6	60.7	25798	1533	14390	1932	544.9	340.1
11	low	69	69.3	58.9	23470	1592	11389	1969	562.5	347.2
23	low	76	72.0	62.5	25440	1632	13404	2192	602.4	371.5
34	high	104	99.0	85.4	37146	2085	21038	2727	753.8	467.3
36	low	104	90.9	81.4	32631	2226	15486	2977	839.9	505.0
25	high	125	116.7	107.2	51001	2572	32148	3479	986.5	595.5
29	low	125	104.1	95.7	43172	2462	24036	3446	978.2	592.3
8	high	132	120.1	109.6	51158	2678	31200	3181	913.0	558.0
7	low	132	106.2	90.8	41377	2415	22138	3149	925.8	545.0
21*	high	132	96.1	85.2	38801	2124	22416	2663	728.8	451.9
14*	low	132	95.3	83.8	36959	2149	20891	2539	687.3	437.0
10*	high	118	103.9	95.3	44160	2314	27913	2781	824.0	493.5
6*	low	118	95.1	86.6	39087	2230	21880	2740	752.8	470.7
30*	high	111	110.5	101.9	44610	2469	26264	3151	899.0	556.3
28*	low	111	95.0	86.8	37672	2279	20270	3035	821.2	510.0
31	control	0	23.0	20.8	6464	547	2266	727	193.3	124.1
16	control	0	27.5	24.7	8265	667	3342	873	247.8	154.5
12	control	0	28.5	25.2	8707	682	3736	785	215.8	138.5

*: animals used in balance trials

Appendix 18. Results of the balance trials of the second experiment described in Chapter 8 on effect of feeding level

Trial*	n	% in T		weight	growth	intake (g/d)			d_T	absorption %		retention %		retention (g/d)		
		Ca	P	(kg)	(g/d)	T	Ca	P	(%)	Ca	P	Ca	P	Ca	P	N
LV25	2	0.81	0.64	35	695	1275	10.48	8.16	79.1	33	40	32	35	3.32	2.82	18.2
LV25	2	0.81	0.64	51	900	1670	13.76	10.69	81.8	48	54	47	44	6.44	4.70	26.6
LV25	2	0.81	0.64	83	770	2159	17.70	13.82	80.4	40	47	37	32	6.44	4.44	24.3
LV25	2	0.81	0.64	103	675	2484	20.38	15.90	82.0	36	47	34	31	6.96	4.86	23.6
LV26	2	0.81	0.64	35	410	958	7.89	6.13	81.1	38	43	38	37	2.96	2.29	13.6
LV26	2	0.81	0.64	53	550	1365	11.24	8.74	83.0	52	56	51	44	5.74	3.88	21.5
LV26	2	0.81	0.64	76	600	1561	12.86	9.99	83.8	50	57	49	43	6.29	4.30	21.8
LV26	2	0.81	0.64	104	765	1879	15.48	12.03	83.1	43	51	42	36	6.42	4.29	21.8
LV27	2	0.85	0.65	31	480	1233	10.64	7.96	70.3	36	35	32	33	3.46	2.66	19.0
LV27	2	0.85	0.65	57	860	1884	16.24	12.16	72.0	36	35	34	34	5.60	4.08	28.8
LV27	2	0.85	0.65	77	890	2194	18.88	14.16	73.3	40	37	39	34	7.31	4.80	29.2
LV27	2	0.85	0.65	104	925	2473	21.30	15.95	74.7	36	35	34	29	7.20	4.58	28.4
LV28	2	0.85	0.65	32	435	899	7.77	5.80	74.8	38	32	34	32	2.64	1.83	14.1
LV28	2	0.85	0.65	62	760	1596	13.75	10.30	75.2	42	38	38	37	5.25	3.78	24.3
LV28	2	0.85	0.65	88	450	1870	16.11	12.06	76.9	42	38	40	34	6.40	4.06	23.8
LV28	2	0.85	0.65	101	415	1907	16.44	12.30	77.0	41	36	39	28	6.44	3.46	14.4

x LV 25: high feeding level; cereal-based diet
LV 26: low feeding level; cereal-based diet
LV 27: high feeding level; by-product based diet
LV 28: low feeding level; by-product based diet

Appendix 19. Results of the balance trials of the third experiment described in Chapter 8 on effect of feeding level

Trial[x]	n	% in T		weight	growth	intake (g/d)			d_T	absorption%		retention%		retention (g/d)		
		Ca	P	(kg)	(g/d)	T	Ca	P	(%)	Ca	P	Ca	P	Ca	P	N
LV29	2	0.86	0.67	44	800	1466	12.78	9.75	84.3	36	35	35	32	4.46	3.14	20.4
LV29	2	0.86	0.67	71	980	2057	17.93	13.68	86.1	45	41	44	40	7.88	5.44	31.6
LV29	2	0.86	0.67	100	1020	2590	22.61	17.22	86.6	47	41	46	39	10.37	6.68	34.8
LV29	2	0.86	0.67	130	910	2775	24.18	18.46	87.6	44	37	43	31	10.31	5.70	31.2
LV30	2	0.86	0.67	40	520	1031	9.00	6.86	88.6	44	42	41	40	3.68	2.75	16.0
LV30	2	0.86	0.67	63	720	1411	12.32	9.39	88.5	50	44	49	42	6.02	3.95	20.8
LV30	2	0.86	0.67	90	720	1741	15.22	11.58	89.6	52	45	51	42	7.77	4.81	25.2
LV30	2	0.86	0.67	116	380	1920	16.75	12.77	88.1	47	42	46	33	7.76	4.16	22.4
LV31	2	0.97	0.89	46	810	1600	15.64	14.16	71.4	24	24	24	20	3.70	2.85	20.5
LV31	2	0.97	0.89	70	1030	2128	20.78	18.84	75.8	39	35	38	31	7.98	5.84	31.9
LV31	2	0.97	0.89	101	1180	2682	26.19	23.74	76.6	38	35	37	29	9.66	6.92	38.0
LV31	2	0.97	0.89	128	610	2825	27.57	25.00	74.6	33	31	33	24	9.09	5.90	31.0
LV32	2	0.97	0.89	41	440	1094	10.69	9.69	77.1	34	32	31	29	3.36	2.81	16.4
LV32	2	0.97	0.89	63	710	1425	13.93	12.61	78.2	38	34	37	30	5.20	3.74	21.7
LV32	2	0.97	0.89	88	630	1758	17.18	15.56	76.6	35	32	35	25	5.96	3.88	20.1
LV32	2	0.97	0.89	113	760	1948	19.04	17.24	78.1	40	35	40	28	7.54	4.80	23.9

x LV 25: high feeding level; cereal-based diet
LV 30: low feeding level; cereal-based diet
LV 31: high feeding level; by-product based diet
LV 32: low feeding level; by-product based diet

Appendix 20. Results of balance trials of the fourth experiment described in Chapter 8 on effect of energy supply

diet*	trial VV	n	weight (kg)	growth (g/d)	% in T			intake (g/d)			d_T (%)	absorption%		retention%		retention (g/d)		
					Ca	P	T	Ca	P	N		Ca	P	Ca	P	Ca	P	N
3	701	4	27	665	0.99	0.80	970	9.78	7.73	33.0	79.8	46	44	38	38	3.76	2.91	15.2
3	702	4	49	740	0.99	0.80	1451	14.57	11.59	51.1	81.3	47	44	45	38	6.52	4.37	24.4
3	703	4	76	995	0.99	0.80	1906	19.13	15.22	67.6	82.6	45	45	41	36	7.86	5.42	29.5
3	704	4	99	952	0.99	0.80	2199	22.08	17.50	79.5	83.5	44	43	41	33	9.04	5.78	30.5
4	705	4	28	740	0.75	0.66	1240	9.49	8.22	36.9	81.4	46	42	39	34	3.70	2.83	17.4
4	706	4	46	805	0.75	0.66	1759	13.51	11.63	51.8	83.2	49	42	46	36	6.20	4.16	23.3
4	707	4	73	1108	0.75	0.66	2252	17.23	14.91	65.4	84.9	47	43	42	34	7.28	5.11	30.8
4	708	4	97	1185	0.75	0.66	2554	19.57	16.72	73.9	84.6	46	42	40	30	7.84	5.02	29.0

* diet 3: feeding level C.V.B. -15 %
diet 4: feeding level C.V.B. +10 %

Appendix 21. Data of the pigs at slaughter of the fourth experiment described in Chapter 8

diet	animal	age (d)	live weight (kg)	empty body weight (kg)	dry weight	nitrogen (g)	fat (g)	ash (g)	Ca (g)	P (g)
	C 1	0	14.8	*	3783	340	1023	429	118.4	72.0
	C 2	0	15.0	*	3911	374	1118	402	111.9	68.0
	C 3	0	18.8	*	4788	466	1568	-	-	-
1	Gr 1	88	106.2	95.4	39557	2599	20259	2602	701.7	458.3
1	Gr 2	88	100.8	92.4	38689	2600	18524	2856	802.3	501.5
1	Gr 3	102	102.0	94.0	36054	2708	16178	2743	743.9	482.3
1	Gr 4	96	111.2	97.3	41295	2744	21008	2736	752.2	485.2
2	Re 1	88	101.2	92.4	39055	2612	19048	2596	721.1	455.0
2	Re 2	96	105.8	96.5	35993	2657	16931	2549	679.2	442.6
2	Re 3	102	106.0	95.7	35477	2850	14493	2845	780.1	486.9
3	B 11	109	102.0	93.0	36474	2747	16232	3155	930.4	561.2
3	B 12	102	105.2	94.5	33666	2483	13246	2885	820.0	500.0
3	B 13	109	103.5	95.3	32404	2928	11224	2998	808.5	520.3
3	B 14	109	107.5	98.2	33336	3031	11670	3107	884.4	545.1
4	Ye 1	88	104.2	95.5	40459	2562	21567	2596	727.8	461.2
4	Ye 2	96	110.0	98.0	39538	2775	19253	2670	722.6	477.2
4	Ye 3	102	103.5	92.7	37778	2719	19207	2518	696.9	444.9
4	Ye 4	96	108.0	93.4	38558	2581	19285	2745	737.7	484.3

Appendix 22. Results of the balance trials of the first experiment described in Chapter 9 on effect of dietary lysine concentrations

diet*	trial VV	n	weight (kg)	growth (g/d)	g/kg T		intake (g/d)			d_T (%)	absorption %		retention %		retention(g/d)		
					Ca	P	T	Ca	P		Ca	P	Ca	P	Ca	P	N
A	395	2	36	563	12.5	7.2	1196	15.09	8.61	78.9	41	40	37	40	5.53	3.43	12.8
A	396	2	56	580	9.3	6.4	1627	15.30	10.41	78.5	28	30	26	28	3.91	2.86	15.9
A	397	2	78	688	9.3	6.4	2048	19.26	13.11	80.2	32	34	31	31	5.92	4.09	21.1
A	398	2	98	655	9.3	6.4	2326	21.87	14.89	78.3	22	27	20	23	4.45	3.49	20.1
B	399	2	35	477	11.2	6.8	1185	13.41	8.06	80.0	51	40	46	39	6.19	3.18	12.5
B	400	2	56	588	9.0	6.2	1570	14.30	9.73	78.0	26	26	24	25	3.49	2.47	15.9
B	401	2	75	762	9.0	6.2	1971	17.96	12.23	78.4	37	34	35	32	6.28	3.96	21.3
B	402	2	95	702	9.0	6.2	2270	20.67	14.08	79.4	33	35	32	33	6.60	4.62	25.9
C	403	2	35	510	8.2	6.1	1171	9.74	7.14	78.6	41	39	36	39	3.51	2.76	15.0
C	404	2	54	512	9.4	6.3	1639	15.58	10.33	79.1	33	34	31	29	4.83	3.02	13.7
C	405	2	72	679	9.4	6.3	2007	19.08	12.64	78.1	33	41	31	36	5.89	4.55	17.5
C	406	2	95	607	9.4	6.3	2347	22.30	14.78	79.1	27	30	25	24	5.54	3.57	18.4
D	407	2	36	542	15.6	7.9	1186	18.63	9.37	74.8	32	33	28	33	5.29	3.12	14.8
D	408	2	55	589	10.1	6.7	1621	16.55	10.86	77.1	32	30	29	30	4.83	3.24	17.8
D	409	2	76	722	10.1	6.7	2023	20.65	13.56	76.2	27	32	26	30	5.27	4.10	22.4
D	410	2	95	619	10.1	6.7	2311	23.58	15.48	77.2	30	34	28	31	6.72	4.84	25.2

* diet A = 7.7 g lysine/kg T fed to barrows
diet B = 8.6 g lysine/kg T fed to boars
diet C = 9.7 g lysine/kg T fed to barrows
diet D = 10.8 g lysine/kg T fed to boars

Appendix 23. Results of the balance trials of the second experiment described in Chapter 9 on effect of dietary lysine concentrations

diet**	trial VV	n	weight (kg)	growth (kg/d)	%in T Ca	%in T P	T	intake (g/d) Ca	intake (g/d) P	d_T (%)	absorption% Ca	absorption% P	retention% Ca	retention% P	retention(g/d) Ca	retention(g/d) P	retention(g/d) N
1	656	4	36	0.74	0.65	0.57	1385	9.19	7.91	80.5	52	41	49	38	4.51	3.05	16.8
1	657	4	48	0.70	0.65	0.57	1826	12.19	10.39	82.2	54	42	51	39	6.21	4.08	22.9
1	658	4	77	1.00	0.65	0.57	2414	16.01	13.67	82.7	50	42	48	38	7.70	5.15	28.4
1	659	4	98	0.88	0.65	0.57	2731	18.11	15.59	83.9	49	40	47	34	8.46	5.33	30.6
2	660	4	35	0.74	0.79	0.61	1381	11.10	8.43	80.2	48	40	44	36	4.84	3.00	18.0
2	661	4	47	0.66	0.79	0.61	1813	14.55	11.09	81.1	51	41	48	38	6.95	4.15	25.2
2	662	4	76	1.06	0.79	0.61	2363	18.96	14.37	83.1	51	41	47	35	8.97	5.05	30.0
2	663	4	98	1.04	0.72	0.61	2727	19.78	16.71	84.0	46	41	43	35	8.51	5.86	33.6
3	664	4	35	0.74	0.70	0.59	1373	9.81	8.13	81.3	48	42	45	39	4.46	3.16	20.1
3	665	4	47	0.69	0.70	0.59	1813	12.93	10.78	82.3	48	41	46	38	6.00	4.06	26.0
3	666	4	76	1.06	0.70	0.59	2375	16.88	14.08	84.1	49	42	47	37	7.92	5.24	34.2
3	667	4	98	0.95	0.70	0.59	2728	19.51	16.15	84.6	50	41	48	34	9.42	5.55	34.5
4	668	4	36	0.82	0.74	0.61	1377	10.38	8.35	79.5	48	39	42	38	4.37	3.20	20.2
4	669	4	49	0.74	0.74	0.61	1853	13.98	11.21	81.6	59	45	55	44	7.73	4.87	29.2
4	670	3*	78	1.03	0.74	0.61	2415	18.14	14.57	82.9	54	43	50	39	9.05	5.70	35.1
4	671	4	99	1.16	0.74	0.61	2777	20.87	16.88	84.6	53	46	49	39	10.25	6.59	33.8

* one animal out of trial

** diet 1 = 7.7 g lysine/kg T fed to boars and gilts
diet 2 = 8.6 g lysine/kg T fed to boars and gilts
diet 3 = 9.7 g lysine/kg T fed to boars and gilts
diet 4 = 10.8 g lysine/kg T fed to boars and gilts

Appendix 24. Results of the balance trials described in Chapter 13 on effect of dietary fat

Trial* VV	n	% in T Ca	% in T P	weight (kg)	growth (g/d)	T	intake (g/d) Ca	intake (g/d) P	d_T (%)	absorption% Ca	absorption% P	retention% Ca	retention% P	retention(g/d) Ca	retention(g/d) P	retention(g/d) N
597	3	0.68	0.61	54	701	1463	10.07	8.93	82.2	42	37	40	32	4.04	2.83	-
598	3	0.63	0.58	69	716	1583	10.15	9.10	85.1	53	46	51	40	5.21	3.64	-
599	3	0.63	0.58	84	741	1794	11.52	10.31	85.1	53	45	52	36	5.93	3.70	-
603	3	0.89	0.61	51	667	1423	12.78	8.68	82.1	40	38	39	36	4.93	3.13	-
604	3	0.84	0.58	65	681	1531	13.04	8.80	84.4	46	39	44	38	5.72	3.36	-
605	2	0.84	0.58	83	786	1780	15.18	10.24	83.0	38	36	37	31	5.56	3.06	-
606	3	0.84	0.58	97	713	1973	16.84	11.35	84.6	43	45	42	35	7.03	4.01	-
607	3	0.84	0.58	109	640	2023	17.27	11.63	85.0	42	45	40	36	6.97	4.13	-
608	3	0.84	0.58	120	660	2088	17.82	12.01	84.6	36	40	34	31	6.12	3.75	-
622	4	0.84	0.58	73	647	1664	14.15	9.57	81.4	36	46	36	38	5.04	3.63	-
672	4	0.86	0.62	92	646	2092	18.09	12.86	87.0	31	35	31	28	5.59	3.61	18.4
673	4	0.80	0.57	91	708	1866	15.04	10.64	87.5	36	42	35	32	5.23	3.35	18.1
674	4	1.16	0.57	90	671	1864	21.74	10.63	86.3	30	37	29	35	6.21	3.60	18.0
675	3	0.80	0.57	92	688	1874	15.10	10.68	87.7	36	40	35	33	5.15	3.49	18.1

* trial VV597: basal diet 1
" VV598: basal diet 1 + soybean oil
" VV599: basal diet 1 + tallow
" VV603: basal diet 1 + $CaCO_3$
" VV604: basal diet 1 + $CaCO_3$ + soybean oil
" VV605: basal diet 1 + $CaCO_3$ + tallow
" VV606: basal diet 1 + $CaCO_3$ + industrial fat 1
trial VV607: basal diet 1 + $CaCO_3$ + industrial fat 2
" VV608: basal diet 1 + $CaCO_3$ + industrial fat 3
" VV622: basal diet 1 + $CaCO_3$ + industrial fat 4
" VV672: basal diet 2
" VV673: basal diet 2 + tallow
" VV674: basal diet 2 + $CaCO_3$ + tallow
" VV675: basal diet 2 + coconut fat

Appendix 25. Results of the balance trials described in Chapter 11 on effect of dietary fibre

diet*	trial VV	n	weight (kg)	growth (g/d)	% in T Ca	% in T P	intake (g/d) T	intake (g/d) Ca	intake (g/d) P	d_T (%)	absorption % Ca	absorption % P	retention % Ca	retention % P	retention (g/d) Ca	retention (g/d) P	retention (g/d) N
A	572	3	42	595	0.86	0.65	1214	10.58	7.93	82.4	40	39	39	33	4.11	2.65	18.4
A	573	3	64	738	0.86	0.65	1655	14.39	10.77	83.4	43	41	42	35	6.08	3.77	24.2
A	574	3	95	860	0.86	0.65	2130	18.58	13.88	84.2	41	40	40	32	7.37	4.40	29.8
B	575	3	41	595	0.86	0.67	1215	10.79	8.24	72.1	38	36	38	31	4.08	2.52	16.9
B	576	3	64	746	0.86	0.67	1716	14.93	11.47	71.2	34	33	34	26	5.04	3.00	20.9
B	577	3	92	802	0.86	0.67	2173	18.94	14.48	73.6	39	37	38	28	7.20	4.09	23.6
C	578	3	40	543	0.84	0.66	1215	10.32	8.04	81.0	46	43	44	35	4.58	2.83	15.6
C	579	3	64	698	0.84	0.66	1700	14.46	11.20	81.0	41	41	40	32	5.78	3.59	20.2
C	580	3	93	813	0.84	0.66	2148	18.19	14.22	81.1	40	40	39	30	7.13	4.32	26.7
D	581	3	39	512	0.86	0.68	1220	10.71	8.31	71.0	35	38	35	28	3.72	2.36	13.2
D	582	3	62	595	0.86	0.68	1722	14.98	11.68	72.2	36	39	35	28	5.17	3.23	20.0
D	583	3	92	699	0.86	0.68	2182	18.97	14.79	72.1	34	35	33	25	6.27	3.68	26.3

diet A: XF = 59 g/kg T; digestible lysine = 7.0 g/kg T
" B: XF = 139 " ; " = 6.4 "
" C: XF = 62 " ; " = 5.8 "
" D: XF = 133 " ; " = 5.4 "

Appendix 26. Results of the balance trials described in Chapter 12 on effect of dietary Ca/P ratio

diet*	trial VV	n	weight (kg)	growth (g/d)	% in T		intake (g/d)				d_T (%)	absorption%		retention%		retention (g/d)		
					Ca	P	T	Ca	P	N		Ca	P	Ca	P	Ca	P	N
1	376	3	48	573	0.22	0.42	1438	3.49	6.01	-	81.2	64	50	64	42	2.22	2.50	-
1	377	3	72	763	0.24	0.41	1966	5.23	7.95	-	80.6	61	40	60	33	3.14	2.65	-
1	378	3	98	607	0.16	0.40	2064	3.78	8.35	-	80.4	56	41	55	24	2.09	2.02	-
2	373	3	42	620	0.48	0.40	1338	6.81	5.34	-	79.5	58	39	46	39	3.14	2.07	-
2	374	3	68	807	0.38	0.41	1795	7.32	7.37	-	81.0	58	44	48	43	3.50	3.16	-
2	375	3	96	787	0.36	0.41	2139	8.26	8.68	-	79.9	56	40	52	40	4.25	3.45	-
3	367	9	47	588	0.63	0.40	1446	9.45	5.79	42.0	79.9	52	39	32	38	3.06	2.24	17.6
3	368	9	70	720	0.58	0.41	1841	11.27	7.62	53.3	79.6	57	39	32	39	3.56	2.95	21.1
3	369	9	99	693	0.60	0.40	2122	13.25	8.48	64.3	79.3	54	36	32	35	4.27	2.98	24.9
4	370	8	46	620	0.63	0.59	1418	9.26	8.31	40.2	80.3	48	49	47	41	4.35	3.43	18.2
4	371	7	71	793	0.62	0.57	1868	12.13	10.65	51.6	79.2	47	44	47	36	5.67	3.84	23.0
4	372	9	99	701	0.55	0.53	2118	12.25	11.13	58.8	80.0	44	42	44	28	5.33	3.16	25.2

* diet 1: basal diet without supplementary Ca and P
2: " " plus 0.20% Ca
3: " " plus 0.40% Ca
4: " " plus 0.40% Ca and 0.16% P

Appendix 27. Results of the balance trials of the first experiment described in Chapter 13 on effect of phytase concentration

diet*	trial VV	n	weight (kg)	growth (g/d)	%in T		intake (g/d)			d_T (%)	absorption%		retention%		retention(g/d)	
					Ca	P	T	Ca	P		Ca	P	Ca	P	Ca	P
1	411	3	41	638	0.21	0.37	1280	3.01	4.76	81.8	42	27	38	26	1.15	1.26
1	412	3	69	714	0.21	0.37	1884	4.43	6.99	83.8	53	34	50	31	2.21	2.18
1	413	3	101	778	0.21	0.37	2408	5.70	8.94	83.9	61	37	61	30	3.46	2.64
3	414	3	39	529	0.19	0.66	1300	2.73	8.65	75.4	30	36	28	20	0.77	1.73
3	415	3	62	542	0.19	0.66	1863	3.91	12.32	75.7	47	40	47	19	1.83	2.36
3	416	3	98	557	0.19	0.66	2487	5.25	16.52	76.6	45	42	44	18	2.32	2.91
5	417	3	41	581	0.40	0.67	1369	5.74	9.17	75.8	47	38	46	27	2.62	2.48
5	418	3	67	690	0.40	0.67	1936	8.25	12.98	76.5	45	37	44	23	3.65	3.00
5	419	3	98	556	0.40	0.67	2478	10.04	16.59	76.6	40	37	39	22	4.34	3.64
6	420	3	42	594	0.64	0.67	1380	13.80	9.11	75.4	43	36	42	34	3.85	3.09
6	421	3	68	706	0.64	0.67	1948	19.48	12.88	76.8	44	38	42	32	5.59	4.15
6	422	3	99	614	0.64	0.67	2488	24.88	16.35	76.4	31	35	30	26	4.96	4.38

* diet 1: phytase-deficient
diet 3, 5 and 6: phytase rich

Appendix 28. Results of the balance trials of the second experiment described in Chapter 13 on effect of phytase concentration

diet*	trial VV	n	weight (kg)	growth (g/d)	%in T Ca	%in T P	T	intake (g/d) Ca	intake (g/d) P	d_T (%)	absorption% Ca	absorption% P	retention% Ca	retention% P	retention(g/d) Ca	retention(g/d) P
1	431	3	44	698	0.19	0.38	1307	2.90	5.00	84.9	59	40	58	33	1.70	1.63
1	432	3	70	768	0.19	0.38	1902	4.30	7.21	85.2	64	36	64	29	2.73	2.10
1	433	3	99	714	0.19	0.38	2404	5.16	9.18	85.0	51	36	50	24	2.60	2.17
2	437	3	44	710	0.16	0.50	1362	2.60	6.87	82.9	36	45	35	21	0.91	1.44
2	438	3	68	667	0.16	0.53	1853	3.70	9.86	83.9	55	50	55	22	2.02	2.20
2	439	3	100	766	0.16	0.56	2391	4.50	13.50	87.1	61	58	60	18	2.71	2.42
3	434	3	43	655	0.15	0.63	1372	2.45	8.68	78.3	53	50	51	28	1.26	2.40
3	435	3	68	673	0.15	0.63	1913	3.51	12.16	78.3	62	50	61	20	2.15	2.43
3	436	3	98	579	0.15	0.63	2508	4.33	15.87	79.5	64	54	63	20	2.71	3.11
4	440	3	43	619	0.25	0.64	1369	3.84	8.75	78.4	50	48	48	32	1.86	2.84
4	441	3	71	685	0.25	0.64	1986	5.62	12.67	78.2	55	47	54	26	3.04	3.35
4	442	3	100	757	0.25	0.64	2510	6.95	16.00	80.3	57	52	56	28	3.91	4.50
5	443	3	44	696	0.37	0.63	1415	5.59	8.86	79.0	56	48	55	34	3.08	3.00
5	444	3	71	804	0.37	0.63	1965	7.86	12.32	79.3	54	45	53	27	4.16	3.35
5	445	3	99	780	0.37	0.63	2505	9.81	15.69	79.7	56	50	56	29	5.46	4.51

x diet 1: phytase-deficient
diet 2: phytase-deficient plus $Na_2HPO_4.7H_2O$
diet 3, 4 and 5: phytase rich

Appendix 29. Results of the balance trials of the third experiment described in Chapter 13 on effect of type of diet

diet*	trial LV	n	weight (kg)	growth (g/d)	%in T		intake (g/d)			d_T (%)	absorption%		retention%		retention(g/d)		
					Ca	P	T	Ca	P		Ca	P	Ca	P	Ca	P	N
A	6	2	70	900	0.85	0.71	1970	16.90	14.05	85.0	45	47	44	38	7.52	5.34	27.1
A	6	2	88	1060	0.85	0.71	2145	18.42	15.29	86.2	60	54	58	45	10.75	6.94	32.1
B	7	2	59	930	0.92	0.80	1893	17.58	15.12	68.2	37	26	29	26	5.12	3.87	26.3
B	7	2	90	1020	0.92	0.80	2362	21.86	18.81	72.4	41	31	36	30	7.80	5.72	32.5
C	8	2	66	955	1.32	1.07	2088	27.90	22.31	69.3	29	20	20	20	5.49	4.42	30.6
C	8	2	90	940	1.32	1.07	2370	31.61	25.36	70.7	25	19	19	18	6.09	4.68	30.0
D	9	2	69	915	1.00	0.69	2055	20.66	14.10	74.6	41	33	31	32	6.38	4.56	29.3
D	9	2	79	935	1.00	0.69	2122	21.34	14.64	75.0	45	36	33	35	7.10	5.19	30.8

* diet A: cereal-based diet
  diet B: maize by-products diet
  diet C: tapioca-linseed-rice bran diet
  diet D: tapioca-wheat middling-linseed-citruspulp diet

Appendix 30. Results of the balance trials of the first experiment described in Chapter 14 on feed phosphates

diet*	Trial VV	n	weight (kg)	growth (g/d)	% in T Ca	% in T P	intake (g/d) T	intake (g/d) Ca	intake (g/d) P	d_T (%)	absorption % Ca	absorption % P	retention % Ca	retention % P	retention (g/d) Ca	retention (g/d) P
	534	4	39	607	0.50	0.39	1302	6.98	5.05	83.0	51	32	34	32	2.40	1.61
Basal	535	4	69	772	0.50	0.39	2008	10.63	7.83	85.6	62	45	48	44	5.14	3.48
	536	4	99	620	0.50	0.39	2455	13.11	9.50	85.5	58	44	49	43	6.41	4.09
	537	3	39	673	0.71	0.55	1282	9.50	7.04	83.8	45	41	45	36	4.26	2.54
DCP	538	3	69	762	0.71	0.55	2003	14.77	11.06	83.9	44	41	43	32	6.37	3.60
	539	3	97	674	0.71	0.55	2431	17.93	13.30	83.3	30	35	29	24	5.23	3.19
	540	3	39	649	0.71	0.56	1286	9.57	7.17	83.6	47	45	46	40	4.43	2.86
HOS	541	3	69	738	0.71	0.56	1992	14.73	11.05	84.6	45	45	45	36	6.60	3.93
	542	3	98	720	0.71	0.56	2434	17.99	13.61	83.6	32	37	32	27	5.69	3.73
	543	3	40	614	0.76	0.56	1333	10.61	7.50	84.4	46	45	46	41	4.83	3.07
CUR	544	3	70	782	0.76	0.56	2015	15.96	11.29	84.6	43	42	41	34	6.57	3.83
	545	3	97	599	0.76	0.56	2446	19.37	13.75	83.9	35	40	34	27	6.48	3.73
	546	3	40	629	0.72	0.56	1296	9.74	7.27	83.7	46	49	44	39	4.28	2.84
SUP	547	3	67	583	0.72	0.56	2012	14.96	11.57	82.6	40	46	38	29	5.73	3.37
	548	3	87	122	0.72	0.56	2126	15.93	11.95	82.4	33	43	31	23	4.99	2.76

* Basal: basal diet without supplementary P
DCP : " " plus dicalcium phosphate
HOS : " " " Hostaphos
CUR : " " " Curaphos
SUP : " " " Superphosphate

Appendix 31. Results of the balance trials of the first experiment described in Chapter 15 on effect of pelleting

diet	trial VV	n	weight (kg)	growth (g/d)	% in T Ca	% in T P	intake (g/d) T	intake (g/d) Ca	intake (g/d) P	d_T (%)	absorption % Ca	absorption % P	retention % Ca	retention % P	retention (g/d) Ca	retention (g/d) P
meal	487	3	36	464	0.60	0.48	1342	8.50	6.45	80.4	40	37	34	36	2.94	2.29
"	488	3	68	680	0.60	0.48	1973	12.39	9.49	81.0	43	38	41	37	5.05	3.47
"	489	3	98	712	0.60	0.48	2421	15.26	11.62	81.9	42	38	41	35	6.26	4.06
pelleted	493	2	38	500	0.62	0.48	1331	8.63	6.42	80.9	39	38	37	38	3.19	2.44
"	494	3	70	776	0.62	0.48	1943	12.53	9.34	81.7	44	41	42	40	5.27	3.78
"	495	3	100	765	0.62	0.48	2464	15.88	11.89	83.0	45	42	44	41	6.29	4.87
meal	484	3	36	512	0.79	0.64	1316	10.80	8.37	79.1	37	37	37	30	3.96	2.55
"	485	3	67	754	0.79	0.64	1935	15.77	12.29	80.8	38	38	37	31	5.80	3.81
"	486	3	98	756	0.79	0.64	2472	20.08	15.70	81.2	31	33	30	24	5.97	3.77
pelleted	490	3	37	482	0.78	0.64	1342	10.84	8.52	80.3	35	38	34	31	3.72	2.67
"	491	3	67	702	0.78	0.64	1965	15.77	12.54	81.3	33	39	32	34	5.12	4.25
"	492	3	100	768	0.78	0.64	2399	19.19	15.25	82.7	33	38	33	29	6.25	4.44

Appendix 32. Results of the balance trials vv 478 to vv 486 described in Chapter 15 on effect of dietary Cu level

diet*	trial VV	n	Ca	P	weight (kg)	growth (g/d)	intake (g/d) T	intake (g/d) Ca	intake (g/d) P	d_T (%)	absorption % Ca	absorption % P	retention% Ca	retention% P	retention (g/d) Ca	retention (g/d) P	intake Cu (mg/d)	Cu in faeces (mg/d)
Low Cu	478	3	0.75	0.60	35	476	1290	10.14	7.75	80.0	38	35	37	31	3.72	2.43	11.1	11.4
"	479	3	0.75	0.60	68	754	1965	15.29	11.82	81.3	41	40	40	34	6.19	4.04	-	-
"	480	3	0.75	0.60	100	778	2428	18.93	14.65	82.8	42	41	41	33	7.78	4.87	21.0	21.7
Medium Cu	481	3	0.76	0.62	36	488	1271	10.10	7.87	80.6	40	38	39	30	3.91	2.39	153	136
"	482	3	0.76	0.62	67	714	1944	15.33	12.02	81.0	38	40	38	32	5.79	3.86	-	-
"	483	3	0.76	0.62	99	768	2408	19.00	15.04	81.7	33	35	32	27	6.17	4.04	290	268
High Cu	484	3	0.79	0.64	36	512	1316	10.80	8.37	79.1	37	37	37	30	3.96	2.55	301	299
"	485	3	0.79	0.64	67	754	1935	15.77	12.29	80.8	38	38	37	31	5.80	3.81	-	-
"	486	3	0.79	0.64	98	756	2472	20.08	15.70	81.2	31	33	30	24	5.97	3.77	565	592

x Low Cu: in diet 9 mg Cu/kg T
Medium Cu: in diet 120 mg Cu/kg T
High Cu: in diet 229 mg Cu/kg T

Curriculum vitae

Age Wiebren Jongbloed werd op 7 september 1944 geboren te Wijtgaard (gemeente Leeuwarden). Na het behalen van het diploma MULO-B aan de Willem Frederikschool voor Christelijke M.U.L.O. te Leeuwarden in 1961, behaalde hij in 1964 het einddiploma aan de Bijzondere Hogere Landbouwschool te Leeuwarden. Vervolgens vervulde hij de militaire dienstplicht. In 1967 begon hij zijn studie aan de Landbouwhogeschool te Wageningen. In januari 1974 studeerde hij af in de richting Akker- en Weidebouw, met de ingenieursvakken de Leer van het grasland, de Veevoeding en de Dierfysiologie. Vanaf 4 februarti 1974 is hij als wetenschappelijk onderzoeker werkzaam bij het Instituut voor Veevoedingsonderzoek te Lelystad met als opdracht het onderzoek naar de fosforhuishouding bij varkens. Tevens verrichtte hij onderzoek naar de energetische benutting van voeder door varkens. Sinds 1977 leidt hij de afdeling Eénmagigen van het instituut.