Animal 17 (2023) 100987

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

Review: The amazing gain-to-feed ratio of newly weaned piglets: sign of efficiency or deficiency?

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ARTICLE INFO

Article history:
Received 13 February 2023
Revised 31 August 2023
Accepted 7 September 2023
Available online 14 September 2023

Keywords:
Edema
Hypophosphatemia
Insulin
Refeeding syndrome
Swine

ABSTRACT

Shortly after weaning, piglets generally eat dry feed poorly; but nevertheless, a phenomenal gain-to-feed ratio is achieved as they gain about as much weight as they eat (150–200 g/d). The high gain-to-feed ratio, though, cannot be explained by their nutrient intake or nutrient repartitioning. Analyses based on tissue composition and bio-electrical impedance data showed that newly weaned piglets lose fat, maintain protein, and gain large amounts of water because of edema. This edema, which may well contribute up to one kg of BW, seems to be triggered by refeeding syndrome. Refeeding syndrome in adult humans occurs when subjects fast for an extended period of time (weeks) that results in downshifts in metabolic activity and concomitant shedding of phosphate (**PO_4**), magnesium (**Mg**), and potassium (**K**) in urine. If food is abruptly reintroduced, thus, resulting in strong insulin spikes, metabolism is triggered but hampered by a lack of PO_4, Mg, K, and thiamine, causing hypophosphatemia, metabolic stress, and edema. In piglets, the same process appears to happen immediately after weaning but in hours rather than weeks, possibly linked to their high metabolic rate. Refeeding syndrome can be lethal in humans but does not appear to be directly lethal in piglets. Our attempts to prevent it through altered diet composition and/or controlled feeding programs have not resulted in better performance at the end of the nursery phase. A practical ramification of weaning-induced edema is that growth and gain-to-feed ratio data immediately after weaning should be interpreted with caution. In addition, diets arguably should be formulated to not strongly trigger insulin release, while high lysine levels are not needed as the gain is not based on protein accretion.

Implications

Newly weaned pigs typically eat around maintenance during the first week after weaning but gain weight because of edema, not protein or fat tissue accretion. Positive weight gain in this first week after weaning should, thus, not be interpreted as healthy. This edema is caused by refeeding syndrome for which piglets seem very sensitive, aggravated by diets with a high glycemic index, i.e., containing rapidly digestible carbohydrates. Therefore, diets for newly weaned piglets should be formulated to minimize the glycemic load while amino acids, minerals, and vitamins should be provided to manage health, not weight gain.

Introduction

Newly weaned piglets, in the over a thousand trials performed by the authors in the last two decades, typically eat 1–2 kg of feed in the first week after weaning and grow with a gain-to-feed ratio of approximately 1. This high efficiency has been considered a quality of the newly weaned piglet, and to our knowledge, few, if any, have questioned these efficiency figures. Reconciling these numbers based on feed intake and nutrient partitioning, however, fails. This implies that another mechanism may exist that affects weight gain and gain-to-feed ratio in the newly weaned piglet.

The findings summarized in this review explaining this phenomenon are built on a large number of experiments carried out over two decades under a variety of conditions, ranging from invasive trials with individually housed piglets to field experiments in various parts of the world. Piglets were weaned at ages ranging from 18 to 28 days onto diets formulated to commercial standards

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https://doi.org/10.1016/j.animal.2023.100987
1751-7311/

using highly digestible and high-quality raw materials. Problems with feed efficiency were seen in well over 1 000 experiments that encompassed an estimated 1 000 000 piglets. No evidence was found that regional, housing, age, or diet effects existed on the described phenomenon. In an estimated 50 of those experiments with approximately 20 000 piglets in total, measurements were taken or treatments were implemented to understand the described phenomenon or to normalize feed efficiency (data not reported are deemed confidential by the sponsor of the respective trials). Hence, the focus is not placed on these input factors but on the physiology underlying the phenomenon.

Modeling growth of the newly weaned piglet

Growth models are typically aimed at growing-finishing pigs or sows and often contain a disclaimer that models should not be applied to newly weaned piglets. Nevertheless, when discussing the rules of energy metabolism that form the basis of these models, no disclaimers are made that these rules do not apply to the newly weaned piglet. One exception is that the water-to-CP ratio is greater in piglets in their first weeks of life (Emmans and Kyriazakis, 1995), an effect that we have incorporated in the calculations below.

For the maintenance energy requirement of swine, a value around 750 kJ NE/kg$^{0.6}$ is used routinely (Everts, 2015). Maintenance is then defined as the energy required in the postabsorptive phase to maintain BW; maintaining BW implies that pigs do not gain or lose energy. Applying this equation for a piglet weaned at 6–7 kg BW onto a diet with 10.6 MJ NE/kg feed translates to a requirement of 207–227 g feed/d for maintenance.

However, the newly weaned pig should not be compared with a growing-finishing pig in a postabsorptive state. The stress of weaning, separation from the sow, a new environment with associated microbiome, fights for establishing a new social hierarchy, etc., are an energy drain for the newly weaned pig. In addition, weaning compromises gut health, reducing nutrient digestibility and absorption (Pluske et al., 2003). Consequently, the amount of feed needed per day to prevent weight loss for the newly weaned pig should arguably be more than the 207–227 g/d calculated above. Kies (2005) showed that maintenance is 12% greater during the first week after weaning as compared to 3 weeks after weaning.

Comparing actual with modeled performance data

Curiously, piglets that eat at the maintenance requirement calculated above still gain weight, with gain-to-feed ratios that approach 1, despite the stress endured. Plotting performance data of individual pigs (Fig. 1; pigs weaned at 24 days of age at 6.84 kg onto a commercial phase I feed, n = 36) shows that this high efficiency applied to all pigs in the population we tested. Extrapolating actual performance data to 0 g/d feed intake actually implied that piglets do not lose weight when not eating, thus, implying that the maintenance requirement is zero. We, the authors, have run well over 1 000 trials with an estimated 1 000 000 piglets with many different nutritional interventions and in conditions ranging from intensive research trials to commercial scale test facilities, and this phenomenon is consistently present. This means that parameters used to model the growth performance of growing-finishing pigs should not be applied to piglets, or that the gain of piglets is caused by factors other than healthy tissue gain.

Newly weaned pigs are in a negative energy balance but gain water

Work carried out by the authors and also by Whittemore et al. (1981) indicates that an important mechanism explaining this weight gain has apparently been overlooked. Whittemore analyzed changes in piglet body composition before weaning (day -1; Fig. 2) and piglets at 2, 4, 6, or 8 days after weaning (weaned at 21 days of age; Fig. 2). Before weaning piglets gained approximately 40 g of protein, 40 g of lipid, and 220 g of water per day. After weaning, piglets lost lipid tissue implying that feed intake indeed was well below maintenance (NRC, 1998). Despite losing lipid, the newly weaned piglets did not lose or gain protein. In line with this, Bruininx et al. (2002) used indirect calorimetry to show that piglets had a negative energy balance resulting in catabolism of body fat during the first week after weaning. Energy retained as protein was numerically positive but only by a few grams per day. These data illustrate that, when fed energy below maintenance energy requirements, piglets prioritize maintaining body protein stores over body fat. Hence, the model data included in Fig. 1 are fundamentally wrong for newly weaned piglets, but even that inaccuracy does not explain the high gain-to-feed ratio of the piglets.

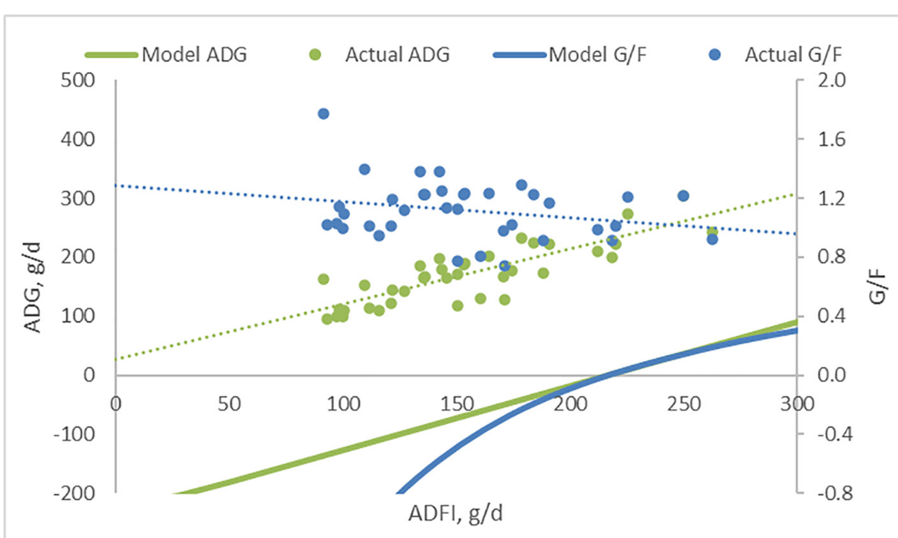

Fig. 1. Relationship between average daily feed intake and gain or gain-to-feed ratio for individual piglets (dots; pigs weaned at 24 days of age onto a commercial diet, unpublished data from Trouw Nutrition) as compared to the theoretical gain and G/F calculated using nutrient partitioning equations from van Milgen and Noblet (1999).

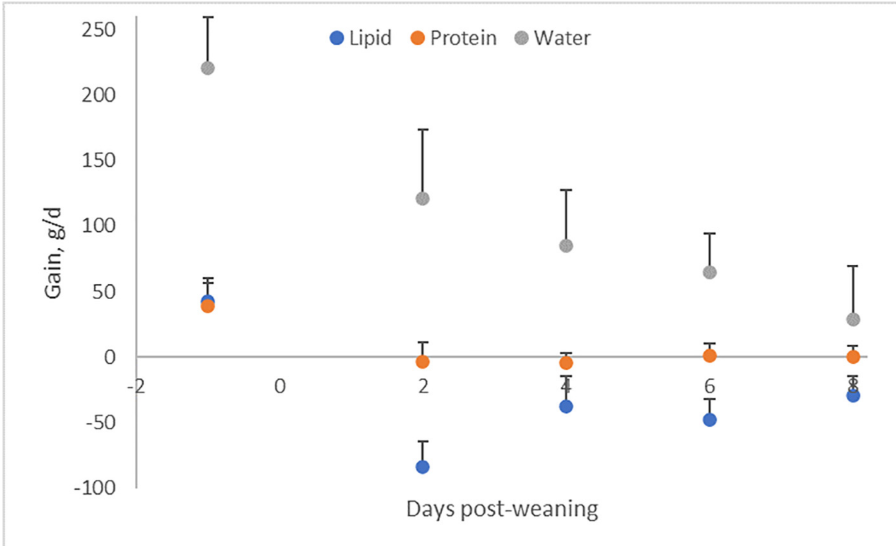

Fig. 2. Gain of lipid, protein, and water of piglets prior to weaning (day -1) and immediately following weaning. Source: Whittemore et al. (1981).

The BW gain could be explained by newly weaned piglets gaining water as shown by Whittemore et al. (1981) (Fig. 2). This water gain was *not* linked to protein gain until at least 7 days postweaning, resulting in a net gain in BW while eating below maintenance. Bruininx et al. (2002) reported a gain-to-feed ratio of 0.8, despite piglets loosing adipose tissue and hardly gaining protein. In line with these findings, Sève (1982) showed that pigs weaned at 10 days of age had a greater water content at 35 days of age than non-weaned controls of the same age (76.0 vs 69.4%). The weaned pigs, though, contained less body fat while protein content was similar (water/protein ratio of 5.0 vs 4.5), in line with the findings of Whittemore. Interestingly, the piglets weaned at 35 days of age did not show an increase in water content at 60 days of age (69.9%) implying that weaning at a very early age may be a confounding factor. Zijlstra et al. (1996) also showed that at 7 days postweaning, the percentage of fat was decreased while water was increased in piglets weaned at 18 days of age onto a dry starter diet. Although this increase in water content was noted in the referenced papers, none linked it to a health perturbation.

Our own work also indicates that this water gain may be edema rather than the result of ‘healthy’ tissue gain. Analysis of the DM content of Biceps femoris tissue sampled at different ages (see Diether et al., 2023 for experimental details) showed that in the days immediately after weaning dehydration occurred resulting in greater DM content (Fig. 3; pigs weaned at 24 days of age around noon onto a commercial phase I feed containing 1.25% Lys and 10.7 MJ NE). Piglets were effectively fasting immediately after weaning. This was also related to the frequent entry of people in the pens for collecting animals. Piglets, therefore, started with low feed intake but typical water intake during the first week after weaning: daily feed intake: 11, 59, 109, 66, 57, 53, and 99 g/d and daily water intake 184, 519, 561, 337, 369, 329, and 468 g/d for d0-7, respectively. However, when the piglets started eating well (around day 7 after weaning in this study), the DM content of Biceps femoris dropped to values below those observed before weaning (from 275 to 255 ± 14 g/kg, $P < 0.01$) lasting up to day 28 after weaning (final measurement). Similar results were obtained by using bio-electrical impedance on these pigs (Fig. 4, $P < 0.05$; for an explanation of the technology see Mitchell and Scholz, 2009) to study changes in body composition of the entire piglet, implying that the DM changes in Biceps femoris may be extrapolated to other muscles. Assuming that 60% of the body experienced this change in DM content, this translates to a weight gain of 0.5 kg. In lungs, the DM content also dropped after piglets started eating above maintenance (from 190 to 183 ± 7 g/kg, $P = 0.03$). In liver, only numeric effects of day on DM were seen. Depletion of liver glycogen may well confound this measure. In this study, we observed that six out of twenty piglets had flaccid livers on day 5 that may have been caused by hepatic ballooning degeneration (Jordao et al., 2020). In the same study, we also observed that the blood hematocrit content increased after weaning (day 7 vs -1; $P < 0.01$; Fig. 5). Upon opening the body cavity, we observed liquid in the body cavity of 4, 3, and 2 piglets on days 3, 5, and 7, respectively (n = 20 per timepoint). Those piglets had greater hematocrit levels (34.7 vs 29.3 ± 3.93%, $P = 0.03$) than the piglets in which no liquid in the body cavity was observed. High hematocrit can be caused by leaky blood vessels that allow plasma and albumin to escape from blood vessels into the interstitial space throughout the body and into the body cavity. The incidence of both abnormalities may well be underestimated because the experiment was not designed to study them.

These findings were discussed with Dr. P. Bikker and Dr. N. Ferguson in light of their modeling work (CVB and Watson models, respectively; Halas et al., 2018; Ferguson, 2015). Both acknowledged that they were unable to explain the gain observed in newly weaned piglets based on nutrient intake. Therefore, edema development may be a plausible explanation of the gain observed in newly weaned piglets.

Insulin induces edema

We hypothesize that edema observed in piglets during the early phase of weaning is induced by insulin. Insulin, when given to subjects with little exposure to it due to fasting or neglected diabetes, is well known to cause edema. Insulin induces edema through various mechanisms (Walmsley, 2013; Largeau et al., 2021) as follows:

- Insulin stimulates kidneys to increase the reabsorption of water and sodium and, thus, triggers water retention.
- The lack of insulin upon weaning downregulates the metabolism of cells so that potassium (**K**) and phosphate (**PO_4**), accompanied by water, are lost from the cell and subsequently from the body via urinary excretion. This causes cells to shrink and

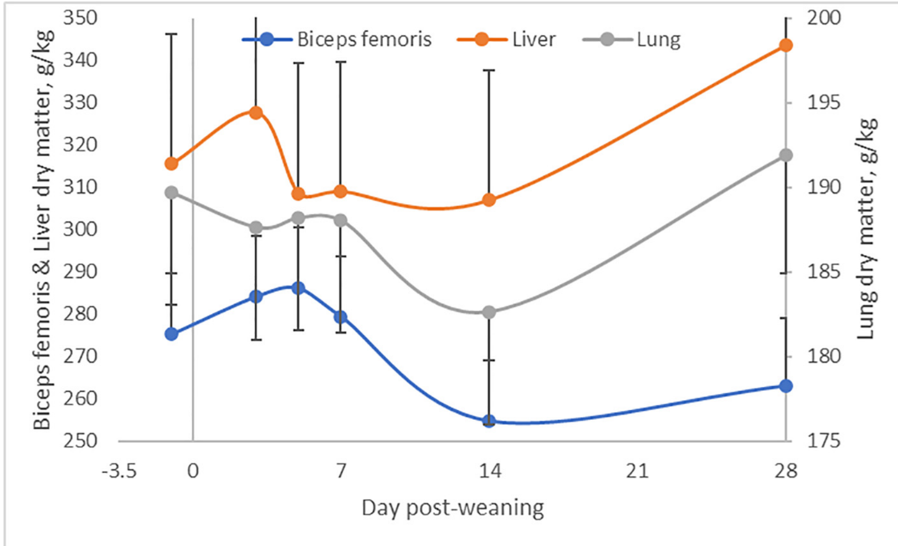

Fig. 3. Changes in DM content in Biceps femoris, lungs, and liver of piglets after weaning. Piglets (n = 10 for days -1 and 28, n = 20 for days 3, 5, 7, and 14: unpublished data from Trouw Nutrition) were weaned at 24 days of age onto a commercial feeding program and sampled at the indicated days.

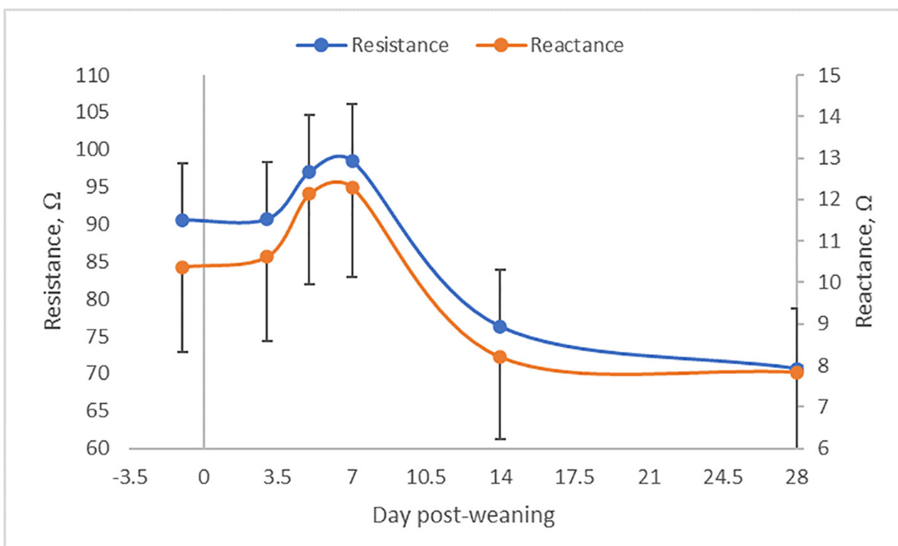

Fig. 4. Bio-electrical impedance across the torso of piglets after weaning. Piglets (n = 10 for days -1 and 28, n = 20 for days 3, 5, 7, and 14: unpublished data from Trouw Nutrition) were weaned at 24 days of age onto a commercial feeding program and bio-electrical impedance was measured at the indicated days.

explains the dehydration seen in muscle shortly after weaning (this is not due to inadequate water intake). Once insulin is reintroduced, K and PO_4, and other osmolytes (e.g., taurine; not shown) are pulled back into the cells resulting in edema. This phenomenon fits with the changes in muscle DM seen at different time points after weaning (Fig. 3).

- Insulin makes blood vessels leaky, allowing for plasma and albumin to escape, increasing the concentration of hemoglobin in blood. This leaked plasma can accumulate in, e.g., the body cavity resulting in what looks like Kwashiorkor (Benjamin and Lappin, 2022). This phenomenon matches the changes in hematocrit (and albumin; not shown) concentrations seen in blood at different time points after weaning (Fig. 5).

For humans, several cases are published that report these events, for example, Evans et al. (1986) described the case of a woman with neglected diabetes, weighing only 38 kg. Following insulin therapy, she gained 19 kg or 50% of her BW over 3 weeks; this gain was nearly all edema. Once recognized, treatments for edema (diuretics and salt-free albumin infusions) were initiated that resulted in the loss of about 10 kg of BW within days.

Given that our observations match the description of insulin-induced edema, it is suggested that the newly weaned piglet is intolerant to insulin (this as undesirable effects occur). Measurements of insulin preweaning have shown that the plasma insulin level was only 0.014 µg/L despite piglets drinking ample sow milk (Fig. 6; pigs weaned at 24 days of age onto a commercial phase I diet and sampled at predefined time points not linked to eating pattern; same pigs as shown in Fig. 3). Sow milk contains lactose as key carbohydrate, which provides approximately 19% of the calories (calculated using data from Beyer et al., 2007). Lactose has a lower glycemic index than glucose polymers (0.41 of that of glucose: Romero-Velarde et al., 2019). Moreover, suckling piglets typically drink milk roughly every hour (Valros et al., 2002)

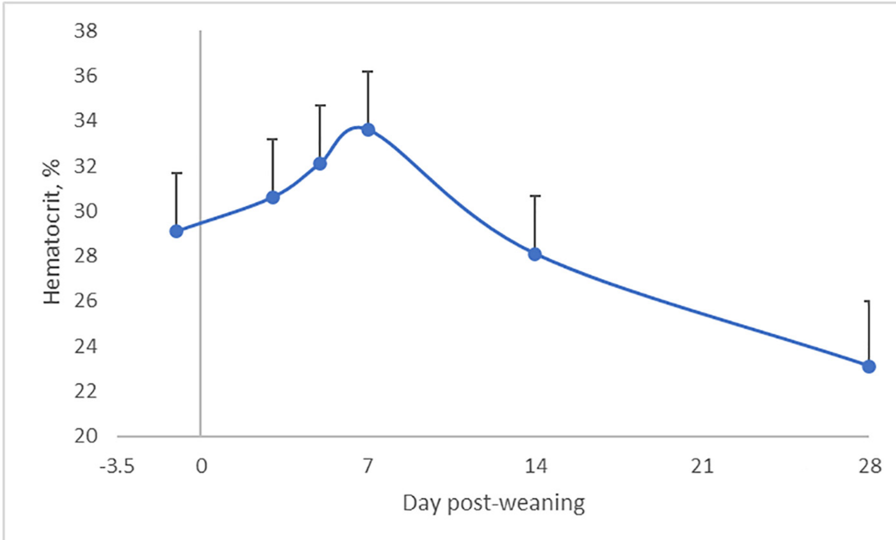

Fig. 5. Hematocrit of piglets after weaning. Piglets (n = 10 for days -1 and 28, n = 20 for days 3, 5, 7, and 14: unpublished data from Trouw Nutrition) were weaned at 24 days of age onto a commercial feeding program and sampled at the indicated days.

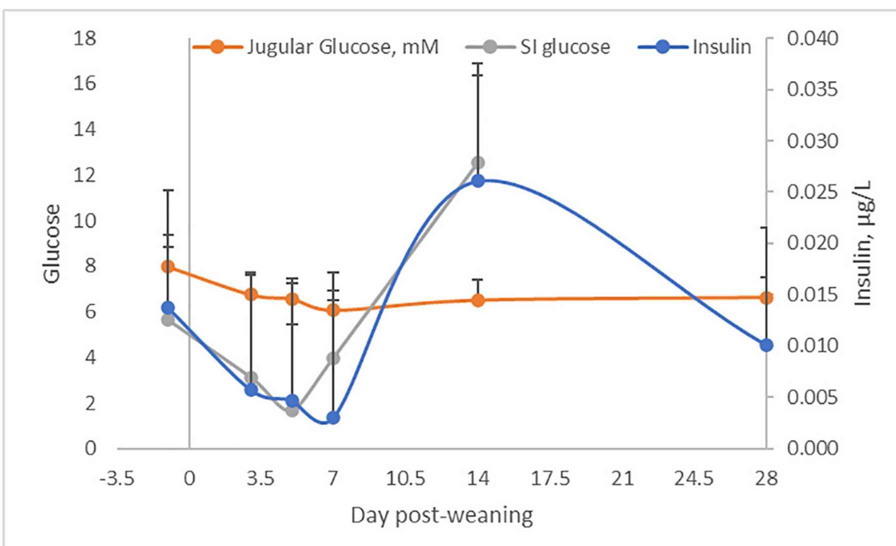

Fig. 6. Plasma glucose and insulin and small intestine (**SI**) glucose (no units and no data for day 28) in weaned piglets (n = 10 for day -1 and 28, n = 20 for days 3, 5, 7, and 14: unpublished data from Trouw Nutrition).

providing a nearly constant nutrient influx into the small intestine. Consequently, large increases in plasma glucose may not occur after suckling, thus preventing high insulin peaks. This may explain why piglets at the early weaning stage have physiological responses to high glycemic carbohydrates as if they had never seen insulin before. In commercial practice, we commonly feed piglets after weaning diets with extremely high glycemic indices as they contain high amounts of digestible starch, likely extruded, and supplemented with sucrose (commonly providing over 40% of the dietary energy). These diets are typically consumed erratically shortly after weaning, an eating pattern that can further aggravate glycemic load.

Feeding piglets routine nursery diets indeed led to high insulin peaks when feed intake became quantitatively important (Fig. 6; day 14 vs day 7: $P < 0.01$; day 14 vs day -1: $P = 0.07$). Interestingly, on day 28, despite greater feed intake than on day 14 (810 vs 210 g/d, respectively), insulin responses were notably lower than on day 14 ($P = 0.02$), implying that the newly weaned piglets had difficulty managing blood glucose when first exposed to high dietary intakes of digestible carbohydrates.

In these same pigs, glucose was measured in portal vein plasma (not shown), jugular vein plasma, small intestinal content, and large intestinal content (not shown); the intestinal samples were only collected up to day 14 (Fig. 6; same pigs as for Fig. 3). Jugular glucose was lowest on day 7 ($P = 0.07$ vs day -1) but did not correlate with insulin ($R^2 = 0.05$; $P = 0.11$). Small intestinal glucose, however, correlated significantly with serum insulin ($R^2 = 0.29$; $P < 0.01$). Small intestinal glucose was also lower on day 5 than day -1 ($P = 0.03$), and greater on day 14 than day -1 ($P < 0.01$). This observation fits with the work of Date (2020) who proposed that amylase activity in the small intestine is regulated by the host to control glucose uptake. A downside of such regulation is that glucose can accumulate in the small intestine, potentially causing osmotic stress and triggering growth of potentially pathogenic bacteria that may cause postweaning diarrhea in piglets (Ohlsson, 2021).

Mismatch between insulin and phosphate real culprit

Evans et al. (1986) point at insulin as the cause of edema; however, we propose that edema may actually be caused by a misalignment between insulin and factors that are required for insulin to exert its effects on metabolism, notably PO_4, as described by Knochel (1981). Insulin's role is to stimulate metabolic activity; however, boosting metabolic activity requires that PO_4 and magnesium (**Mg**) are present for the generation and stabilization of ATP and NADPH, for activation of enzymes, etc. (DeFronzo and Lang, 1980). Our data showed that PO_4 is rapidly excreted in urine following weaning (Fig. 7; pigs weaned at 24 days of age onto a commercial phase I feed containing 1.25% Lys and 10.7 MJ NE), presumably as metabolic activity changes from high (rapid growth) to low (fasting). The PO_4 loss of nearly 12 mmoles (or 1.8 mmol/kg BW) within the first 24 hours after weaning should be placed in the context of blood levels of PO_4 of approximately 2 mM preweaning. These data illustrate that the piglet is liberating vast amounts of PO_4 from metabolic stores within cells (such as ATP, phospho-creatine), and indeed, Biceps femoris PO_4 drops postweaning (Fig. 8; P = 0.02; data collected in the experiment described for Fig. 3). This PO_4 is likely not liberated from bone as blood Ca remained steady (Fig. 8), and urinary Ca also did not change significantly ($P > 0.05$; Fig. 7). When the piglet subsequently resumes feed intake and consequently boosts its metabolic activity to resume rapid growth, PO_4, however, is in short supply in tissues such as muscle and liver, resulting in a pull of phosphate from extra-cellular to intra-cellular causing hypophosphatemia (Fig. 8: $P < 0.01$). Consequently, insulin cannot exert its intended metabolic effects (DeFronzo and Lang, 1980) leading to edema, a phenomenon that is described in the human physiology literature as refeeding syndrome (Knochel, 1981; Marinella, 2003; Korbonits

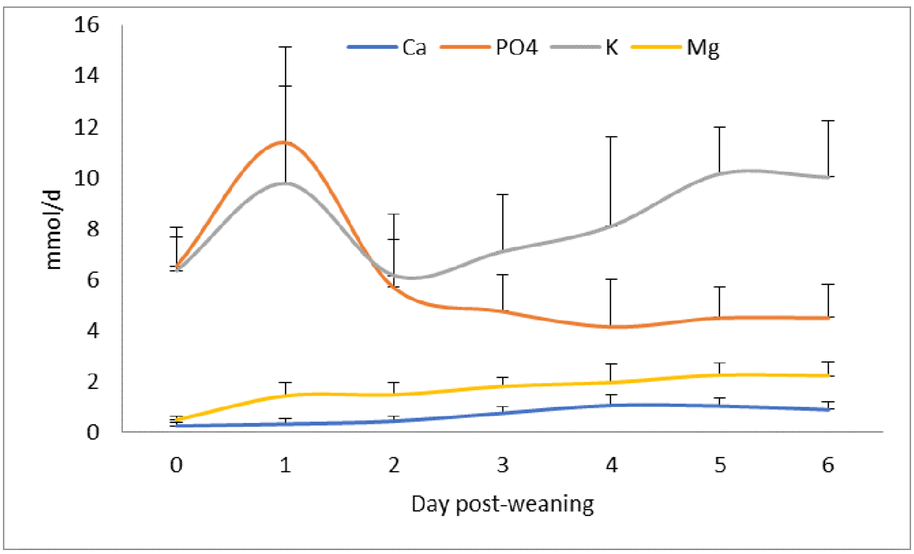

Fig. 7. Urinary mineral losses of piglets following weaning at 24 days of age onto a commercial phase I diet (data from 16 pens each housing three piglets, unpublished data, Trouw Nutrition).

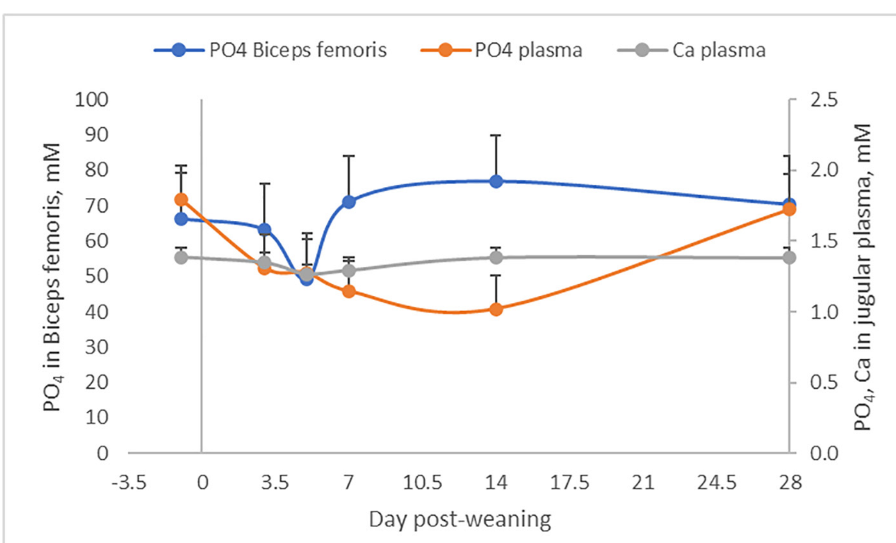

Fig. 8. Plasma and Biceps femoris phosphate and plasma Ca of piglets (n = 10 for day -1 and 28, n = 20 for days 3, 5, 7, and 14: unpublished data from Trouw Nutrition) following weaning at 24 days of age.

et al., 2007). In adult humans, weeks of fasting followed by abrupt refeeding are required for the refeeding syndrome to cause complications. In newly weaned piglets, refeeding syndrome may occur within hours due to the piglets' higher metabolic rate before weaning and their metabolic rate potential after weaning, given that they are fed properly. This creates a strong metabolic difference between fed and fasted piglets, and consequently, larger shifts in PO_4 needs. In literature on the refeeding syndrome, Mg, K, and thiamine are also implicated (for reviews see Knochel, 1981; Marinella, 2003; Korbonits et al., 2007), but our data (not shown) indicate that their role is less important in piglets.

Fig. 9 visualizes hypothetical flows of PO_4 around weaning. Prior to weaning, the piglet has a high metabolic activity and, thus, a high metabolic demand for PO_4 (ATP, P-creatine, etc.). At weaning, this metabolic PO_4 demand drops strongly as feed intake is interrupted, and consequently, protein and fat accretion stop, as discussed above. This results in urinary excretion of the PO_4 hydrolyzed from ATP and P-creatine. When feed intake resumes erratically, a strong demand for PO_4 in energy metabolism is created. However, this PO_4 is not available which results in an acute deficiency impairing metabolism that leads to edema. Extra insulin may be secreted by the piglet to overcome this PO_4 deficiency, which may further aggravate the impaired metabolism and edema.

Incorrect diets for nursery pigs

Taking all these findings into account implies that we have developed weaning practices that may not be healthy for the piglet. Typically, pigs are fed diets containing roughly 40% starch, some of which is gelatinized and, therefore, presumably highly digestible. These diets commonly include some sugar to improve palatability. The glycemic load of such diets is very high, especially when consumed at a high rate and erratically as done by piglets immediately after weaning. Indeed, insulin levels in piglets that only recently started eating show much higher values than prior to weaning (Fig. 6). Notably, blood samples from these piglets were obtained at preset times; no consideration was given to feed intake patterns of the piglets, and feed was provided ad libitum. Likely, if samples had been timed properly after the large erratic meals that newly weaned piglets can consume, even higher levels of insulin would have been observed on day 14. In contrast, on day 28, when feed intake had stabilized but at a notably higher level than on day 14, insulin levels were comparable with levels found preweaning again.

In human literature on insulin-induced edema, the edema is not seen as a serious threat to health. In our studies, we failed to see piglets with a normal gain-to-feed ratios despite various interventions, even when varying starch properties drastically (van Kempen et al., 2007). Consequently, we were unable to correlate the edema with health or weight gain over the entire nursery phase. Edema in lungs is seen clinically as a health threat, and an important question is how edema affects the piglet's susceptibility to respiratory disease. The changes in the liver also deserve a closer look; why did some livers turn flaccid, how does this affect their functioning, and in how many pigs does this occur? The edema observed in muscle may not present a serious health challenge. The change in blood composition due to leaky blood vessels may affect the perfusion and oxygen supply of tissues, such as ears, and, thus, pose a risk for ear necrosis. Hypophosphatemia can impede oxygen release from red blood cells, as it prevents the formation of 2,3-bisphosphoglycerate that triggers oxygen release, thus, causing hypoxia despite free access to air (Knochel, 1981; van Kempen et al., 2013). When severe, this may lead to suffocation, a phenomenon that may occur in approximately 1 in 2 000 weaned piglets (Lavoue et al., 1994).

Whether insulin affects gut health is not clear based on our review of the literature. Data exist indicating that insulin increases gut permeability (McRoberts et al., 1990), similar to what happens in blood vessels. Gut health problems are indeed common in people suffering from metabolic syndrome (Teixeira et al., 2012). Hence, the effects of insulin and gut permeability require further study. The high levels of glucose in the intestines on day 14 also deserve further study, as this may trigger bacterial overgrowth and diarrhea (van Kempen and Boerboom, 2023).

An error in the composition of our piglet diets is that they are aimed at protein gain after weaning (i.e., amino acid ratios for protein gain) while in the first week after weaning, protein gain is likely low, if at all present. Consequently, 1.2–1.4% digestible lysine is arguably not what pigs need at this stage of life. However, this does not mean that the piglets do not need protein. Upon weaning the piglet experiences both metabolic and health stress for which amino acids such as cysteine, histidine, and tryptophan are required. In line with this, plasma levels for those amino acids decreased drastically after weaning (data not shown). To our

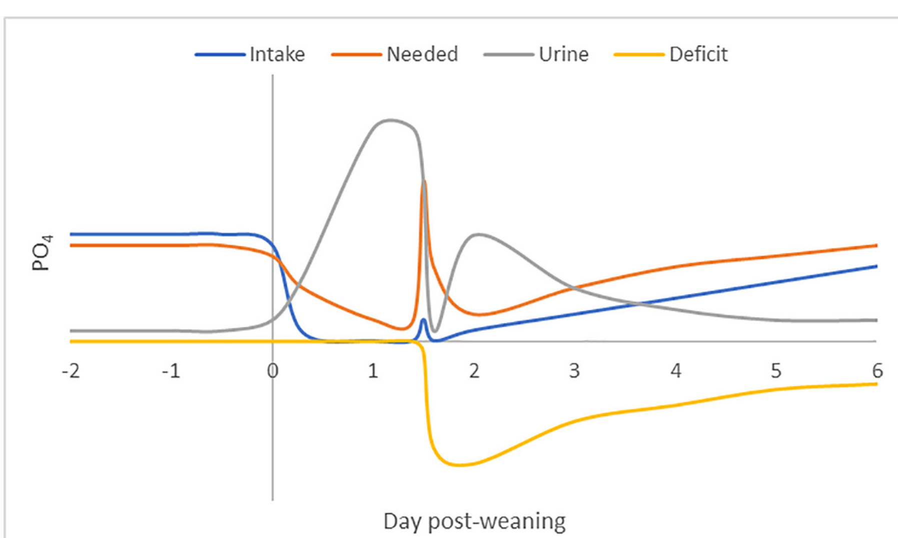

Fig. 9. Hypothetical representation of phosphate metabolism in the newly weaned pig consuming an erratic meal 1.5 d after weaning. A deficit in phosphate impairs metabolism, which among others can lead to edema.

knowledge, information about the ideal amino acid pattern for newly weaned piglets is not yet available. The same lack of information exists for mineral requirements: the urinary losses of PO_4 and K and the high metabolic need, especially for PO_4, upon triggering insulin imply that these minerals may well be more important in newly weaned piglets than others linked to e.g., protein gain.

Conclusion

It is universally accepted that weaning compromises gut health in piglets; however, it also affects systemic and metabolic health. Newly weaned piglets seem to tolerate high levels of insulin poorly, likely due to a shortage of PO_4, which leads to the development of edema through refeeding syndrome. This edema, rather than actual tissue growth, explains the rapid weight gain of the newly weaned pig. Arguably, we need to completely revisit how to feed newly weaned piglets as thus far we have misinterpreted high postweaning gain-to-feed ratios as a positive: they certainly are not.

Ethics approval

The invasive studies reported in this paper were approved by the Dutch Animal Ethics Committee (AVD2040020184665 and AVD2040020184545) and carried out at the Swine Research Centre of Nutreco B.V. (Sint Anthonis, the Netherlands).

Data and model availability statement

Data were not deposited in an official repository as they are deemed confidential by the sponsor.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence-assisted technologies in the writing process.

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Author contributions

TvK: design and interpretation of experiments, writing of manuscript.
TH: design and execution of experiments, critical review of manuscript.
WG and **RZ:** critical review of manuscript.

Declaration of interest

TvK was employed, and TH is employed by Trouw Nutrition (Nutreco), the company that funded and hosted several of the experiments.

Acknowledgements

The team of the Swine Research Centre, St. Anthonis, the Netherlands, for carrying out the various research trials, and Amy van Kempen for editing the text.

Financial support statement

This work was supported by Trouw Nutrition.

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