Reviews on the mineral provision in ruminants (III): MAGNESIUM METABOLISM AND REQUIREMENTS IN RUMINANTS

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PREFACE

In the Netherlands the ´Handleiding Mineralenonderzoek bij rundvee in de praktijk´[1] is a well-known publication that has been used already for decades as a guide to trace and treat mineral disorders in cattle. The fifth edition of this guidebook was published in 1996. The content of this publication was largely identical to that of the fourth edition (1990). Therefore the (independent) committee that is responsible for the contents of the guidebook (the 'Commissie Onderzoek Minerale Voeding'[2], COMV) decided in 2000 that a thorough revision was desired.
The committee was of the opinion that, if possible, the available scientific literature should be summarized and evaluated once again. Furthermore, attention should be paid to the mineral provision of categories of cattle other than dairy cattle, as well as to that of sheep and goats. Finally, the basic principles for the calculation of the mineral requirements should be described in a transparent way.

The intended revision was made possible as the Dutch 'Ministerie van Landbouw, Natuur en Voedselkwaliteit' (LNV), the 'Productschap Diervoeder' and the 'Productschap Zuivel'[3] were willing to subsidize this extensive and ambitious project.
The COMV decided to execute the project as follows.

- External experts, invited by the COMV, should summarize and evaluate the relevant literature in a so-called 'basal document' (with two exceptions to be written in English).
- Subsequently, these documents should be critically evaluated by the COMV.
- These basal documents should then be used to write and arrange the several chapters of the revised 'Handleiding'.

The revised 'Handleiding' is available (in the Dutch language) since October 2005, under the title 'Handleiding mineralenvoorziening rundvee, schapen en geiten.'[4] This book is published by the 'Centraal Veevoederbureau' (CVB; Central Bureau for Livestock Feeding) in Lelystad, as was also the case for the previous edition.

The COMV was of the opinion that the valuable basal documents, that became available during the course of this project, should be published too. By doing so everyone has the possibility to trace the basis for the text of the revised 'Handleiding'. The CVB was gladly willing to issue these documents as CVB Documentation reports. In connection with this the authors and the members of the COMV have disclaimed all rights and have assigned them to the Productschap Diervoeder, of which the CVB is one of the services.
For an overview of the CVB Documentation Reports that will appear in this context, you are referred to an Annex in the back of this report.

Utrecht/Lelystad, November 2005.

Professor dr. ir. A.C. Beynen	Dr. M.C. Blok
Chair of the COMV	Secretary of the COMV and Head of the CVB

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1 Guidebook on mineral research for cattle in practice.
2 Committee for research on mineral nutrition
3 The Ministry for Agriculture, Nature and Food quality, the Product Board Animal Feed and the Dutch Dairy Board, respectively.
4 Guidebook mineral provision cattle, sheep and goats.

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CONTENT

LIST OF ABBREVIATIONS

Abbreviation	Unit	Description
ADF		Acid detergent fibre
BW	kg	Body weight
D		Days of conception
DM		Dry matter
DMI	kg	Dry matter intake
GI		Gastro-intestinal tract
PD_a		Apical membrane potential
PD_t		Transmural potential difference
PTH		Parathyroid hormone

1 PHYSIOLOGICAL FUNCTIONS OF MAGNESIUM

Magnesium (Mg) was recognized to be an essential nutrient near 1925 (3). Magnesium is a co-factor of various enzymes (81) and it influences the activity of more than 300 cellular enzymes that are involved in energy metabolism, protein synthesis, cell growth and reproduction, synthesis of DNA and RNA and stabilization of mitochondrial membranes (4,129,151). Furthermore, Mg acts in concert with calcium (Ca) ions, on proper functioning of cardiac- and skeletal muscles. Magnesium is, together with Ca, also important for the transmission of signals by the nervous system (52) and it was suggested by Martens and Schweigel (99) that low Mg concentrations (< 0.7 mM) in the cerebrospinal fluid (5) causes uncontrolled synaptic activity of cells in the central nervous system which results in the clinical signs of hypomagnesaemia; i.e. tetany. Apart from its role in signal transmission, Mg is also important for the secretion of parathyroid hormone (PTH) (86,156) and the sensitivity of PTH receptors (42, 86,104). Magnesium may also be of importance in vitamin D metabolism; Mg deficiency may lead to a reduced synthesis and/or an impaired target organ response to 1,25-dihydroxyvitamin D (104,121,135).

2 DISTRIBUTION OF MAGNESIUM BETWEEN TISSUES

The total body Mg content is about 0.45 g/kg in cattle and a similar value was found for sheep (9). Thus, it can be estimated that an adult dairy cow with a live weight of 650 kg contains about 290 g Mg. About 70% of the total body content is stored in bone (9, 52). It has been indicated by Blaxter and McGill (14) that 30% of the Mg in bone can be mobilized in young animals so as to support extra cellular Mg concentrations.

Extra cellular Mg accounts for about 1% of total body Mg (104,127, 151). The normal plasma Mg concentrations for cattle range from 0.8-1.2 mmol/L (70) and approximately 70% of total plasma Mg is in the ionic form (104)(151), while the remainder is mainly bound to albumin (33). Since 71% of total body Mg is recovered in bone and extra cellular fluid, it follows that 29% of total body Mg will be present within cells. Indeed, next to potassium (K), Mg is the most abundant intracellular cation (4,55). Intracellular total Mg concentrations may be in the order of 15-17 mmol/L (55, 127,128). However, only a small proportion of the total intracellular Mg is in the ionic form and concentrations of free Mg^{2+} ranging from 0.1 to 1.0 mmol/L have been measured (25, 33, 151).

3 MAGNESIUM METABOLISM

3.1 Absorption

3.1.1 Site of Mg absorption

Bovine saliva contains about 0.17 (range 0.12-0.25) mmol Mg/L (103). Similar mean values are reported for ovine saliva: 0.18 mmol/L (43), 0.23 mmol/L (parotid saliva, range 0.09-0.66 mmol/L) and 0.25 mmol/L (submaxillary saliva, range 0.05-0.5 mmol/L) (154). Thus, the contribution of salivary Mg to the total Mg pool in the rumen is quantitatively unimportant. In other words, the amount of Mg present in the rumen is primarily of dietary origin. The data shown in Table 1 clearly indicate that Mg is predominantly absorbed prior to the proximal duodenum. From a regression analysis of the amount of Mg absorbed prior to the proximal duodenum versus the amount absorbed along the total gastro-intestinal tract, it was calculated that the total amount of Mg apparently absorbed is about 77% of the amount absorbed prior to the duodenum (Fig. 1). This result indicates that, on average, net Mg secretion occurs distal to the proximal duodenum. Indeed, in almost all cases Mg flow at the end of the ileum was greater than the Mg flow at the proximal duodenum. In some cases, listed in Table 1, a small net absorption was observed in the large intestines. Interestingly, Meyer and Busse (102) have shown that rectal infusion of Mg effectively increased the plasma Mg concentration. This result suggests that the lower part of the GI-tract is permeable to Mg. However, under normal feeding conditions, the amount absorbed in the large intestines seems not to overrule the amount of Mg secreted in the small intestines (Table 1).

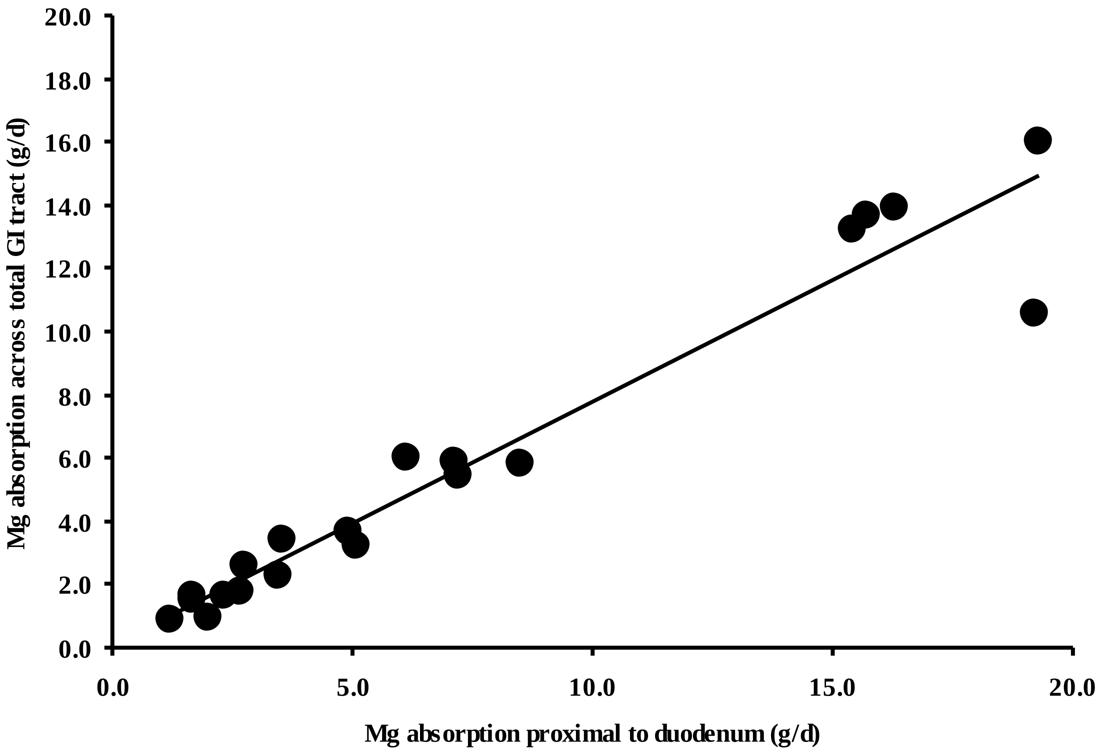

Figure 1: Relationship between the amount of Mg absorbed prior to the proximal duodenum and that absorbed along the total gastro-intestinal (GI) tract in cattle (data are taken from Table 1). The linear correlation coefficient and regression formula are: $r = 0.94$; $y = 0.768 x + 0.1$ ($n = 20$, $p = < 0.001$). (The outcome of regression analysis remains essentially the same when the 5 data points in the upper right corner of the graph are excluded).

Table 1: Flow of magnesium along the gastro intestinal tract of cattle

Reference	Species	Body weight (kg)	n	Mg-intake (g/day)	Mg-intake + saliva- Mg (g)	Abomasum (g)	Proximal duodenum (g)	Terminal ileum (g)	Faeces (g)
(124)	cow	441	2	18.3	19.1		14.8	15.5	14.9
(116)	cow	615	5	54.1			34.8		38.1
			5	55.2			39.5		41.54
			5	53.4			34.2		42.8
			5	55.1			39.7		41.9
			5	53.5			37.2		39.6
(93)	cow	not given	7	14.5			11.8		11.9
(78)	2 cows 2 steers	205-350	4	6.95			5.29	4.68	5.46
			4	7.09			4.41	4.69	5.33
			4	6.99			4.67	4.93	5.34
			4	14.09			6.88	7.93	8.64
			4	12.47			6.33	7.58	6.46
			4	14.1			6.99	7.93	8.19
			4	10.13			6.67	8.70	7.84
			4	11.76			6.86	7.79	8.06
(47)	steers	261	6	4.52		2.85		3.01	2.88
			6	4.52		2.51		3.38	3.54
			6	4.3		3.09		3.48	3.42
(48)	steers	350	8	17.4			12.3	13.0	14.2
			8	17.9			9.4	12.0	12.1

n = number of animals.

Table 2: Flow of magnesium along the gastro intestinal tract of sheep

Reference	Species	Body weight (kg)	n	Mg-intake (g/day)	Abomasum (g)	Proximal duodenum (g)	Terminal ileum (g)	Faeces (g)
(49)	sheep	36	6	1.40	0.70		0.91	0.83
			6	1.44	0.80		1.10	0.99
			6	1.48	0.90		1.19	1.15
			6	1.11	0.64		0.87	0.81
			6	1.76	0.96		1.26	1.18
(46)	sheep	41	Not given	1.10		1.01	0.92	0.88
				1.76		1.44	1.76	1.23
				1.15		0.63	0.93	0.97
				1.84		1.38	1.61	1.34
				1.27		1.03	1.29	1.04
				2.04		1.42	1.79	1.44
(117)	sheep	42	6	2.82	2.35		2.45	2.59
			6	2.72	2.29		2.67	2.62
(111)	sheep	adult	2	1.22		1.21	1.38	1.05
			2	1.49		1.18	1.42	1.27
			2	1.49		1.13	1.16	1.04
(45)	sheep	43	3	1.67		1.09	1.17	1.04
			3	1.68		1.07	1.24	1.04
			3	1.68		1.06	1.24	1.05
			3	1.67		1.36		1.05
			3	1.68		1.43		1.08
(13)	sheep	adult	6	2.74		2.08	2.53	1.91
(159)1	sheep	adult	3	1.13		0.93		0.80
			3	1.16		1.07		0.95
			3	1.18		0.99		0.89
(118)	sheep	40	6	1.00	0.58		0.67	0.55
			6	1.00	0.51		0.67	0.48
			6	1.00	0.49		0.59	0.56
(59)	sheep	33	5	0.96	0.75			0.79
			5	1.83	1.26			1.28

Reference	Species	Body weight (kg)	n	Mg-intake (g/day)	Abomasum (g)	Proximal duodenum (g)	Terminal ileum (g)	Faeces (g)
			5	1.96	0.88			1.11
			5	1.87	1.73			1.08
			5	1.85	0.93			1.03
(51)	sheep	67	4	2.25	0.49			1.44
			4	1.85	0.67			0.88
			4	1.26	0.41			0.59
(50)	sheep	60	2	0.83	0.34			0.62
			2	0.81	0.42			0.68
			2	0.87	0.62			0.77
(169)[2]	sheep	29	4	1.30	0.66		0.52	0.72
			4	1.21	0.68		0.56	1.10
			4	1.22	0.60		0.48	0.77
(169)	sheep	29	4	1.26	0.54		0.50	0.69
(100)[3]	sheep	adult	3	1.29		0.99		0.94
			3	2.29		1.77		1.68
			3	3.29		2.80		2.55
			3	4.29		3.69		3.27
(24)[4]	sheep	43	16	1.30		1.17		0.85
			16	1.80		1.52		1.18
			16	2.30		2.04		1.45
			16	3.10		2.88		2.14

n = n umber of animals
[1] Supplemental KCl solution was infused into either rumen or duodenum.
[2] Supplemental $KHCO_3$ solution was infused into various sites of the gastro-intestinal tract.
[3] Supplemental $MgCl_2$ solution was infused into the rumen.
[4] Supplemental KCl and $MgCl_2$ solutions were infused into the rumen.

Compared to the data in cattle (Table 1), the data derived from sheep (Table 2) are not that straight forward with respect to the major site of Mg absorption. When all data are combined, it appears that only 22% of the variance in Mg absorption is accounted for by the variance in Mg absorption proximal to the duodenum. However, in 4 out of the 14 studies listed, aqueous solutions containing K- and Mg salts, were used to manipulate K or Mg supply to the animals. Combining the data from the studies of McLean et al. (87), Tomas and Potter (166) and Dalley et al. (149), it appears that mean Mg absorption prior to the duodenum contributes for only 54% of Mg absorption from the total gastro-intestinal (GI) tract, while on the basis of the data from Wylie et al. (169) a range of 110 to 482% can be calculated. Thus, it may be suggested that manipulation of Mg or K supply by means of infusions into the GI tract of sheep introduced extra errors in estimating Mg flow along the GI tract.
When the data of McLean et al. (87), Tomas and Potter (166), Dalley et al. (149) and Wylie et al. (169) are omitted from the data set (Table 2), it appears that still only 38.4% of the variance in Mg absorption is accounted for by Mg absorption proximal to the duodenum. The outcome of the latter regression is highly influenced by the data points marked with an arrow (Figure 2). Although it cannot be defended on the basis of information yet available, omission the two indicated data points yield a regression formula which rather good resembles that derived from cattle; i.e. y = 0.69 x + 0.1 (R^2_{adj} = 54%, $p < 0.001$, $n = 34$).

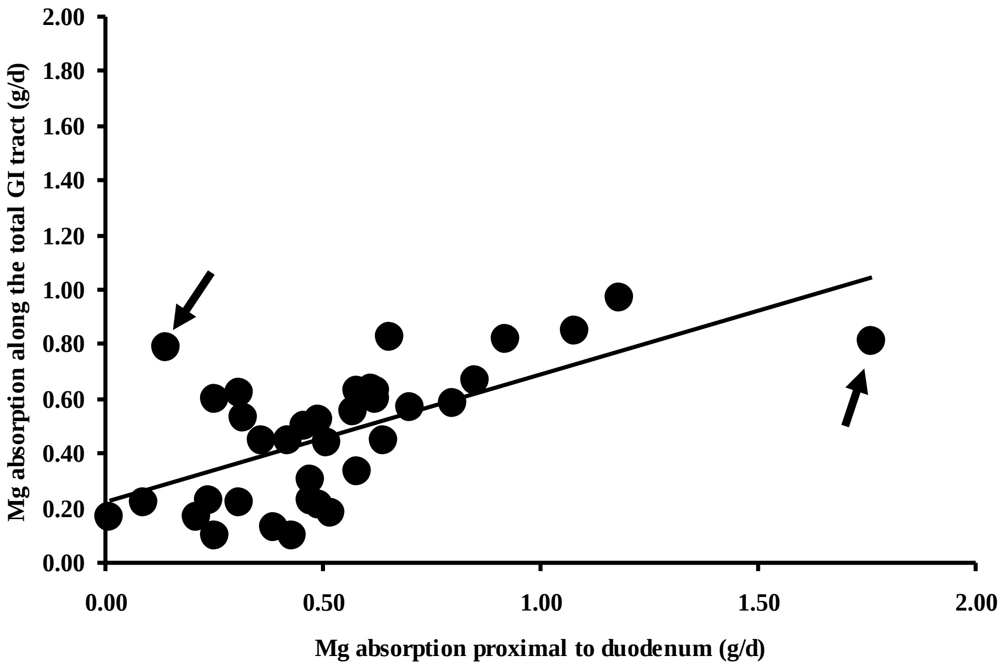

Figure 2: Relationship between the amount of Mg absorbed prior to the proximal duodenum and that absorbed along the total gastro-intestinal (GI) tract in sheep (data are taken from Table 2). The linear correlation coefficient and regression formula are: $r = 0.63$; y = 0.467 x + 0.2 ($n = 36$, $p = < 0.001$).

Thus, it may be assumed that also in sheep the majority of ingested Mg is absorbed proximal to the duodenum. Robson et al. (122) proposed a model of Mg metabolism in sheep, and suggested that the compatibility between predicted and measured Mg absorption was only satisfactory when the model included a second site of Mg absorption. Indeed, there is evidence that Mg can be absorbed posterior to the forestomachs (Table 2), but it was demonstrated by Tomas and Potter (160) and Pfeffer and Rahman (110), that post-ruminal Mg infusions could not maintain plasma Mg levels in sheep. Therefore, it may be concluded that post ruminal Mg absorption, if any, is not very important in maintaining Mg balance.

3.1.2 Dietary interactions on Mg absorption

It was demonstrated by Kemp (69) that cows that were grazing on pastures that were heavily dressed with potash (K) and nitrogen (N), had an increased incidence of grass tetany. The grass grown on such pastures was high in N and K (69), and it was suggested by Kemp et al. (72) that Mg absorption was impaired after the feeding of grass rich in N and K. Consequently, controlled experiments were designed to study the effects of N and K on Mg absorption. However, it appeared that under controlled conditions, high crude protein intakes did not depress Mg absorption (39,45, 69,153). It is well known that the crude protein content of herbage is directly related to that of phosphorus (71). Thus, in the observed negative relationship between serum Mg concentration and crude protein content of herbage (69, 72), crude protein might have acted as surrogate variable for P. This could imply that increasing intakes of P reduce Mg absorption. Indeed, when dietary P concentration was increased from 2.2 to 6.4 g P/kg dry matter a depressant effect of high P intake on Mg absorption was found (140). Although the dietary P concentration was in the upper range of practical values in this study, it was concluded that high P intakes might enhance the risk for Mg deficiency especially when concurrent intakes of Mg are low. With respect to K, many controlled experiments have shown a negative relationship between K intake and Mg absorption (38)(49,50,58,79,105,112). The underlying mechanism is explained in paragraph 3.1.3.

It is well known that Na deficiency inhibits Mg absorption in ruminants (95,97). The Na induced reduction in Mg absorption may be explained by the fact that in Na deprived ruminants, the salivary K concentration is dramatically increased which may cause high ruminal K concentrations (CVB Documentation report nr. 36; Sodium metabolism and requirements in ruminants). Consequently, ruminal K concentrations may resemble those observed after high K intakes and it is well known that such conditions inhibit Mg absorption. Indeed, Na intakes above requirement did not influence the absorption of Mg (79, 95, 112).

Wilson et al. (168) demonstrated that plasma Mg concentration was maintained within the normal range when cows were offered supplemental starch when grazing a tetany-prone pasture. Furthermore, Pfeffer et al. (111) showed that replacement of hay by rolled barley, which raised the starch content of the diet, increased apparent Mg absorption in sheep. Absorption of Mg might have been improved because of the ingested starch. Indeed, in controlled studies by Giduck and Fontenot (41) and Schonewille et al. (136), a significant rise in Mg absorption was observed in sheep and goats respectively, when the diet was supplemented with starch. Similarly, the intake of supplemental soluble carbohydrates, such as glucose, sucrose, and lactose, has also been shown to increase Mg absorption in sheep (41,90,119). In contrast, Schonewille et al. (142) could not demonstrate an effect of supplemental starch on Mg absorption in dry cows, probably because there was a lack of effect of starch on ruminal pH. The intake of increased amounts of soluble carbohydrates or rapidly fermentable carbohydrates (21,92) may lower ruminal pH due to an increased production rate of volatile fatty acids. A decrease in pH may raise the solubility of Mg (23,44,157), which in turn could enhance the availability of Mg for absorption across the ruminal epithelium (54). Alternatively, it has been shown in-vitro (84) that short-chain fatty acids (SCFA) versus gluconate stimulated Mg absorption. Thus, it may be that the SCFA's stimulated the electroneutral component of Mg absorption by the provision of extra protons to Mg^{2+} /H^+ exchangers (84,134) located in the apical membrane of the epithelium (98).

3.1.3 Mechanisms of Mg absorption

The process of Mg uptake by rumen epithelial cells consists of a K-sensitive (electrogenic) and a K-insensitive, carrier-mediated transport component (83,85). Magnesium uptake through the electrogenic transport component depends on the concentration of Mg in the soluble fraction of rumen contents and the apical membrane potential (PDa) across the rumen epithelial cells (intracellular content is negative relative to rumen content). At low ruminal K concentrations, the apical membrane potential provides a driving force for Mg uptake by rumen epithelial cells, but high ruminal K concentrations cause a depolarization of the apical membrane potential, which reduces Mg uptake (83). Thus, the observed decrease in Mg absorption at high ruminal K concentration is caused by the K-induced change in the apical membrane potential. Because the transmural potential difference (PD_t) is directly related to PD_a, it follows that a change in PD_a causes an alteration of PD_t (83). Indeed, it is well known that the K-induced decrease in Mg absorption is correlated with an increased PD_t (94,96). It has been demonstrated (35, 83) that, under *in vitro*-conditions with isolated sheep rumen epithelium, both the PD_t and the PD_a are correlated with the logarithm of the luminal K concentrations. This means that the change in PD_t and PD_a is much higher when the luminal K concentration increases from 20 to 40 mmol/L compared with the same increase from a level of 80 to 100 mmol/L. Indeed, it was shown by Jittakhot et al. (64), that the K induced reduction in Mg absorption appeared to be non-linear and that Mg absorption was maximally suppressed at ruminal K concentrations of approximately 125 mmol/L, at least in sheep. In this study (64), the lowest efficiency of Mg absorption (% of intake) was observed when the sheep were fed a diet containing 59 g K /kg dry matter. In contrast to the observations in sheep, Mg absorption was significantly lower when cows were fed rations containing 75 versus 48 g K/kg dry matter. This observation was explained by the fact that the highest ruminal K concentrations observed were about 100 mmol/L (63). Thus, it was concluded that in cows the dose-response relationship between Mg absorption and K can be assumed linear.

The K-independent, carrier-mediated transport component at the apical membrane is based on exchanging one Mg ion for two hydrogen ions (82, 134). Currently, it is believed that Mg transport across the basolateral membrane solely depends on a carrier-mediated process (137), which might be based on the exchange of a Mg ion for two Na ions (147). The presence of carriers transporting Mg across the rumen epithelium provides a theoretical basis for the idea that Mg absorption can become saturated. However, it was indicated by Jittakhot et al. (66), that apparent Mg absorption in dry cows, might become saturated at a ruminal Mg concentration of 17.5 mmol/L, which was related to a dietary Mg content of about 12 g/kg dry matter. Such high values are beyond the range used in practice. Thus, it is unlikely that the process of Mg absorption becomes saturated under practical feeding conditions.

3.1.4 Availability of supplemental Mg sources

Magnesium sulphate is considered a well available source of Mg for ruminants (53). Indeed, it was shown by Van Ravenswaay et al. (164) that Mg–sulphate versus MgO and magnesite was most effective in increasing the urinary Mg excretion in lambs (Table 3). Furthermore, reagent grade Mg-carbonate is also considered well available, but Mg-carbonate in the form of magnesite (Table 3) appears to be the least favourably source of supplemental Mg (53). Magnesite is an $MgCO_3$-rich ore, which has to be heated (calcined) so as to oxidize Mg-carbonate into Mg-oxide. Indeed, “raw” magnesites and those calcined at temperatures lower than 650 ºC are poorly available to ruminants while those calcined at a temperature of 800ºC or higher are well available (167). In practice, calcined magnesites (MgO) are an important source of supplemental Mg (137). It was shown by Schonewille et al. (144), that urinary Mg excretion varied considerably between three sources of Mg (calcined magnesites), which could not be fully explained by a difference in method of production. Apart from the possibility that the origin (seawater versus ore) of MgO may play a role (165), particle size is of great importance with respect to the availability. Indeed, Mg sources with smaller particle size have a higher solubility, both in-vitro and in-vivo, and produced a significant higher urinary output (62, 144,170). Thus, it is recommended to assess the quality of calcined magnesites before using it in practice (144).

3.2 Excretion

Currently, there is no experimental proof for any specific Mg-regulating hormone (8), which implies that the amount of Mg absorbed in excess of requirement is to be excreted in urine. Renal handling of Mg is a filtration-reabsorption process in which a part of the filtered Mg is reabsorbed and the remainder is excreted in the urine (10, 25,29,115). Thus, urinary Mg excretion is raised when the filtered load exceeds the tubular reabsorption capacity. The renal threshold for plasma Mg was found to be 0.70-0.75 mmol/L (127)(86). When plasma Mg falls below this value virtually all of the filtered Mg is reabsorbed and urinary Mg excretion declines to zero (125,155).

Table 3: Availability of Mg sources

Reference	Animals	Response criterion	Rank order of availability
Van Ravenswaay et al. (164)	lambs	urinary Mg excretion	Mg-sulphate > calcined magnesite (MgO) > magnesite ($MgCO_3$)
Ammerman et al. (7)	wethers	Mg balance	Mg-sulphate > MgO, $MgCO_3$[1] > magnesite
Hurley et al. (59)	lambs	Mg absorption	Mg-citrate, Mg-hydroxide, Mg-mica[2] > MgO[3]
Lough et al. (88)	dairy cows	lactational responses	MgO[3] = chelated Mg[4]
		in-vitro solubility	chelated Mg > MgO[5]
Schaefer et al. (133)	heifers[6]	pH rumen fluid	MgO (reagent grade) > $MgCO_3$[1] > MgO (feed grade)
Schonewille et al. (144)	cows	urinary Mg excretion	MgO-A > MgO-B > MgO-C[7]

[1] Reagent grade
[2] Mineral colloidal clay product (smectite-vermiculite)
[3] Feed grade
[4] Mg chelated with isolated soy protein
[5] Measured after incubation (0-48 h) of supplemented concentrate in rumen fluid, as total Mg in either liquid or solid phase after ultracentrifugion.
[6] rumen fistulated animals
[7] MgO-A was derived from seawater; MgO sources B and C were commercially available calcined magnesites.

4 MAGNESIUM REQUIREMENTS

4.1 Dairy cows

4.1.1 Maintenance

Estimates of the endogenous faecal Mg losses adapted by the ARC, NRC and INRA (Table 4) are all the same (3 mg/kg BW), but original estimates (Table 5) are quite variable between studies and range from 1.5 to 6 mg/kg BW (Table 5) with a mean of 3.5 mg/kg BW (SD 1.94). Because the various estimates listed in Table 5 are based on both the mean of a group animals or individual cows, it seems reasonable to calculate the weighed mean of the listed estimates; i.e. 3.9 mg/kg BW. A similar value (4 mg/kg BW) is also used by the DLG to calculate the endogenous faecal Mg losses expressed on the basis of DM intake (Table 4). The discrepancy between the value of 3.9 mg/kg BW and that adapted by the ARC, is explained by the fact that the ARC used both data from cattle and sheep so as to estimate the endogenous faecal Mg losses. Indeed, when data obtained from cattle and sheep are combined, a mean value of 3 mg/kg BW can be calculated. However, because the use of data obtained only from cattle is preferred, it is suggested to adapt a rounded value of 4 mg /kg BW so as to estimate the endogenous faecal Mg losses.

Table 4: Summary of estimates of endogenous Mg losses expressed in mg/kg BW, unless otherwise noted

	Endogenous/inevitable losses			
	Dermal/Sweat	**Faecal**	**Urine**	**Total**
Dairy cows				
CVB (18)	not given	not given	not given	not given
ARC (9)	0	3	0	3
DLG (31)	not given	not given	not given	0.2 g/kg DM intake[1]
NRC (109)	not given	3	0	3
INRA (60)	not given	3	2	5
Beef cattle				
CVB (18)	not given	not given	not given	not given
ARC (9)	0	3	0	3
DLG (30)	not given	not given	not given	0.2 g/kg DM intake[2]
NRC (108)	not given	not given	not given	3
INRA (60)	0	3	2	5
Sheep				
CVB (18)	not given	not given	not given	not given
ARC (9)	0	3	0	3
NRC (107)	not given	not given	not given	not given
INRA (60)	0	3.5	1.5	5
Goats				
CVB (18)	not given	not given	not given	not given
ARC (1)	0	3	0	3
DLG (32)	not given	not given	not given	0.2 g/kg DM intake[3]
NRC (106)	not given	not given	not given	not given
INRA (60)	not given	not given	not given	not given
Kessler (77)	not given	not given	not given	3.5

[1] Value taken from beef cattle.
[2] Calculated on the basis of an endogenous Mg loss of 4 mg/kg BW and a dry matter intake of 2% of BW.
[3] Value taken from dairy cattle.

Table 5: Estimates of the endogenous faecal loss (mg / kg BW) in cattle and sheep

Cattle			
Reference	**Animals/ n**	**Method**	**Endogenous faecal loss**
(155)	dry cow / 2	Artificial diet, low in Mg	2.0
(126)	Lactating cow / 4	Artificial diet, low in Mg	6.0
(152)	Lactating cow / 2	Isotope dilution	1.5
(14)	Lactating cow / 1	Isotope dilution	3.0
	Lactating cow / 1	Isotope dilution	5.0

Sheep			
Reference	**Animals/ n**	**Method**	**Endogenous faecal loss**
(6)	wether / 12	Artificial diet, low in Mg[1]	2.9[2]
(89)	wether / 1	Isotope dilution	5.0
(36)	wether / 1	Comparative balance with Mg 28	3.7
(80)	ewes / 6	Mg28	3.2
(16)	ram / 1	Isotope dilution	5.0
	ram / 1	Isotope dilution	2.1
(58)	sheep / 4	Isotope dilution	2.9
	sheep / 4	Isotope dilution	2.0
	sheep / 4	Isotope dilution	3.4
	sheep / 4	Isotope dilution	1.9
(114)	ewes / 1	Isotope dilution	2.4
	ewes / 1	Isotope dilution	1.6
	ewes / 1	Isotope dilution	1.8
	ewes / 1	Isotope dilution	2.1

[1] Wethers were also infused with varying levels of intravenous Mg, regression of endogenous faecal loss on serum Mg concentrations.
[2] Calculated for a serum Mg concentration of 1.03 mmol/L.

Inevitable urinary Mg losses were considered unimportant by both the ARC and the NRC (Table 4). In contrast, an inevitable urinary Mg loss of 2 mg/kg BW was implicitly suggested by INRA and they refer to a paper of Kemp and Geurink (75), but it was not possible to recalculate a value of 2 mg/kg BW on the basis of the information provided. Under controlled conditions, it was shown by Storry and Rook (155), Rook et al. (126) and Rook and Balch (125), that urinary Mg losses were negligible at low Mg intakes. Thus, it is suggested to ignore the inevitable urinary Mg losses when calculating the net maintenance requirement of Mg.
As far as we know, dermal Mg losses are not quantified. Therefore, the suggested that total net Mg requirement for maintenance in dairy cows is 4 mg/kg BW.

4.1.2 Pregnancy

The net requirement for pregnancy set by the ARC (Table 6) was calculated on the basis of following formula:

Mg content of foetus and adnexa (g) = 0.025 x Birth weight x $10^{3.988 - 5.826*(EXP(-0.00285*D))}$
where D = days from conception in the range of 141 to 281 (=parturition)

Assuming a birth weight of 44 kg, Mg retention in foetus and adnexa was calculated to be 0.23 and 0.36 g/day during the first and second month of the dry period respectively. On the basis of slaughter experiments, House and Bell (56) reported an Mg accretion rate of 0.18 g/day between 190 and 270 days after conception. When the same time interval is used to predict Mg retention during pregnancy on the basis of the formula provided by the ARC (9), a value of 0.21 g/day can be calculated. Thus, Mg accretion rate during pregnancy seems to be properly predicted by the formula provided by the ARC (9). Because this formula offers the possibility to estimate Mg requirement in the course of time, it is suggested to adapt the formula of the ARC (9) to calculate the net Mg requirement of the gravid uterus during pregnancy.

4.1.3 Growth

The Mg requirement for growth of the NRC was adapted from the ARC (Table 6). The value used by the ARC is derived from castrated males (Shorthorn, Hereford) with a body weight ranging from 70 to 490 kg. The net Mg requirement for growth set by INRA (Table 6) is comparable to the value used by the ARC, and it is indicated that it may be applied for animals with a BW ranging from 150 to 600 kg without further specification. The slightly lower estimates for the net Mg requirement for growth set by the DLG (Table 6) are obtained from slaughter experiments with young bulls (Fleckvieh, not further specified). Thus, the Mg requirement for growth appears to range from 0.38 to 0.45 g/kg of growth and it is suggested to adapt a tentative, mean value of 0.42 g/kg growth as the estimate for the net Mg requirement for growth of replacement heifers.

4.1.4 Milk production

The Mg content of milk seems rather constant because all the values indicated by the several councils listed in Table 6, are practically identical. However, a value of 0.12 g/L of milk seems to be a relative high estimate since other values reported were 0.109 (124), 0.113 (123), 0.103 (17), 0.100 (130), 0.111 (26), 0.109 (27). In contrast, Dennis and Hemken (28) reported a value of 0.134 g Mg/L of milk while Kemp et al. (72) found a mean value of 0.120 g/L, which is similar to the value reported by the ARC (9). When all the listed values are combined, the calculated mean Mg content of milk appears to be 0.114 (SD 0.1098) g/L. However, in absolute terms the difference between the calculated mean Mg content of milk and that set by the several councils is rather small. Therefore, it seems opportune to adopt a value of 0.12 g Mg/L also.

Table 6: Summary of estimates of net Mg requirements for foetal retention, growth and milk

	gravid uterus (g/d)	growth (g/kg gain)	milk (g/L)
Dairy cows			
CVB (18)	not given	not given	0.12
ARC (9)	0.36[1] (8-4 weeks ante partum)	0.45	0.125[2]
	0.23 (4-0 weeks ante partum)		
DLG (31)	0.07 (6-4 weeks ante partum)	0.38	0.12
	0.10 (3-0 weeks ante partum)		
NRC (109)	0.33 (late gestation) [3]	0.45	0.12
INRA (60)	0.14 (6-0 weeks ante partum)	0.4 (150-600 kg BW)	0.12
Beef Cattle			
CVB (18)	not given	not given	not given
ARC (9)	not given	0.45	not given
DLG (30)	not given	0.38 (< 900 g growth/d)[4] 0.35 (1200 g growth /d)	not given
NRC (108)	0.33 (late gestation)[3]	0.45	0.12
INRA (60)	not given	0.4 (150-600 kg BW)	not given
Sheep[5]			
CVB (18)	not given	not given	not given
ARC (9)	0.03 (9-5 weeks ante partum)[6]	0.41 (10-45 kg BW)	0.17
	0.09 (4-0 weeks ante partum)		
NRC (107)	not given	not given	not given
INRA (60)	0.03 (6-0 weeks ante partum)	0.4 (10-50 kg BW)	not given
Goats			
CVB (18)	not given	not given	not given
ARC (1)	0.03 (9-5 weeks ante partum)[6]	0.45	0.13 (Saanen/Toggenburg)
	0.09 (4-0 weeks ante partum)		
DLG (32)	0.08 (4-0 weeks ante partum)[7]	0.4	0.12
NRC (106)	not given	not given	not given
INRA (60)	0.03 (6-0 weeks ante partum)	not given	not given
Kessler (77)	[8]	0.4 (<39 kg)	0.14

[1] Calf with birth weight of 44 kg.
[2] British Friesian cows
[3] Not further specified
[4] Fleckvieh steers with a BW in the range from 200 to 650 kg.
[5] Mg accretion due to wool production range from 0.5 to 2 mg/day at growing rates from 2.7-11.0 g/day.
[6] Total birth weight of 8 kg
[7] Total birth weight of 6 kg
[8] Accretion of Mg during pregnancy is not given, but the Mg content of goat foetus is estimated to be 0.3 g Na/kg foetus at term.

4.2 Beef cattle

4.2.1 Maintenance

The net maintenance requirements set by the ARC and INRA for beef cattle are similar to those of dairy cattle (Table 4). The German estimate for the inevitable Mg losses is expressed as a function of feed intake; i.e. 0.2 g/kg DM and is similar to the estimate adopted for dairy cows (Table 4). This value is calculated under the assumption that the inevitable Na loss equals 4 mg/kg BW and that the animals have a DM intake of 2% of BW.
The ARC, INRA, NRC and DLG (Table 4) do not distinguish between dairy cows and beef cattle in their approach for estimating the Mg requirement for maintenance. Therefore, we consider it opportune to apply also a value of 4 mg/kg BW for estimating the endogenous faecal Mg losses in beef cattle. Because inevitable urinary Mg losses can be ignored (paragraph 4.1.1) and no data are available to estimate dermal and/or sweat losses in beef cattle, we suggest to use a value of 4 mg / kg BW so as to estimate the total net Mg requirement for maintenance in beef cattle.

4.2.2 Growth

Specific factorial estimates concerning net Mg requirement for growth in steers are only provided by the DLG (Table 6) and are based on slaughter experiments with young bulls (Fleckvieh, not further specified). Furthermore, the Mg requirements for growth of dairy cattle provided by the ARC are also based on observations in beef cattle (see paragraph about dairy cows). The value adopted as the Mg requirement for growth by the NRC was taken from the ARC (Table 6). The net Mg requirement for growth set by INRA (Table 6) is comparable to the value used by the ARC, and it is indicated that it may be applied for animals with a BW ranging from 150 to 600 kg without further specification regarding the animals used. Thus, the Mg requirement for growth appears to range from 0.38 to 0.45 g/kg of growth and it is suggested to adopt a tentative, mean value of 0.42 g/kg growth as the estimate for the net Mg requirement for growth of beef cattle. Factorial estimates with respect to pregnancy and milk (suckling cows) are not given by any of the listed councils.

4.3 Sheep

4.3.1 Maintenance

The estimates for the faecal endogenous Mg losses set by the ARC and INRA are more or less similar, values are 3 and 3.5 mg/kg BW respectively (Table 4). The difference between these values is unclear because the value adapted by INRA is not further specified. The estimate for the endogenous faecal Mg losses of sheep provided by the ARC is based on sheep data provided in Table 5. These estimates are quite variable between studies and range from 1.6 to 5 mg/kg BW (Table 5) with a mean of 2.9 mg/kg BW (SD 1.13). Although the various estimates listed in Table 5 are based on both the mean of a group animals or individual cows, the calculated weighed mean of the listed estimates yields a similar value; i.e. 2.8 mg/kg BW. Thus, it is suggested to adapt a rounded value of 3 mg /kg BW so as to estimate the endogenous faecal Mg losses in sheep.

Inevitable urinary Mg losses were considered unimportant by both the ARC and the NRC (Table 4). In contrast, an inevitable urinary Mg loss of 1.5 mg/kg BW was implicitly suggested by INRA (no reference cited). However, Meyer (101) has shown that in hypomagnesemic sheep the urinary Mg concentration dropped to almost zero. Furthermore, Schneider et al. (135) reported a daily urinary Mg output of 0.3 mg/kg BW in sheep with a plasma Mg concentration of 0.63 mmol/L. A similar low urinary Mg excretion of 0.2 mg/kg BW was observed in sheep with an Mg intake of about 0.6 g/day by House and Mayland (57). Finally, Field et al. (37) referred to unpublished work indicating that the inevitably urinary Mg loss may be less than 10 mg/day (BW of the sheep not given). Thus, it seems that an inevitable urinary Mg loss of 1.5 mg/kg BW as suggested by INRA is too high. Therefore, it is suggested to ignore the inevitable urinary Mg losses when calculating the net maintenance requirement of Mg in sheep. Because no data are available to estimate dermal Mg losses in sheep, we suggest to use a value of 3 mg/kg BW so as to estimate the total net Mg requirement.

4.3.2 Pregnancy

The net requirement for pregnancy set by the ARC (Table 6) was calculated on the basis of following formula:

Mg content of foetuses and adnexa (g) = $0.25 \times \text{Birth weight} \times 10^{1.044 - 7.644*(EXP(-0.01626*D))}$
where D = days from conception in the range of 63 to 147 (=parturition)

Assuming a total birth weight of twins of 8 kg, Mg retention in foetuses and adnexa was calculated to be 0.03 and 0.09 g/day during 9 to 5 weeks and 4-0 weeks before parturition respectively. The net Mg requirement for pregnancy provided by INRA (Table 6) is not precisely assessed (no reference), but is about half the value of that estimated on the basis of the formula provided by the ARC for the last 6 weeks of pregnancy; i.e. 0.08 g/day. The difference between the ARC and INRA estimates may be related to the number of foetuses. We arbitrarily suggest to adapt the formula provided by the ARC (Table 6) to estimate the Mg requirement of the gravid uteri during gestation.

4.3.3 Growth and milk production

With respect to the net requirement of Mg for growth, both the ARC and INRA (Table 6) use the same value; i.e. 0.4 g Mg/kg BW. Therefore, we suggest to adapt the same value for the net requirement of Mg for growth. The Mg content of sheep milk is only provided by the ARC (Table 6), which is the mean of 0.19 (n=12) and 0.15 (n=12) g Mg/kg of milk. Both Underwood and Suttle (161), and Todd (158) adapted a value of 0.17 g Mg/kg to estimate the net Mg losses caused by milk production. Furthermore, the value provided by the ARC is in line with that provided by the USDA (162); i.e. 0.18 g/kg of milk (n=62). As far as we know, there are no reported values available of Dutch breeds such as the Texel and Zwartbles breed, but data on the Mg content of milk of several other breeds are reported. When the values reported by Fuente et al. ((40), Spanish breeds), Polychroniadou and Vafopoulou ((113), Greek breeds), Sawaya et al. ((132), African breeds) and Coni et al. ((22), Italian breeds) are combined, it appeared that the Mg content of ewe's milk ranges from 0.088 g Mg/kg (113) to 0.442 g Mg/kg (22). It can be speculated that the variation in Mg content of sheep milk is, at least partly, explained by time in lactation. Although Shiga et al. (150) reported that the Mg content was virtually constant during the first four weeks of lactation, it cannot be excluded that the Mg content of milk changes when lactation progresses (2). Alternatively, genetic factors might be of great importance in determining the Mg content of sheep milk. It is clear that this issue is not yet settled, and we arbitrarily suggest to use a tentative value of 0.17 g Mg/kg of milk so as to estimate the net Mg requirement of lactating sheep.

4.4 Goats

4.4.1 Maintenance

Kessler (Table 4) provides an estimate on the net Mg requirement for maintenance in goats, but he did not specify the source of basal data. Indeed, it seems that there are no sufficient data to derive specific recommendations on the maintenance requirements of goats (1). Therefore, both the ARC and DLG (Table 4) based their values on those adapted for cattle and sheep (ARC) and steers (DLG). Therefore, we suggest that the approach to calculate the net maintenance requirements of Mg in goats can be similar to that of sheep. Thus, we suggest that the total net Mg requirement for maintenance in goats can be estimated as follows: 3 (faecal loss) + 0 (urinary loss) = 3 mg/kg BW.

4.4.2 Pregnancy

Both the ARC and INRA (Table 6) adapted the Mg requirements for pregnancy in goats from sheep. Furthermore, Kessler (Table 6) uses a value of 0.3 g Mg/kg foetus as the net requirement for pregnancy. However, it appears that this value represents the Mg content of newborn goat kids, which is obviously not the same as the Mg accretion rate (g/d) during pregnancy. The estimate on Mg accretion rate during pregnancy provided by the DLG (Table 6) is based on the Mg content of newborn kids (0.3 g/kg BW) and a regression formula, which describes the course of the DM development of the conceptus. When the same time interval (28 days a.p. until birth) and birth weight (6 kg) are used, the approach adapted by the DLG and the formula used by the ARC to calculate Mg accretion rate during pregnancy in sheep, yield a similar value; i.e. 0.08 and 0.07 g Mg/day respectively. Therefore, we arbitrarily suggest to adapt the formula provided by the ARC (Table 6) to estimate the Mg requirement of the gravid uteri during gestation.

4.4.3 Growth and milk production

Factorial estimates for goats with respect to the Mg requirement for growth are provided by Kessler, ARC and DLG (Table 6). However, it appears that only the value provided by the DLG is based on slaughter experiments in kids, with an estimated range in BW from 14 to 45 kg, of White German Improved Goats. The ARC uses the value as set for cattle, and Kessler refers to work also cited by the DLG (Table 6). Thus, it is suggested to apply a value of 0.4 g Mg/kg growth so as to calculate the net Mg requirement for growth.

Both the ARC and DLG provide data on studies reporting the Mg content of goat milk (Table 6). When these data are combined with those reported by Jenness (61), it appears that there are 12 independent studies reporting the Mg content of goat milk. The range between the lowest and the highest values, 0.08 and 0.21 g Mg/L respectively, was quite large, and the overall mean Mg content of milk on the basis these studies was calculated to be 0.14 g Mg/L (SD = 0.029). It is arbitrarily suggested to apply a mean value of 0.14 g Mg/L of milk so as to calculate the net Mg requirement for milk production in goats.

4.5 Coefficient of absorption

4.5.1 Dairy cows

In the practice of feed formulation it is preferred to calculate the amount of Mg required on the basis of net requirement and the efficiency of true Mg absorption. However, quantitative information on the relationship between dietary K, Mg intake and the efficiency of Mg absorption is scarce. In this paragraph an attempt is made to estimate the percentage of true Mg absorption in relation to the K content of the ration. For this purpose, balance data from

16 independent studies with dairy cows were used (Table 7). All studies provided quantitative information with respect to feed intake (dry matter, Mg and K), Mg excretion in both faeces and urine, and body weight (BW). Six studies reported also data on Mg excretion due to milk production because in these studies lacating animals were used.
In order to calculate the gross Mg requirement on the basis of the factorial approach, the efficiency of true Mg absorption is needed. Unfortunately, only apparent Mg absorption was measured in the studies listed in Table 7. Thus, the reported values of apparent Mg absorption had to be converted into values representing the true Mg absorption. It was already indicated (paragraph 4.1.1.) that the endogenous faecal Mg losses could be estimated at 4 mg/kg BW. Consequently true Mg absorption (g/d) was calculated as follows: true Mg absorption = apparent Mg absorption + 0.004 x body weight. In general, the efficiency of true Mg absorption (% of Mg intake) can be estimated by regressing true Mg absorption (g/d) against Mg intake (g/d). The slope of this regression formula, multiplied by 100%, represents the efficiency of true Mg absorption. In order to account for the effect of dietary K on the efficiency of Mg absorption the regression model needs to be extended with an additional term; i.e. the dietary K concentration. Therefore, all data were classified on the basis of the dietary K concentration, into three groups (with the use of the directive "GROUPS" in Genstat 4.2). Characteristics of the three groups, generated by Genstat, are shown in Table 8. The following regression model was used: true Mg absorption (g/d) = Mg intake (g/d) + Mg intake (g/d)•Kgroup (low K, medium K and high K). This model estimates the mean efficiency of Mg absorption (% of intake) for each group of K. It appeared that this regression model explained 90.1% (R^2_{adj}) of the observed variance in true Mg absorption (p <0.001, n =59) and the estimated mean efficiencies of Mg absorption were found to be (mean ± SE): low K, 26.6 ± 1.00; medium K, 20.6 ± 1.54 and high K, 15.1 ± 1.71.

Table 8. The ranges and mean dietary K concentrations of the three groups computed by Genstat and the estimated efficiency of Mg absorption (% of intake)

Group	Number of observations (n)	Mean dietary K content (g K/kg DM)[1]	Range in dietary K content (g K/kg DM)
Low K	19	17.2	8.4 – 25.2
Medium K	21	31.0	26.0 – 34.0
High K	19	44.6	34.9 – 75.6

Furthermore, the mean effect of the dietary K concentration on the efficiency of true Mg absorption (% of intake) appears to be rather constant and not dependent on the level of the dietary K concentration. The difference of the mean dietary K concentration between the low and the medium K group is 13.8 g K/kg DM which is associated with a decrease in Mg absorption of 6 percentage units; i.e. 0.43 percentage units/g K DM. Likewise, the decrease in Mg absorption between the medium and high K group is calculated to be 0.41 percentage units/g K DM. This outcome is in line with Jittakhot et al. (63), who concluded that under practical conditions the inhibitory effect of the dietary K concentration on Mg absorption is linear. Thus, it is suggested to adapt the values listed in Table 9 so as to calculate the gross Mg requirement in dairy cows, irrespective their level of production. Indeed, it was concluded by Jittakhot et al. (67) that the absolute amount of Mg absorbed is determined Mg intake rather than dry matter intake or milk yield. Thus, the efficiency of Mg absorption is independent of the plane of nutrition and physiological status.

Table 7: Data used for regression analysis to estimate Mg absorption[1]

Reference	DM intake (kg/d)	K (g/kg DM)	Mg intake (g/d)	BW (kg)	Mg absorption (g/d)		n
					apparent	true	
Field et al. (38)	5.1	12.7	2.3	350	0.28	1.68	6
	5.0	12.7	5.0		1.27	2.67	6
	4.4	12.7	7.8		1.60	3.00	6
	4.7	38.0	2.1		-0.39	1.01	6
	4.5	38.0	4.5		0.29	1.69	6
	4.4	38.0	7.9		0.67	2.07	6
Schonewille et al. (142)	6.4	33.0	12.3	750	0.70	3.70	25
Schonewille et al. (139)	6.7	40.6	40.7	700	4.90	7.70	6
	6.7	46.7	41.2		4.90	7.70	6
	6.0	34.0	47.8		9.10	11.90	6
	6.7	34.0	42.5		4.60	7.40	6
	6.9	30.7	42.7		3.10	5.90	6
	6.9	43.6	42.8		5.00	7.80	6
Schonewille et al. (140)	7.5	11.3	40.2	540	10.95	13.11	12
Schonewille et al. (145)	6.5	26.0	15.1	671	1.62	4.30	6
	6.4	42.6	13.9		0.29	2.97	6
	6.7	43.1	14.7		0.28	2.96	6
Kemp et al. (72)[2]	10.9	26.0	11.8	500	1.60	3.60	2
	12.3	31.0	13.8		2.75	4.75	2
	11.8	32.0	14.5		3.80	5.80	2
	11.7	18.0	14.4		2.45	4.45	2
	12.3	33.0	16.7		2.20	4.20	4
	11.9	34.0	14.8		2.30	4.30	2
	12.0	21.0	19.6		3.60	5.60	4
	11.8	20.0	15.9		1.95	3.95	2
	11.5	37.0	15.7		2.35	4.35	4
	12.7	41.0	18.6		2.10	4.10	1
	10.5	30.0	15.9		1.65	3.65	2
	9.2	17.0	17.3		3.90	5.90	2
	10.0	16.0	20.1		3.90	5.90	4

Reference	DM intake (kg/d)	K (g/kg DM)	Mg intake (g/d)	BW (kg)		Mg absorption (g/d)		n
						apparent	true	
Rahnema et al. (116)	17.4	18.7	54.3	615		13.46	15.92	25
Schonewille et al. (143)	8.0	21.9	39.4	620		5.75	8.23	12
Schonewille et al. (141)	8.9	17.6	40.3	630		5.70	8.22	10
Rogers and Van 't Klooster (124)[2]	10.5	37.3	12.8	440		1.95	3.71	2
	8.9	8.4	14.0			2.60	4.36	2
	9.1	11.1	17.6			3.55	5.31	2
	11.9	31.4	23.6			3.55	5.31	2
	11.7	15.8	23.9			5.65	7.41	2
Jittakhot et al. (63)	7.1	20.5	41.1	790		5.20	8.36	6
	7.5	48.2	41.0			5.30	8.46	6
	8.0	75.6	40.0			0.80	3.96	6
	7.1	20.9	68.9			12.80	15.96	6
	7.5	47.8	69.6			8.90	12.06	6
	8.0	75.5	68.7			4.80	7.96	6
Jittakhot et al. (2001, unpublished)	20.5	44.7	111.4	600		11.80	14.20	6
Schonewille and Beynen (138)	13.4	34.9	36.3	600		4.40	6.80	6
	12.0	25.2	35.6			7.00	9.40	6
Schonewille et al. (146)	6.8	39.0	17.7	660		2.20	4.84	4
	6.4	34.9	17.5			2.40	5.04	4
	6.1	30.3	17.3			3.00	5.64	4
	5.8	25.2	17.2			3.70	6.34	4
Jittakhot et al. (66)	7.0	30.3	27.1	706		3.42	6.24	6
	7.0	30.8	44.6			6.96	9.78	6
	7.1	30.8	64.2			11.86	14.68	6
	7.1	31.2	83.5			17.11	19.93	6
	7.1	30.4	100.4			20.16	22.98	6
	7.2	30.8	124.3			21.96	24.78	6
Jittakhot et al. (67)	18.6	30.7	68.1	600		9.00	11.40	6
	18.6	30.8	116.3			18.50	20.90	6

[1] Apparent Mg absorption is calculated by: Mg intake (g/d) – Faecal Mg excretion (g/d). True Mg absorption is calculated as: apparent Mg absorption + (4 x Body weight (BW) / 1000).
[2] Dataset from Kemp et al. (72) and Roger and Van 't Klooster (124) were derived by pooled data with respect to the same cows fed similar diets.

Table 9: Suggested values on the efficiency of true Mg absorption at three levels of dietary K[1]

Dietary K concentration (g/kg of DM)	Efficiency of true Mg absorption (% of intake)
15	28
30	21
45	15

[1] At different K concentrations the efficiency of true Mg absorption can be estimated with the use of the factor 0.45/ g K DM, or with the relation: Efficiency of true Magnesium absorption (% of intake) = 34,9 – 0,450 * K (g/kg DS).

4.5.2 Beef cattle, sheep and goats

Currently, there are no specific data available on the efficiency of true Mg absorption in beef cattle. However, the data listed in Table 7 is primarily based on non-lactating dairy cows and cover a wide range of dietary K and Mg concentrations. Therefore, we arbitrarily suggest to adapt the values on true Mg absorption in dairy cows also for beef cattle.
The ARC does not differentiate between sheep and cattle with respect to the efficiency of Mg absorption. However, there are indications that sheep versus cattle absorb Mg more efficiently. When sheep and cattle are fed the same ration in terms of ingredient composition, it appears that apparent Mg absorption in sheep is 1.7 times higher compared to that of cattle (Table 10). These observations are based on apparent Mg absorption, and they may not be extrapolated to true Mg absorption. The data from Reid (120) cannot be converted into true Mg absorption because BW of the animals is not given. Body weights of the cows and sheep used by Jittakhot et al. (65, 66) were 706 and 74.8 kg, respectively. On the basis of an endogenous faecal Mg excretion of 4 and 3 mg/kg BW, values on true Mg absorption were found to be 22.9 and 30.2 (% of intake) for cows and sheep, respectively. The ratio of the two latter values is 1.3.

Table 10: Apparent Mg absorption in sheep and cattle fed rations with the same ingredient composition

Reference	Ration	Apparent Mg absorption		
		cattle (% of Mg intake)	**sheep (% of Mg intake)**	**Ratio**
Reid (120)	Alfalfa, Ad lib.	17.7	27.6	1.6
Reid (120)	Orchardgrass, Ad lib.	13.6	23.1	1.7
Jittakhot et al. (65, 66)	Concentrate based, restricted	12.6	23.1	1.8

Thus, we arbitrarily suggest to apply the values listed in Table 9 and raise them by a factor 1.3 so as to estimate the coefficient of true Mg absorption (% of intake) in sheep. Because there are no specific data on true Mg absorption in goats, it is suggested to use a coefficient of true Mg absorption similar to that of sheep.

4.6 Mg allowance

From a practical point of view, it is important te recognize that the data presented in Table 9, are based on group means of Mg absorption. Thus, when these data are used in the practice of feed formulation, safety margin should be used to meet the requirements of individual cows that are above the group mean level of absorption. Unfortenately, there are no data available to estimate the within-animal variation of mg absorption, but an attempt was made to estimate the combined analytical and within- and between animal variation in Mg absorption, Data were taken from studies of Jittakhot et al. (63,66) and Schonewille et al.(142,145,146) and it appeared that the coefficient of variation for absolute true Mg absorption is 18%. About 95% of the cows will have a Mg absorption of 36% plus or minus the mean. In other words, individual cows with the lowest Mg absorption absorb 64% of the group mean. Therefore, it is suggested to multiply the gross Mg requirement by the reciprocal of 64% (= 1.6), when calculating the Mg allowance.

5 MAGNESIUM DEFICIENCY

Clinical hypomagnesaemia, often referred to as grass tetany (in Dutch: kopziekte), grass staggers or hypomagnesaemic tetany is observed when plasma Mg has decreased to 0.4 mmol/L or lower (26). This disease has been characterised by Sjollema (153) as follows: "occurrence of sudden, rapid attacks, often terminating fatally which appear almost exclusively in milk cows, and then mostly during the first days that cows are out on grass". The clinical sign of hypomagnesaemia (tetany) might be explained (99) by concurred low Mg concentrations (< 0.7 mM) in the cerebrospinal fluid (5) causing uncontrolled synaptic activity of cells in the central nervous system.

It has been recognized by Seekles and Hendriks (148) that the incidence of grass tetany was increased during periods of a high growth rate of grass. A high growth rate of grass is, apart from climatological factors, related to the extent of fertilization of the pastures. Indeed, Kemp (69) demonstrated that cows that were grazing on pastures, which were heavily dressed with potash (K) and nitrogen (N), had an increased incidence of grass tetany.

Subclinical hypomagnesaemia occurs when plasma Mg ranges between 0.4 and 0.8 mmol/L (70), which is associated with an increase of the incidence of milk fever (hypocalcaemic paresis puerperalis) (12,131,163). The mechanism underlying this relationship is not clear, but it might be related to an inadequate production of parathyroid hormone (PTH), and increased skeletal resistance to PTH or an impaired vitamin D metabolism (see paragraph 1. Physiological functions of magnesium).

6 MAGNESIUM INTOXICATION

In practice, Mg toxicity is not a major problem because Mg balance is well regulated by the kidneys, which can excrete large amounts of absorbed Mg. The maximum tolerable level of Mg set by the NRC (109) is 4 g Mg/kg DM but this value seems to be rather low because Erdman et al. (34) successfully used MgO supplemented rations, containing about 7 g Mg/kg DM, to correct milk fat depression without apparent harm, but the dry matter content of the faeces was decreased by 1.4 percentage units. Jittakhot et al. (66), fed dry cows rations, containing 3.8, 6.4, 9.1, 11.8, 14.1 and 17.3 g Mg/kg DM without any apparent health problems. The animals fed a ration containing 11.8 g Mg/kg DM produced faeces with a somewhat lower consistency, but the animals fed rations containing 14.1 and 17.3 g Mg/kg DM had severe diarrhoea (66).

Chester-Jones et al. (19), observed diarrhoea in steers fed rations containing 14 g Mg/kg DM and occasional evidence of mucosal tissue in the faeces. Severe diarrhoea and the presence of tubular strands of mucosal tissue were observed when steers were fed rations containing either 25 or 47 g Mg/kg DM (19). Furthermore, steers became lethargic and progressive degeneration of the stratified squamous epithelium of rumen papillae was observed when rations contained either 25 or 47 g Mg/kg DM (19). Digestibility of the dry matter responded in a negative, linear fashion to the Mg content of the ration, but the decrease in DM-digestibility was most profound when rations with Mg contents of 25 and 47 g/kg DM were fed.

In a study with wether lambs no typical signs of Mg toxicity such as lethargy, locomotion disturbance and lowered feed intake were observed when the animals were fed rations with Mg contents of 2, 6, 12 or 24 g/kg DM (20). However, when the animals were fed a ration containing 24 g Mg/kg DM severe diarrhoea occurred. The faecal DM content was linearly decreased with increasing Mg intakes, but the texture of the faeces from animals receiving rations with 2 and 6 g Mg/kg DM was considered normal. The consistency of the faeces was more variable among the lambs fed a ration with 12 g/kg DM (20). Finally, apparent digestibility's of DM and ADF decreased linearly with increasing dietary Mg contents and the depressant effect of Mg on DM and ADF digestibility was considered relevant when the ration contained 6 g/kg DM (20).

It is clear that accidental over consumption of Mg is not very likely to cause fatal acute toxicoses under practical conditions. An accidental case of overconsumption of Mg by sheep and cattle has been reported by Van der Kerk (76). The consumption of the Mg enriched concentrates was associated with severe diarrhoea in both sheep and cattle. Furthermore, paralysis and comatose conditions were observed in several sheep and, compared to previous years, an increased mortality rate of sheep and lambs was observed. However, on the basis of the information provided (76), the dietary Mg content could not be calculated and it is not clear whether the excessive intake of Mg was the primary cause of death.

It can be reasoned that the maximum tolerable level of the dietary Mg content is negatively related to the solubility of the supplemental Mg-source applied. In other words, the maximum tolerable level of the dietary Mg is probably higher when the supplemental Mg source has a low solubility. Unfortunately, apart from the study reported by Jittakhot et al. (66), the solubility of the supplemental Mg sources used in the other studies cited in this paragraph, are not known. However, it was considered opportune to assume that the supplemental Mg sources were highly soluble when interpreting the data reported in this paragraph.

Thus, it seems that ruminants can tolerate high dietary Mg concentrations and that, in most cases, occurrence of diarrhoea is limited when the dietary Mg content does not exceed a level of about 10 g /kg DM. However, in order to avoid the risk on a depressed digestibility of the diet, it may be advised to set the maximum tolerable level of at 6 g/kg DM.

7 MAGNESIUM STATUS

It was already indicated that the amount of Mg absorbed in excess of requirement has to be excreted in urine (paragraph 3.2.), which implicates that plasma Mg concentrations can be maintained within the normal range when urinary Mg output is high. It was indicated by Kemp et al. (72) that an adequate Mg supply in cows, is associated with a urinary Mg excretion of at least 2.5 g/day. Indeed, when absolute urinary Mg excretions (g/day) are plotted against plasma Mg concentrations (mmol/L), all plasma Mg values fall within the range of 0.8 to 1.2 mmol/L (Figure 3) when urinary Mg excretion is 2.5 g/day or higher.

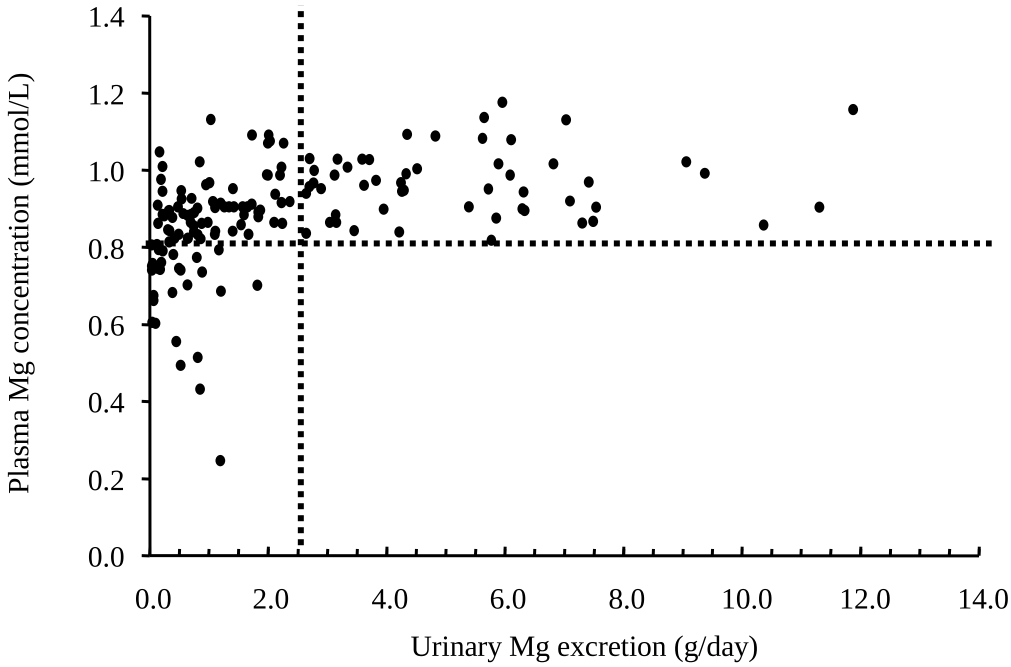

Figure 3. Scatterplot between urinary Mg excretion (g/day) and plasma Mg concentrations (mmol/L). Data are taken from studies by Kemp et al. (72), Schonewille et al. (142,145,146) and Jittakhot et al. (63, 66). The total number of observations is 152.

Furthermore, the data shown in Figure 3, clearly indicate that plasma values of 0.8 mmol/L, or higher, can be maintained at considerable lower urinary Mg excretions which can be simply explained by a decreased surplus of absorbed Mg. Indeed, plasma Mg values around 0.8 mmol/L are still higher than the value of renal Mg threshold; i.e. 0.70-0.75 mmol/L (86, 127). Thus, it seems that animals with plasma Mg concentrations of 0.8 mmol/L or higher are able to maintain their Mg balance.

Furthermore, the data shown in Figure 3 clearly indicate that plasma Mg concentrations show high variation and range from ± 0.25 to ± 1.15 mmol/L when urinary Mg excretion ranges from 0 to 2.5 g/day. In contrast to the situation that plasma Mg values of 0.8 mmol/L, or higher, are maintained in combination with a low urinary Mg output, low plasma Mg values in combination with a relative high urinary Mg excretion is not well understood. However, the lack of relationship between plasma Mg values and urinary Mg excretion does not favour urinary Mg excretion as an index of Mg status. Indeed, the one cow that showed slight clinical symptoms of tetany (72) had a plasma Mg value of 0.25 mmol/L in combination with a relative high urinary Mg output of 1.2 g/day (Figure 3). Clinical cases of hypomagnesemic tetany are closely related to plasma (serum) Mg values of 0.4 mmol/L or lower (68, 69, 153). Furthermore, there is suggestive evidence that plasma Mg values lower than 0.8 mmol/L are associated with an increased risk of milk fever (12, 131, 163). Therefore, we feel that the plasma Mg concentration can be considered as reliable index of Mg status.

Currently, the urinary Mg concentration, instead of absolute urinary Mg excretion (g/day) is considered as a valid index of Mg status. Indeed, it was shown by Kemp (71) that plasma Mg concentrations were at least 0.8 mmol/L when urine contains 4 mmol Mg/L, or higher. However, similar to the situation already described, plasma Mg concentrations varied from 0.16 to ±1.07 mmol/L when the Mg content of urine was lower than 4 mmol/L and most cows (about 70 %) were able to maintain plasma Mg concentrations > 0.8 mmol/L when the urinary Mg concentration dropped to a value as low as 0.8 mmol/L (71). The underlying reason for the preference to use the urinary Mg excretion as an index of Mg status is the fact that differences in Mg supply are reflected in differences in urinary Mg excretion rather than differences in plasma Mg concentrations. Furthermore, Kemp et al. (72) also recommended urinary Mg excretion as preferred index of Mg status, because a decrease in the urinary Mg concentration precedes a drop in the plasma Mg concentration. These arguments cannot be disputed but a drop of the urinary Mg concentration does not automatically result in hypomagnesaemia because the drop in urinary Mg concentration can also be explained by a decrease in the amount of absorbed Mg in excess of requirement. Furthermore, it may be that the use of the urinary Mg concentration as an index of Mg status easily results in over supplementation of Mg, especially when high K rations are fed. In this condition, the K induced reduction in Mg absorption will decrease the urinary Mg concentration, which is aggravated by an increased volume of urine to be excreted (11). In conclusion, the use of plasma Mg concentration as an index of Mg-status in cattle is preferred. Finally, although not of primary interest, from a practical point of view it is interesting to know that the costs of Mg measurement in urine is about twice the costs of that in plasma (Gezondheidsdienst voor Dieren).

8 PREVENTION OF MAGNESIUM DEFICIENCY

8.1 Short term

Magnesium deficiency can simply be prevented by raising the dietary Mg content to adequate levels. Dutch commercial concentrates are generally rich in Mg and may contain 4-5 g Mg/kg. This high Mg content is obtained by the addition of approximately 2.5 g of Mg to each kg of concentrate produced, usually in the form of MgO (137). Thus, an adequate Mg supply to animals receiving concentrates can readily be achieved under practical conditions (91). On the basis of energy and protein supply relative to their requirements, dry cows can be adequately fed rations without concentrates. In this condition, Mg-rich mineral mixtures or a good quality feed-grade MgO can be used so as to increase Mg supply to the cows. From a practical point of view it is important to dust the latter Mg sources on relative moist feedstuffs to improve adherence of the supplemental Mg-source (91). Under grazing conditions, grass can be dusted with 30 kg MgO/ha. (73). It has been shown by Kemp and Geurink (73), that this method of Mg supplementation effectively prevents hypomagnesaemia in cows fed grass as the sole source of nutrition.

8.2 Long term

Magnesium deficiency due to low intrinsic Mg content of roughages can be prevented, at least theoretically, by fertilization of soils with appropriate amounts of Mg. Indeed, fertilization of the soil with 100 kg MgO/ha (in the form of MgSO4, “kieseriet”) has been shown to increase the Mg content of grass (74). However, the increase in Mg content of the grass was rather small and depended on the type of soil. Application of 100 kg MgO/ha induced a mean increase of 0.5 g Mg/kg DM on sandy soils while the Mg content of grass was raised by 0.4 and 0.2 g Mg/kg DM on peat and clay respectively (74). Caution is warranted to apply higher amounts of Mg fertilization because it will decrease the Ca content of the grasses (74). However, the observed increases in the Mg content of grass were considered insufficient so as to prevent hypomagnesaemia (74)(91), and it was recommended to supplement rations with an appropriate amount of Mg. An alternative way to increase the Mg content of the herbage may be the use of clovers because they have about a two times higher Mg content than grasses (15). This might be relevant especially in the practice of organic farming.

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ANNEX: Overview of the series of CVB documentation reports 'Reviews on the mineral provision in ruminants'

- CVB Documentation report Nr. 33: Reviews on the mineral provision in ruminants I: Calcium metabolism and requirements in ruminants (A.M. van den Top)
- CVB Documentation report Nr. 34: Reviews on the mineral provision in ruminants II: Phosphorous metabolism and requirements in ruminants (H. Valk)
- CVB Documentation report Nr. 35: Reviews on the mineral provision in ruminants III: Magnesium metabolism and requirements in ruminants (J.Th. Schonewille and A.C. Beynen)
- CVB Documentation report Nr. 36: Reviews on the mineral provision in ruminants IV: Sodium metabolism and requirements in ruminants (J.Th. Schonewille and A.C. Beynen)
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