Magnesium Absorption by Lactating Dairy Cows on a Grass Silage-Based Diet Supplied with Different Potassium and Magnesium Levels

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ABSTRACT

The objective of the present study was to investigate the interactions of dietary K intake typical for forage-based diets on Mg balance in lactating dairy cows. Six lactating multiparous cows of the Swedish Red and White breed in midlactation were used. Two concentrations of Mg (1.9 and 4.3 g/kg of dry matter) and 3 concentrations of K (19, 28, and 37 g of K/kg of dry matter) were obtained by adding appropriate amounts of MgO and KHCO₃ to the diet. The experimental setup was a 6 × 6 Latin square design with a 2 × 3 factorial arrangement of treatments. Each experimental period lasted 14 d (9-d treatment adaptation period and 5-d data collection). There was no effect of Mg or K dietary supplementation on milk yield. Supplementing the ration with K did not significantly affect the Mg apparent absorption, urinary Mg excretion, or plasma Mg concentration. The Mg balance, estimated as the Mg losses in milk and urine, was positively related to Mg intake but not affected by K intake. The amount of apparently digested Mg was related to the Mg balance. The apparent digestibility ranged from 0.12 to 0.24 with no effect of mineral supplementation. There was a significant curvilinear relationship between plasma Mg and urinary Mg excretion, with a more marked increase in urinary Mg excretion at higher plasma levels of Mg.

Key words: magnesium, potassium, absorption, dairy cow

INTRODUCTION

Magnesium is a mineral essential for various functions in the mammalian cells. If the outflow of Mg with milk, urine, and feces exceed inflow, hypomagnesemia occurs because of the lack of hormonal mechanisms of homeostasis (Martens and Schweigel, 2000). The K content of the ration is considered an important risk factor in the development of hypomagnesemia in rumi-

nants because it reduces the digestibility of Mg (Greene et al., 1983; Martens and Schweigel, 2000). In practice, the K-induced reduction in Mg digestibility is often overcome by adding different Mg sources to the diet. Weiss (2004) compiled data from 8 experiments with lactating dairy cows in which apparent digestibility of Mg was measured by using total collection of feces and urine. The apparent Mg digestibility linearly decreased by 0.075 per percentage unit of K in the diet. The average K level in the diets was 16 g/kg of DM. However, in many areas with intensive dairy production, K content in forage is often >30 g/kg of DM (Fisher et al., 1994; Schonewille et al., 2000). The forestomachs are the main site of Mg absorption in adult ruminants (Tomas and Potter, 1976; Greene et al., 1983). Most of the Mg is absorbed through the rumen epithelium by transcellular systems. One system is sensitive to K and uses the potential difference of the apical membrane as the major driving force. This system works primarily at low ruminal Mg concentrations. The second system is K-insensitive and the absorbed Mg ion is exchanged with hydrogen ions or Mg is cotransported with anions. The K-insensitive system is assumed to work at higher ruminal Mg concentrations (Martens and Schweigel, 2000). In vitro studies indicate that Mg solubility declines sharply as ruminal pH rises above 6.5 (Dalley et al., 1997). However, in in vivo studies in sheep, ruminal pH did not significantly affect Mg absorption (Giduck et al., 1988). Malabsorption of Mg from the forestomachs is not compensated for in the intestines (Tomas and Potter, 1976). Excess Mg absorbed from the diet is excreted in the urine. Any change in Mg balance is counterbalanced by corresponding changes in urinary excretion (Ram et al., 1998). Thus, urinary Mg is a good indicator of whether a sufficient amount of available Mg is ingested (Martens and Schweigel, 2000). Magnesium toxicosis is not evident as a clinical problem. However, an excessive addition of Mg may decrease palatability and cause diarrhea because of osmotic effects (NRC, 2001). Information about the effects of high levels of K on Mg absorption in lactating cows is limited. The aim of the present study was to investigate the interactions of dietary K intake typical of forage-based diets on Mg balance in lactating dairy cows.

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Table 1. Dry matter content, chemical composition, and calculated values for ME of feeds

Item	Silage	Concentrate
DM, %	38	89
ME, MJ/kg of DM	11.1	13.6
CP, g/kg of DM	72	201
AAT, ¹ g/kg of DM	158	122
PBV, ² g/kg of DM	41	10
Ash, g/kg of DM	87.6	
NH ₃ -N, % of N	5.2	
pH	4.0	

¹AAT = AA absorbed in the small intestine.

²PBV = protein balance in the rumen.

MATERIALS AND METHODS

Cows and Experimental Design

The animal procedures were approved by the Uppsala Local Ethics Committee. Six lactating multiparous cows (parities 2 to 4) of the Swedish Red and White Breed with mean BW of 606 kg (range 570 to 685 kg) were used. The cows were not pregnant and they were milked twice daily. The average DIM at the start of the experiment were 180 (150 to 209). The cows were held indoors in individual stalls with straw and sawdust as bedding. They had free access to water. The experimental setup was a 6 × 6 Latin square design with a 2 × 3 factorial arrangement of treatments aiming at 2.0 and 4.5 g of Mg/kg of DM and 18, 28, and 38 g of K/kg of DM. The design was balanced for carryover effects. Each experimental period lasted 14 d, and the first 9 d was the pretreatment adaptation period. The cows were randomly assigned to each sequence of feeding.

Diets

The cows were individually fed restricted amounts covering the requirements based on the average milk yield during the first 4 d of each experimental period according to the Swedish feeding recommendations (Spörndly, 2003). The diet consisted of grass silage and concentrate fed separately, with a constant ratio of 60% silage and 40% concentrate on a DM basis. Both silage and concentrate were fed 4 times daily, at 0600, 0900, 1200, and 1700 h, in separate buckets by automatic feeding wagons. The composition of the feeds is shown in Table 1. Appropriate amounts of MgO and KHCO₃ were fed on top of each ration and were manually mixed into the silage. The particle size of MgO was less than 250 µm in diameter.

Collection of Samples

Samples from silage were collected every day during each experimental period. The samples were dried at

60°C in a forced-air oven for 24 h and ground in a hammer mill (1-mm screen). Samples from 1 period were pooled to obtain 1 sample from each of the 6 periods. Orts from silage and concentrates were collected daily and pooled. Orts were treated according to the same routines as the silage. Spot samples of urine were collected once daily during the last 5 d of each period between 0800 and 1000 h. Twenty milliliters of urine was then pooled and stored at -20°C. Rumen fluid was collected by using an esophageal tube at 1200 h on d 12. Blood samples were taken on d 11 and 13 between 0800 and 1000 h from the coccygeal artery or vein into evacuated Vacutainer tubes containing sodium heparin as anticoagulant (Venoject, Terumo Europe N.V., Leuven, Belgium). The samples were centrifuged for 15 min at 1,800 × g within 1 h after sampling, and the plasma was harvested and stored at -20°C until analyzed. Morning and afternoon grab samples of feces were collected twice daily during the last 5 d of each period. Individual cow fecal samples were composited on an equal weight basis and frozen at -20°C. After each period, the samples were thawed and individual samples from each cow and collection period were merged and thoroughly mixed. A representative sample was then freeze-dried and stored until analysis. Milk production was registered daily, morning and evening, during the 5 last days, and a sample of milk was taken at each milking and preserved with bronopol and stored in a refrigerator up to 7 d until analysis for protein, fat, and lactose. An additional 10 mL of milk from each sampling was pooled and frozen -20°C until analyzed.

Analyses

Ground material of feed and feces was dried at 105°C overnight before analysis. Feeds were analyzed for CP by a fully automated Kjeldahl procedure (Technicon, Solna, Sweden). Metabolizable energy in the feeds was calculated from in vitro digestibility (Lindgren, 1979). Amino acids absorbed in the small intestine and protein balance in the rumen were calculated according to the Nordic Protein Evaluation System as described in the Swedish Feed Tables for Ruminants (Spörndly, 2003). The Mg and K concentrations in feeds and feces were determined by optical emission spectral analysis with inductively coupled plasma (Spectro Analytical Instruments GmbH & Co. KG, Kleve, Germany). Samples were analyzed for acid insoluble ash, which was used as an internal marker to determine apparent total-tract Mg digestibility (van Keulen and Young, 1977). The rumen fluid pH was determined with a pH meter (MP125, Mettler-Toledo, Schwerzenbach, Switzerland) immediately following collection. Before analysis, the rumen fluid was filtered through a filter paper and

Table 2. Intake of the experimental diets

Item	Low Mg			High Mg		
	Low K	Medium K	High K	Low K	Medium K	High K
Silage, kg of DM/d	9.3	9.4	9.7	9.7	9.6	9.2
Concentrate, kg of DM/d	5.9	6.1	6.3	6.3	6.3	6.1
MgO, g of DM/d	0	0	0	0.065	0.064	0.060
KHCO ₃ , g of DM/d	0	0.377	0.788	0	0.384	0.716
Total DM, kg of DM/d	15.3	15.9	16.9	16.2	16.4	16.1

centrifuged for 5 min at $16,000 \times g$. Proteins in the pooled milk samples were precipitated by addition of 10% TCA 1:1 by volume, centrifuged for 15 min at $16,000 \times g$, and the supernatant harvested. The plasma, rumen fluid, milk, and urine concentrations of Mg were analyzed by using a quantitative colorimetric method (Magnesium LiquiColor, Stanbio Laboratory, Boerne, TX). Milk composition was determined by Fourier-transform infrared spectroscopy (Fossomatic 5000, N Foss Electric, Hillerød, Denmark). Creatinine in urine was analyzed on a Technicon Auto Analyzer II [Technicon, Solna, Sweden (Technicon method no. SE40011FH4)].

Statistical Analysis and Calculations

Analysis of variance was performed by using PROC MIXED (SAS Institute, 2001). Period and treatment were fixed factors and cow was a random effect. Before statistical analysis, means of the 2 plasma Mg values taken on d 11 and 13 were calculated. The Mg losses in urine were calculated, assuming a daily urinary excretion of 29 mg of creatinine/kg of BW (Valadares et al., 1999).

RESULTS

The DMI did not vary much between treatments (Table 2). There was no effect of Mg or K dietary supplementation on milk yield (Table 3). However, the milk production decreased by almost 6 kg from period 1 to 6 (data not shown). The Mg contents in the consumed diets were 1.9 and 4.3 g of Mg/kg of DM, respectively,

slightly lower than expected. The K contents were 19, 28, and 37 g of K/kg of DM, which was close to the expected content.

Plasma Mg concentrations were significantly influenced by dietary Mg intake, but not by K intake (Table 3). The Mg level in rumen fluid was higher when the cows were fed the diets with a high Mg concentration but was not affected by dietary differences in K intake. The rumen fluid pH increased when the diet was supplemented with K, whereas Mg supplementation did not affect the pH.

The Mg balance, estimated as the Mg losses in milk and urine, was positively related to Mg intake but not to K intake. The amount apparently digested Mg was linearly related to the Mg balance (Figure 1). There was a significant ($P < 0.001$) curvilinear relationship between plasma Mg and urinary Mg excretion (Figure 2). The milk concentration was affected neither by the dietary Mg level nor by the K level, but there was an interaction between the dietary Mg and K levels. In cows not supplemented with extra Mg, the highest milk Mg concentration was observed when the dietary K level was highest (Table 3). On the other hand, in cows supplemented with Mg, the lowest milk Mg concentration was seen at the highest K supplementation level. The K level in the consumed diet did not affect the calculated absorption of Mg. The amount of apparently absorbed Mg was significantly influenced by dietary Mg intake, but not by K intake (Table 4). The urinary excretion of Mg was higher when the cows received the high-Mg diets but was not affected by the K concentration in the diet. The Mg digestibility ranged from 12.5

Table 3. Magnesium concentrations in ruminal fluid, plasma, and milk and ruminal pH, and daily milk yield in cows ($n = 6$) fed different Mg and K supplements

Item	Low Mg			High Mg			SEM	<i>P</i> -value		
	Low K	Medium K	High K	Low K	Medium K	High K		K	Mg	K $\times$ Mg
Ruminal Mg, mM	2.14	2.07	2.17	3.60	3.55	2.97	0.294	0.566	<0.0001	0.426
Plasma Mg, mM	0.79	0.83	0.81	0.90	0.88	0.86	0.038	0.796	0.009	0.415
Milk Mg, mg/L	87	94	97	94	88	88	4	0.720	0.306	0.027
Ruminal pH	6.55	6.59	6.70	6.49	6.58	6.66	0.054	0.040	0.424	0.862
Milk, kg/d	19.6	19.6	20.5	21.2	20.4	19.4	0.939	0.644	0.330	0.054

Figure 1. Relationship between daily apparently absorbed Mg and the Mg balance expressed as Mg intake minus Mg excreted in urine and milk ($n = 36$).

Figure 2. Relationship between plasma Mg concentration and urinary Mg excretion ($n = 36$).

to 24.5% (Table 4). The different mineral supplements did not affect the Mg digestibility.

DISCUSSION

In this study, addition of K to the ration of lactating dairy cows did not affect the Mg balance because apparent Mg absorption, urinary Mg excretion, and plasma Mg concentration were not affected. The results are in conflict with results from previous studies (Fisher et al., 1994; Jittakhot et al., 2004). Fisher et al. (1994) supplemented lactating cows with K, which reduced urinary Mg excretion, indicating a reduced Mg uptake in lactating cows, but there was no significant effect of K on apparent Mg digestibility. In the study of dry cows by Jittakhot et al. (2004), the Mg content of the diets was far above the requirements (NRC, 2001), which might have affected the results.

In sheep, the depressive effects of high ruminal K concentrations were much more pronounced at ruminal Mg concentrations below 2 mM (Care et al., 1984; Ram et al., 1998). In the present study, the rumen fluid concentration of Mg was above 2 mM even when the cows were subjected to treatments with no Mg supplementation. The relatively high level of Mg in rumen fluid may have inhibited the negative effects of K. However, it must be emphasized that the rumen concentration of Mg was determined on only one occasion, approximately 3 h after feeding. It could not be excluded that the Mg content was occasionally below 2 mM during the study. Furthermore, Mg metabolism differs between sheep and cattle, and the validity of sheep as a model for Mg metabolism in cattle has been questioned (Un-

derwood and Suttle, 1999). The Mg apparent digestibility ranging from approximately 0.12 to 0.24 is in line with data reported by Weiss (2004) for lactating dairy cows. The coefficient of absorption for Mg from MgO has been set at 50% (NRC, 2001). A slightly higher digestibility in Mg-supplemented cows would thus have been expected. In this study, however, the apparent digestibility did not differ significantly between Mg-supplemented and nonsupplemented cows ($P = 0.16$), although the digestibility was numerically higher in the treatment groups supplemented with Mg.

The Mg concentration in milk was slightly lower than published values related to dairy cows of the Holstein and Ayrshire breeds and the Jersey-Friesian crossbreed (Fisher et al., 1994; Thielen et al., 2001; Gaucheron, 2005). It cannot be excluded that cows of the Swedish Red and White breed have a lower milk concentration of Mg. There was no effect of Mg or K supplementation on the Mg concentration in milk, but there was an interaction between Mg and K intake. Thus, on low-Mg diets, the highest Mg levels in milk were observed when the cows were given the high K level. On the other hand, in cows receiving the high Mg level, the highest Mg concentration in milk occurred when no extra K was given. We have no explanation for this observation.

The urine excretion of Mg and plasma Mg were positively associated in a curvilinear action. Schonewille et al. (2000) have also shown such an association in dry cows. However, in the present study with lactating cows, the urine excretion was markedly higher. It is possible that there is a productivity-related increment of inescapable urinary Mg losses in lactating cows.

The amount of Mg apparently absorbed increased when the cows were fed the high-Mg diets. This was

Table 4. Balance of Mg in lactating cows fed diets with different Mg and K contents

Item	Low Mg			High Mg			SEM	<i>P</i> -value		
	Low K	Medium K	High K	Low K	Medium K	High K		K	Mg	K × Mg
Intake, g/d	29.6	30.0	31.1	71.1	70.7	67.0	ND ¹	ND	ND	ND
Feces, g/d	22.5	26.3	25.5	54.4	53.9	52.0	3.08	0.842	<0.0001	0.625
Absorption, g/d	7.1	3.8	5.6	17.2	16.8	15.1	2.64	0.676	<0.0001	0.725
Digestibility, %	22.5	12.5	18.0	23.8	24.5	23.7	5.80	0.224	0.160	0.608
Urine, g/d	3.5	2.9	3.0	7.2	5.3	7.1	1.12	0.891	<0.0001	0.563
Milk, g/d	1.7	1.8	2.0	2.0	1.8	1.7	0.09	0.830	0.858	0.003
Balance, g/d	1.8	-0.9	0.6	7.9	9.6	6.3	2.46	0.39	<0.001	0.537

¹Not determined.

reflected by an increased daily excretion of Mg. As expected, there was a significant relationship between the amount Mg apparently absorbed and the calculated balance between intake and excretion (Figure 1). It is interesting that the lactating cows in the present study excreted nearly 5 g of Mg/d even without apparent absorption of dietary Mg. Approximately 2 g, on average, was excreted with the milk and the remaining amount was excreted in the urine. It has been established in cattle that Mg homeostasis is in equilibrium when the daily Mg excretion is approximately 2.5 g (Kemp and Geurink, 1978; Mayland, 1988). In the present study, more than 44% of the cows that were not supplemented with Mg excreted less than 2.5 g of Mg/d in the urine, indicating a marginal Mg supply. Thus, a dietary supply of 1.9 g of Mg/kg of DM was too low for these lactating cows. According to the NRC (2001), 1.8 g of Mg/d would be accurate for the cows in the present study, assuming that K does not interfere with the Mg absorption. However, Weiss (2004) has shown that lactating cows had to consume an additional 18 Mg/d for every 1 percentage unit increase in dietary K above 1% to maintain the same intake of digestible Mg as that consumed when fed a diet with 1% K. In the present study, the K intake of cows receiving no extra K supplementation was 19 g of K/kg of DM. It is possible that this K level caused a reduction in Mg absorption.

Any surplus of absorbed Mg is quantitatively excreted in urine (Martens and Schweigel, 2000). It is therefore intriguing that the amount of Mg apparently absorbed was higher than that excreted. The cows were not pregnant and were virtually not growing. Thus, if the apparently absorbed Mg at least meets the outflow in milk, the surplus will be excreted in urine. It cannot be excluded that the techniques used, with indirect measurements of Mg apparent absorption and urinary excretion, may have caused systematic errors.

The solubility of Mg is negatively related to rumen fluid pH (Dalley et al., 1997). In the present study, the rumen fluid pH was elevated less than 0.2 pH units in cows supplemented with KHCO₃, but K intake did not

affect the concentration of rumen-soluble Mg. It is possible that the change in pH was too small to induce significant effects on Mg solubility. The results of Erdman et al. (1980) corroborate the observation that MgO supplementation did not affect rumen fluid pH in lactating cows.

In the present study with cows consuming 4.3 g of Mg/kg of DM, the consistency of the feces was judged as much wetter (data not shown). This is in line with observations that excess dietary Mg intake causes diarrhea in ruminants as well as in humans (Chester-Jones et al., 1990; Fine et al., 1991).

CONCLUSIONS

In this trial with lactating dairy cows, an increased K intake did not negatively affect apparent Mg absorption. It is possible that the requirement of Mg supplementation to lactating dairy cows fed K-rich diets has been overstated. However, it must be emphasized that the present study covered only diets with K levels from 19 to 37 g/kg of DM. The results further suggest that the inevitable losses of Mg in urine are higher in lactating cows than in dry cows.

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