Macromineral Digestion by Lactating Dairy Cows: Factors Affecting Digestibility of Magnesium*

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ABSTRACT

The objectives of this experiment were to determine dietary factors influencing the apparent digestibility of Mg by lactating dairy cows and to compare empirical apparent digestibility values with Mg absorption coefficients used in the dairy cattle nutrient requirement model of the National Research Council (NRC). Data were compiled from 8 experiments with 39 dietary treatments and 162 cows (all lactating Holsteins) in which apparent digestibility of Mg was measured using total collection of feces and urine. The concentration of dietary Mg ranged from 0.20 to 0.36% of DM (mean = 0.27%). On average, 19% of the dietary Mg came from a Mg supplement (MgO or MgSO₄). The concentration of dietary K ranged from 1.07 to 2.65% (mean = 1.60%). The mean apparent digestibility of Mg was 0.18 and ranged from -0.04 to 0.33. The average digestibility was 30% lower than the mean value calculated by the NRC model. The primary reason for the low average Mg digestibility was high concentrations of dietary K. At a dietary K concentration of 1%, empirical data agreed with NRC estimates, but apparent Mg digestibility decreased 0.075 ($\pm$ 0.035)/percentage unit of K in the diet. Lactating dairy cows had to consume an additional 18 g of 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.

(**Key words:** magnesium, potassium, digestibility)

Abbreviation key: AC = absorption coefficient.

INTRODUCTION

The NRC (2001) expresses Mg requirements on an absorbable basis. The supply of available Mg is calcu-

lated by multiplying the concentration of Mg in feeds by an absorption coefficient (AC). The NRC uses an AC of 0.16 for Mg from all feedstuffs except Mg supplements. The AC for Mg from MgO and MgSO₄ in the NRC is 0.70. Cows do not appear to excrete a significant quantity of endogenous fecal Mg; therefore, apparent digestibility of Mg was used by the NRC subcommittee to estimate its AC. Apparent digestibility data for Mg from lactating dairy cows, especially for cows fed mixed forage and concentrate diets, are limited (Henry and Benz, 1995; NRC, 2001). Because of the limited database and other uncertainties, the NRC subcommittee did not use the mean apparent digestibility of Mg from published studies, rather they reduced the mean by one standard deviation.

Digestibility of Mg is usually reduced when ruminants consume diets with high concentrations of K provided by K supplements (Greene et al., 1983; Poe et al., 1985; Ram et al., 1998) or forages intrinsically high in K (Schonewille et al., 1999). Based on a summary of published data (18 treatment means), Underwood and Suttle (1999) reported a negative relationship between dietary K concentration and apparent digestibility of Mg for lactating cows fed mixed (forage and concentrate) diets. The coefficients (slope and intercept) in that equation appeared different than the coefficients for equations derived from data obtained from sheep or from cows fed only forages (they were not tested statistically). Therefore, data obtained from sheep or from cows fed all-forage diets may not be applicable to lactating cows fed mixed diets. The objective of this experiment was to quantify Mg digestibility in lactating dairy cows fed a variety of mixed diets and to determine whether other dietary factors influenced Mg digestibility.

MATERIALS AND METHODS

Digestibility data from 8 experiments with 39 dietary treatments and 162 lactating Holstein cows or cow-periods (when the experiment was a Latin square) were compiled for this analysis. All data were obtained following the same protocol for total collection of feces and

Received December 5, 2003.

Accepted February 23, 2004.

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*Salaries and research support provided by state and federal funds appropriated to the Ohio Agricultural Research and Development Center, The Ohio State University. Manuscript No. 42-03AS.

Figure 1. Relationship between Mg intake and intake of apparently digested Mg after adjusting for random trial effects. Each point represents a treatment mean ($n = 39$) from 8 different experiments involving 162 cows. The equation is $Y = 2.5 + 0.14X$.

urine (Weiss and Wyatt, 2000). Collection periods were 4 to 6 d, and during the collection period, samples of feeds, orts, feces, and urine were collected daily (sample size was proportional to mass of the material) and composited into single samples within cow. Cows were fed experimental diets for at least 21 d before each collection period. A summary of the treatments and diets can be found in a companion paper (Weiss and Wyatt, 2004). The objectives of the various experiments included the evaluation of different forages, fat supplements, and by-product feeds. Within each experiment, diets were formulated to contain equal concentrations of Mg and to meet or exceed the NRC (1989) requirement for Mg in use at the time of each experiment. In one experiment (Ivancic and Weiss, 2001), 6 diets were formulated to have equal but excessive concentrations of Mg (0.4% of diet DM). A diverse array of feedstuffs was used, but corn silage was the predominant forage, corn grain was the predominant starch source, and soybean meal was the predominant source of supplemental protein (Weiss and Wyatt, 2004). In addition to corn silage, alfalfa hay, alfalfa silage, and orchardgrass silage was fed in some experiments. The nutrient profiles of the diets (Table 1) and production of the cows (Table 2) was diverse.

Magnesium digestibility was not an original objective in any experiment and was not reported previously. Dried (either at 55 C or lyophilized), ground feed, fecal, and ort samples, but not urine or milk samples, were available and were analyzed for Mg. Feed and ort samples were also analyzed for NDF (Ankom, 2003), CP (Kjeldahl procedure; AOAC, 1990), Ca, P, K, and Na. For mineral analyses, samples of forages and feces were dry-ashed (AOAC, 1990), and samples of concentrates

and orts were digested with perchloric acid (AOAC, 1990). Mineral concentrations in all digests were assayed using an inductively coupled plasma spectrophotometer (AOAC, 1990). Apparent digestibility of Mg was calculated as Mg intake minus excretion of Mg in feces divided by Mg intake and is presented as a proportion, not a percentage.

The dependent variables of interest were apparent digestibility of Mg and intake of digestible Mg (g/d). Dietary concentrations (% of DM) of CP, NDF, Ca, P, Mg, Na, and K, and the dietary Na:K ratio were used separately as independent variables. The MIXED procedure of SAS (SAS, 1999) was used to evaluate relationships between dependent and independent variables. Experiment was included in the model as a random class variable (St-Pierre, 2001) and the dependent variable was included as a continuous variable. When an independent variable contributed significantly ($P < 0.10$) to the variation in the dependent variable, the Estimate option was included in the model statement of PROC MIXED. Treatment means ($n = 39$) were adjusted for trial effects (St-Pierre, 2001). The 95% prediction interval was calculated as described by Neter and Wasserman (1974).

RESULTS AND DISCUSSION

Dietary concentrations of Mg ranged from 0.20 to 0.36% of diet DM (Table 1), with an average concentration of 0.27%. Assuming typical diets and DMI, diets with approximately 0.2% Mg will usually meet Mg requirements for lactating cows (NRC, 2001). On average, 19% of dietary Mg came from supplemental sources (either MgO, MgSO₄, or both), but 6 diets contained no supplemental Mg. The average dietary concentration of K was 70% greater than the dietary concentration that will usually meet NRC (2001) requirements for K (about 1%). The vast majority of the dietary K was intrinsic to the feedstuffs. Only 11 diets contained supplemental K and, in those diets, supplemental K was <5% of total dietary K. The average concentration of Na in the diets was 0.25 (diets with 0.22% Na will usually meet NRC (2001) requirements for Na of lactating cows). However 8 diets had Na concentrations lower than NRC (2001) requirements. All diets contained NaCl, and 14 diets contained NaHCO₃.

The apparent digestibility of Mg ranged from about -0.04 to 0.33, with an average of 0.18 (Table 2). The average digestibility of Mg in this data set is similar to the average (0.21) reported by Adedui and Suttle (1999) for lactating cows fed mixed diets.

When intake of digestible Mg (g/d) was regressed on Mg intake (adjusted for trial effects), the equation was (Figure 1):

Table 1. Descriptive statistics for the nutrient composition of diets consumed by cows (DM basis) in the data set (8 experiments, 39 different dietary treatments).¹

Nutrient	Mean	SD	Minimum	Maximum
DM, %	62.8	4.7	53.7	70.4
Forage, %	55	8	41	70
CP, %	16.7	1.1	14.8	18.5
NDF, %	33.9	5.8	24.7	45.5
Supplemental fat, %	...	...	0.0	3.2
Ca, %	0.88	0.09	0.66	1.03
P, %	0.38	0.03	0.34	0.45
Mg, %	0.27	0.04	0.20	0.36
Supplemental Mg, % of total Mg	19.1	14.7	0	47.7
Mg Absorption coefficient ²	0.26	0.08	0.16	0.42
K ₃ , %	1.60	0.51	1.07	2.65
Na, %	0.25	0.10	0.11	0.45
Na:K	0.17	0.09	0.05	0.32

¹Nutrient concentrations in diets were corrected for concentrations in Orts.

²Absorption coefficients of diets calculated using NRC (2001) coefficients for feedstuffs and Mg supplements.

³Eleven diets contained supplemental K (from a mixture of KCl and K₂SO₄). The supplement provided <5% of total dietary K in those diets.

$$\text{Intake of Digestible Mg (g/d)} = 2.5 (\pm 3.9) \quad [1] \\ + 0.14 (\pm 0.06) \times \text{Mg Intake}$$

The values in parentheses are the standard errors for the coefficients, and the standard error associated with trial (SE_{Trial}) was 3.9 and residual standard error (SE_{Res}) was 0.07. The marginal digestibility (i.e., slope) was different from 0 ($P < 0.04$). Although the intercept was not different from 0 ($P > 0.5$), it was retained in the equation because of its high standard error. The high standard error is caused in part by the large distance between the intercept (i.e., intake of 0 g/d of Mg) and the lowest intake of Mg in this data set (38 g/d). At the average intake of Mg in this data set (55 g/d), estimated Mg digestibility (equation [1]) is 0.185. Average Mg digestibility in this data set was about 30% lower than the average AC calculated using NRC (2001) coefficients for these diets (0.26).

A possible reason for the disparity between the AC used by NRC and the experimentally determined Mg digestibility was the presence of dietary antagonists to the absorption of Mg. The AC for Mg in NRC (2001) are static within a feedstuff; no adjustments are made

for possible antagonists. However, K has greatly reduced Mg absorption in ruminants (Greene et al., 1983; Poe et al., 1985; Ram et al., 1998; Schonewille et al., 1999; Underwood and Suttle, 1999). In this data set, increasing concentrations of K in the diet reduced ($P < 0.03$) Mg digestibility (Figure 2). After adjusting for random trial effects, the relationship was:

$$\text{Mg digestibility} = 0.316 (\pm 0.063) \quad [2] \\ - 0.075 (\pm 0.035) \times \text{dietary K (\%)}$$

The SE_{Trial} was 0.0045 and SE_{Res} was 0.004. At the mean concentration of dietary K (1.6%), the 95% prediction interval was the 0.20 ± 0.12 .

Equation [2] is similar to a previous equation (i.e., $\text{Mg digestibility} = 0.28 - 0.052 \times \%K$) derived from data from lactating dairy cows (Underwood and Suttle, 1999). At a dietary K concentration equal to that needed to typically meet NRC requirements for K (approximately 1%), predicted (equation [2]) Mg digestibility is 0.24, which is statistically equal to the average AC derived from NRC coefficients (0.26). Based on equation [2], Mg digestibility would equal 0 at 4.2% K. However,

Table 2. Descriptive statistics for cows and digestibility (n = 39 treatment means from 8 experiments).

	Mean	SD	Minimum	Maximum
BW, kg	618	35	545	713
DIM	186	64	67	272
DMI, kg/d	20.7	2.8	15.4	26.1
Milk yield, kg/d	29.7	6.7	17.3	44.2
DM digestibility	0.67	0.02	0.62	0.71
Mg intake, g/d	55	10.6	38	75
Fecal Mg output, g/d	45	11.9	27	66
Fecal Mg, % of DM	0.66	0.17	0.43	1.04
Mg digestibility	0.18	0.11	-0.04	0.33

Figure 2. The effect of increasing dietary K (% of DM) on apparent Mg digestibility (expressed as a proportion, not percentage) by lactating dairy cows (after adjusting for random trial effects). Each point is a treatment mean ($n = 39$) from 8 experiments and 162 cows. The equation is $Y = 0.316 - 0.075X$.

increased dietary concentrations of Mg can partially offset the negative effects of high dietary K on Mg absorption (Ram et al., 1998). Equation [2] does not account for the effects of variable Mg intakes on digestibility of Mg.

The approaches taken to derive equations [1] and [2] were combined to derive an equation that accounted for the negative effects of dietary concentrations of K and the positive effects of increased Mg intake. The equation was:

$$\begin{aligned} \text{Intake of digestible Mg} = & 4.5 (\pm 4.0) \\ & + 0.24 (\pm 0.07) \times \text{Mg intake} \\ & - 4.4 (\pm 2.2) \times \text{K} \end{aligned} \quad [3]$$

where intakes are in grams per day and K is as a percentage of diet DM. The SE_{Trial} was 15.9 and SE_{Res} was 1.2. The intercept was not different from 0 ($P > 0.25$), but the Mg intake coefficient ($P < 0.01$) and the dietary K coefficient ($P < 0.06$) differed from 0. At a dietary concentration of 1% K, predicted digestibility of Mg equals 0.24. A value that is essentially the same as the AC calculated from NRC coefficients. Because the intercept and the slope for dietary K are essentially the same, when the diet contains 1% K, digestibility of Mg is 0.24 regardless of intake of Mg. If the concentration of K in the diet is 2% and intake of Mg is 38 g/d (minimum value in this data set), predicted Mg digestibility (equation [3]) is 0.13, but when Mg intake increases to 75 g/d (maximum in this data set) predicted Mg digestibility is 0.18. Dividing the coefficient associated with dietary K (4.4) by the coefficient associated with Mg intake (0.24) in equation [3] yields 18.3. There-

fore, to maintain the same intake of digestible Mg as that obtained at a dietary K concentration of 1%, intake of Mg must increase 18.3 g/d for every 1 percentage unit increase in the concentration of dietary K $> 1\%$. For example, if a cow needed to consume 55 g of Mg/d to meet the NRC requirement for Mg when fed a diet with 1% K, consumption would need to be 73 g/d to meet the same requirement if the diet contained 2% K.

High concentrations of dietary K, low ratios of dietary Na to K, and high concentrations of dietary CP are risk factors for grass tetany (NRC, 2001). In this data set, no statistical relationships ($P > 0.35$) were observed between Mg digestibility and the ratio of dietary Na to K, concentration of dietary Na, or dietary CP concentration. Neither the concentration of dietary Ca or P affected Mg digestibility ($P > 0.20$). Rahnema et al. (1994) reported that increased concentrations of dietary fat have reduced digestibility of Mg, but others (Grace and Body, 1989) have reported no effect of fat on Mg digestibility. Of the 39 diets used in this data set, 11 contained supplemental fat (0.5 to 3.2% of diet DM). When fat was included as a class variable (supplemented vs. not supplemented) or as a continuous variable (supplemental fat, % of diet DM) in the statistical analysis, no effect of fat was observed on Mg digestibility. However, the variation in fat concentrations of diets in this data set was limited (most diets contained no supplemental fat). The effect of fat on digestibility of Mg, if any, could not be ascertained reliably from this data set.

CONCLUSIONS

For a variety of diets, Mg digestibility by lactating dairy cows was similar to NRC estimated AC when the concentration of K in the diets was approximately 1%, but digestibility decreased 0.075 for every 1 percentage unit increase in dietary K concentration. To maintain the intake of digestible Mg equal to that obtained when diets contain 1% K an additional 18 g of Mg would need to be consumed for every 1 percentage unit increase in dietary K above 1% of the diet DM.

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