

Can We Differentiate Supplemental Magnesium Sources Nutritionally?

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Abstract

A laboratory test to differentiate the apparent availability of Mg among supplemental sources would be useful. Evaluation directly with cattle to test the reactivity, solubilization (dissolution), and apparent absorption of Mg from various Mg sources in the rumen is tedious, laborious, and expensive. The degree of reactivity in the rumen and release of soluble Mg in the primary absorption site (the rumen) is key to differentiating among various sources. In addition to their solubility, other primary factors that affect solubility include origin (source), specific chemical compound, proper calcining process of magnesium carbonate to yield magnesium oxide (MgO), particle size, and other chemical compounds (e.g., potassium, calcium) in the diet and rumen. When supplemental sources of Mg were tested in the laboratory for solubility, sometimes, but not always, improved lactational performance was detected. Unfortunately, determination and ranking of Mg sources by solubility as an indicator of apparent availability does not appear to be a very reliable test. The “vinegar test” proposed by Goff (2014) is a simple way to characterize the reactivity and alkalizing property of various MgO sources. Test sources that raise the pH in a solution of vinegar (5% acetic acid) are more alkalizing. This also might provide indirect evidence that some MgO sources are more reactive and yield more soluble Mg for absorption from the rumen than others.

However, MgO sources ranking differently in the vinegar test have not been evaluated with dairy cows by measuring differences in apparent digestibility or lactational performance to verify that the test reliably differentiated sources for apparent Mg availability.

Introduction

Dairy cattle rely on a continuous dietary (and ruminal) supply of absorbable Mg to maintain optimal Mg concentrations and homeostasis in blood and extracellular fluids. There are neither specific regulatory (e.g., hormonal) mechanisms to maintain Mg homeostasis (Littledike and Goff, 1987; Schultz et al., 1988; Martens and Schweigle, 2000), nor is there much body storage (NRC, 2001). Therefore, dietary sources with potentially soluble and available Mg to be absorbed from the rumen and reticulum are required daily (Green et al., 1988; Meyer and Zentek, 1990; Martens and Schweigle, 2000; NRC, 2001).

The National Research Council (2001) listed Mg requirements based on estimates of absorbability of Mg. Amount of available Mg supplied by a particular diet is the product of the concentration of total dietary Mg times an absorption coefficient (AC). The NRC (2001) used an AC of 0.16 for Mg for all feed ingredients except supplemental sources. The estimated AC for Mg from MgO and magnesium

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hydroxide was 0.70, 0.90 for magnesium sulfate, and 0.30 to 0.35 for magnesium carbonate and dolomitic limestone (see Table 15-4, page 312; NRC, 2001).

However, some of these estimates are from non-ruminant animal studies and (or) using “reagent grade” Mg salts because no other information was available. Jittakhot et al. (2004) used MgO to increase dietary Mg from 0.39 to 0.64% (adding 7.6 g Mg to the diet from MgO). The increase in apparent absorption of dietary Mg was 3.6 g. This suggests their MgO had a coefficient of absorption of about 0.47, considerably lower than the 0.70 listed in NRC (2001). Additionally, with the lack of research results to make the AC estimations for most feedstuffs, the NRC subcommittee lowered the mean overall AC by 1 standard deviation for practical application to reduce the risk of Mg deficiency. In a meta-analysis of mass balance studies done in Ohio with feedstuffs typical of those in the TriState area, Weiss (2004) calculated an average apparent digestibility for dietary Mg of 0.24 when the dietary K was 1.0% (near the NRC K recommendation). Since released in 2001, many dairy nutritionists suspect that the NRC AC (0.16) is an over-estimation based on cases with relatively low total dietary Mg, suboptimal lactational performance, and (or) sub-clinical Mg deficiency. In most cases with lactating dairy cows some supplemental Mg source is needed to meet requirement for absorbed Mg.

A common question from the feed industry is: “Can we differentiate supplemental magnesium sources nutritionally?” This is asked because: 1) it is known or suspected that there are distinct differences in apparent availability of Mg from a fairly large list of choices for supplemental Mg and 2) it might be desired to provide the greatest apparently available Mg per unit price, or a differential price point

based on apparent availability among sources. Because of the ever evolving number and origin of sources of feed grade Mg, the desire would be to have a relatively quick laboratory method that could: 1) at minimum, reliably, but indirectly, rank a set of sources from best to worst for apparent availability and 2) even better, provide a reasonably accurate value of apparent availability of each source that could be used in ration formulation. For this discussion “apparent availability” is used to define that proportion of Mg from a feed grade source that ultimately is presented in the animal’s blood stream. It is “apparent” because there is some recycling of once-absorbed Mg back into the digestive tract where it can be absorbed again.

Differing apparent availability of various supplemental Mg sources may be influenced by several factors: source or origin; physical and chemical properties; the source’s reactivity in the ruminal fluid; and absorption mechanisms in the rumen and factors influencing those mechanisms. Objectives of this paper are: 1) to characterize known factors that can affect the apparent availability of Mg; 2) summarize associated research to demonstrate effects of the aforementioned factors; and 3) comment on possible simple laboratory tests that might provide information about reactivity and the potential to predict apparent availability of various MgO sources.

Factors Affecting Apparent Availability of Mg from Supplemental Sources

Sources of supplemental Mg

In order to be absorbed from the rumen, the Mg from any basal feed ingredient or supplemental source must first be solubilized and exist in its ionized state (Mg^{+2}) in the fluid of the rumen and reticulum (henceforth called the “ruminal fluid”).

Magnesium carbonate typically is obtained by mining the ores known as mineral magnesites. In rare occasions, these magnesites may be ground directly and offered as a feed source of Mg. However, their Mg availability is very low or non-existent. The Mg in magnesites and dolomite minerals (anhydrous carbonate minerals composed of calcium magnesium carbonate or dolomitic limestone) should be considered totally unavailable for absorption by dairy cattle; absorption coefficient of Mg equal to zero.

The primary use of magnesium carbonate is to produce magnesium oxide (**MgO**) via a calcining process (reduction, oxidization, and burning or roasting with strong heat). Some feed grade MgO sources are produced by calcination of magnesium carbonate. In Scotland, Wilson (1981) found that magnesites calcined for 3 hr at temperatures of 1,472 to 2,012°F resulted in MgO with greater availability for sheep compared with those burned at 1,202°F or less, or at greater than 2,372°F. In another Scottish study, MgO resulting from higher temperature calcination (1,472 to 2,012°F) had greater apparent Mg availability compared with MgO from lower temperature (932 to 1,202°F) calcination (Adam et al., 1996.). Higher temperatures result in greater surface area by breaking down the magnesium carbonate particles, thus increasing the potential for solubilization and release of Mg into the ruminal fluid.

Magnesium oxides

Magnesium oxides are commonly used Mg salts in dairy diets typically with at Mg content ranging between about 51 to 59% (Urdaz et al., 2003). They are included in dairy rations to alkalize the rumeno-reticular ecosystem when rations are lower in forage than normal and when supplemental Mg is needed to meet requirements. The desire to differentiate

supplemental MgO sources obviously is not new. Long ago Michigan State University researchers (Emery et al., 1965; Thomas et al., 1969) studied dietary and metabolic effects of magnesium oxide (an alkalizer) and sodium bicarbonate (a buffer) on milk fat concentrations in cows fed restricted-roughage rations. They found that milk fat concentration, milk yield, ruminal pH, and molar percentages of ruminal acetate, iso-butyrate, and iso-valerate were increased by feeding MgO and that some of the effects could be additive with the joint feeding of sodium bicarbonate. The authors speculated that beyond the alkalizing effects of MgO that Mg *per se* may act to increase uptake of plasma acetate and triglycerides at the mammary gland to affect milk fat concentration.

Other Mg sources, besides MgO, available for supplementation in dairy rations include magnesium sulfate • 7 H₂O (Epson salts; 9.8% Mg) and magnesium chloride • 2 H₂O (18% Mg); both are soluble in ruminal fluid and their Mg has relatively high availability for absorption; however, they are relatively low in Mg. These so-called anionic salts are included sometimes in pre-fresh supplements to provide an available source of Mg, as well as the respective anion to reduce dietary cation-anion difference and to help acidify close-up cows to aid in prevention of periparturient hypocalcemia. However, with their relatively low Mg concentration and risk to reduce feed intake (they are not very palatable), their inclusion in rations is typically fairly low. Also, unlike the potential of some of the more reactive MgO sources, magnesium sulfate and chloride provide no alkalizing action in the rumen. Magnesium phosphate (**MgP**) that was originally from Sweden and chelates of Mg were tested in the USA, but they never became viable commercial products, although MgP showed promise as a supplemental source of Mg and P for lactating dairy cows (O'Connor et al., 1988);

neither of these sources has alkalizing properties in the rumen.

Particle size

Following their early work characterizing the lactational responses to MgO as a ruminal alkalizer and Mg's metabolic influence to overcome "low-milk fat syndrome", Thomas et al. (1969) and Emery et al. (1965) delved more deeply into the apparent bioavailability of Mg from MgO (Jesse et al., 1981). They examined the effects of particle size from MgO (~56% Mg) using the same magnesium carbonate ore from the same calcining process on availability of Mg by 3 techniques. They used a loading technique in which cows consuming a Mg-adequate diet were given separately an excess load of 4 different particle sizes of MgO into the rumen and then they quantified the relative amount of Mg appearing in urine over time, which was a function of size of the load and the availability of the Mg treatments (varying in particle size). A second technique measured changes in milk fat production of cows fed a restricted-roughage diet. Cows fed the more readily available MgO treatments were expected to increase milk fat, indicating differences in relative Mg availability among particle size treatments. They demonstrated that MgO ground to pass through a 200-mesh screen size (-200) or a 20 mesh (-20) screen resulted in more Mg in urine of cows compared with the baseline (with no Mg treatment fed) Mg excretion. In another study, increased milk fat concentration, milk fat yield, and blood serum Mg concentration resulted when cows were fed MgO with -20 (finest), 30 to 100, or 12 to 40 mesh screen size compared with no MgO supplementation. Authors suggested that differences resulted from the greater solubilization in ruminal fluid of MgO with finer particle size, as noted also in their *in vitro* incubation work (described below). MgO sources should be ground as fine as possible,

while still meeting Occupational Safety and Health Administration standards, to increase potential for solubilization and availability of the MgO for absorption of the Mg.

Solubility of the MgO at the varying particle sizes noted above also was characterized in an *in vitro* ruminal fermentation system (Jesse et al., 1981). Release of solubilized Mg after incubation (0, 3.5, 6, 12, and 24 hr) in strained, centrifuged rumen fluid (without added buffer) was characterized. Maximum concentration of soluble Mg occurred at 12 hr from the most finely ground (-20 screen mesh size) MgO; about 30% less soluble Mg (on a relative basis) was present with 12 to 40, or 30 to 100 screen mesh sizes at 12 and 24 hr of incubation. Ruminal fluid pH *in vitro* had similar patterns as soluble Mg relative to incubation time and MgO particle size. It was concluded that MgO with the finer particle size resulted in more soluble Mg potentially available for ruminal absorption. For the particular MgO source tested, even the unground coarse material was partially reactive with some solubilization and apparent absorption of Mg using the 3 testing techniques (Jesse et al., 1981).

Following the work of Jesse et al. (1981), researchers at the University of Florida set about characterizing the *in vitro* solubility of 11 feed grade sources of Mg, 8 of which were MgO (Beede et al., 1992). The *in vitro* system was a modification of the techniques of Tilley and Terry (1963) and Jesse et al. (1981). The system included strained ruminal fluid from a ruminally fistulated cow fed alfalfa plus trace mineralized salt, McDougall's artificial saliva buffer, and solubilization of Mg in sample tubes (in triplicate) was characterized at 0, 6, 12, 24, 36 and 48 hr of incubation of 0.5 g of ground dietary concentrates containing the different Mg sources (Beede et al., 1989). The pH of the buffered *in vitro* rumen system was maintained

at an average ~ 6.78 and ranged from 6.94 (0 hr) to 6.64 (36 hr) across the 48-hr incubation. Average percentage of the total Mg from the supplemental Mg sources solubilized in the 48 hr rumen incubation was 13.9% and ranged from 1.4 to 27.9%. Average solubilization percentages (in parentheses) for the different sources were: Min-Ad U.S.A. (1.4%); SuperMag-Greek (MgO) (6.5%); MagFeed-Greek (MgO) (7.6%); Mg phosphate-Swedish (11.2%); Chinese-MgO (11.4%); BayMag58-Canadian (MgO) (14.2%); Magal-Spanish (MgO) (14.5%); CoMag-Turkish (MgO) (14.6%); FeedOx-U.S.A. (MgO) (20.4%); MagOx-U.S.A. (MgO) (22.6%); and Rumen-Mate-U.S.A. (27.9%). There are 2 very important points to understand about these solubilization percentages: 1) they were determined from Mg sources nearly 30 years ago and very likely are not representative of products today, even of the same name and origin; and 2) the values are not apparent absorption or availability values, but rather the percentage of the total Mg in the source that was found in the soluble fraction of the *in vitro* rumen incubation after 48 hr.

Subsequent to the assessment of Mg solubility using the *in vitro* rumen system, a lactation performance experiment was conducted using 4 of the MgO sources: MagFeed-Greek (7.6% soluble Mg from MgO in the *in vitro* system), Magal-Spanish (14.5% soluble Mg from MgO), BayMag58-Canadian (14.2% soluble Mg from MgO), and MagOx-U.S.A. (22.6% soluble Mg from MgO). Thus, MgO sources evaluated in the lactation experiment ranged from 7.6 to 22.6% in soluble Mg from the *in vitro* rumen system. Particle size distributions of each source are reported in Beede et al. (1992). On average, MagFeed-Greek had the largest particle size and MagOx-U.S.A. had the smallest particle size, with BayMag58-Canadian and Magal-Spanish having intermediate average particle sizes.

Eighty-six midlactation Holstein cows were used in a randomized incomplete block design. The basal diet was 55% concentrate, 13% alfalfa hay, and 32% corn silage, dry basis. The basal TMR (Control) without Mg supplementation contained 0.21% total Mg. The 4 supplemental MgO sources were each supplemented in the basal diet to provide total dietary Mg concentrations of 0.27, 0.35, and 0.46%. Daily DMI was greater when cows were fed MagFeed-Greek vs. Magal-Spanish, BayMag58-Canadian, and MagOx-U.S.A. ($P < 0.02$) and DMI was greater with Magal-Spanish vs. BayMag58-Canadian and MagOx-U.S.A. ($P < 0.08$). Milk yield was greater with MagFeed-Greek vs. Magal-Spanish, BayMag58-Canadian, and MagOx-U.S.A. ($P < 0.12$). There was no effect on 3.5% FCM yield. Milk fat concentration (in parenthesis) was lower ($P < 0.05$) when cows were fed Control (3.50%) versus MagFeed-Greek (3.61%), Magal-Spanish (3.73%), BayMag58Canadian (3.70%), and MagOx-U.S.A. (3.65%), respectively. There were no differences in milk protein percentages due to the 4 MgO supplemental sources.

When the effect of dietary Mg concentrations (pooled across MgO sources) was considered, there was significant lactational performance responses. Daily DMI declined linearly ($P < 0.001$) as total dietary Mg increased from 0.21% (Control) to 0.46%, about a 3% decline. Overall, 3.5% FCM yield increased linearly ($P < 0.05$) as total dietary Mg increased from 0.21 to 0.46%, with a 5.3% increase with 0.27% Mg compared with 0.21% (pooled across MgO sources). Milk fat percentage also increased ($P < 0.05$) from 3.5% (Control) to 3.72, 3.68 and 3.62% with 0.27, 0.35, and 0.46% total Mg, respectively. Increasing dietary Mg did not affect milk protein percentage, and there were no MgO treatment by dietary Mg concentration interactions detected.

There was some lactational performance effects detected related with MgO source and its solubility in the *in vitro* rumen system. However, the source (MgO-Greek) with the lowest (7.6%) apparent *in vitro* solubility among the 4 MgO sources had the greatest numerical DMI, milk yield, 3.5 FCM yield, and milk fat percentage. Overall, it does not appear that the *in vitro* solubility test in a buffered system suggests anything about lactational responses one should expect.

Absorption of Mg in the rumen and interfering compounds

In adult ruminants, the rumen and reticulum are the principal locations of Mg absorption (Martens and Gabel, 1986). Thus, it is critical in adult dairy cattle that this divalent cation (Mg^{+2}) be soluble in ruminal fluid and presented at the ruminal epithelial cells for absorption. In pre-ruminant calves and non-ruminants, Mg absorption is primarily from the small intestine; Mg salts that are poorly soluble in neutral pH water can be solubilized by action with HCl in the abomasum or stomach. This facilitates absorption of Mg in the small intestine. However, in ruminants, Mg absorption is dependent on the concentration of Mg^{+2} in the ruminal fluid where pH typically is greater than 5.8. However, ruminal pH can be less than 5.5 for considerable lengths of time (e.g., 3.1 to 9.7 hr) in lactating dairy cows (Oba and Allen, 2000).

Once solubilized in the ruminal fluid, the ionized Mg^{+2} can be absorbed at the interface of the rumen epithelial cell apical membrane. Absorption of Mg^{+2} is either by an active transport system (transcellular system) or by a passive or paracellular transport system (Ebel, 1990; Martens and Schweigel, 2000; NRC, 2001). The concentration gradient of Mg between ruminal fluid and blood is the motive

force for the transcellular system. This system is very effective, even when soluble Mg^{+2} concentrations in ruminal fluid are quite low. The presence of short chain fatty acids in the ruminal fluid can help promote Mg uptake by this mechanism.

Paracellular transport works based on the electrochemical gradient with high concentrations of Mg in ruminal fluid, forcing greater quantities of Mg through permeable tight junctions between epithelial cells into the extracellular space (Ebel, 1990; Martens and Schweigel, 2000). However, K inhibits this transporter because high K concentration promotes passive diffusion of K into the ruminal epithelial cells, causing a reduction in the potential difference across the apical membrane. Because the major negative charge inside the cells was the primary factor causing movement of Mg through these channels, the high K greatly reduces the effectiveness of the paracellular transport system for Mg. The effect of K was demonstrated in dairy cattle (see below). Sodium, ammonium, and Ca ions in the ruminal fluid can have similar effects on paracellular Mg absorption (Urdaz et al., 2003).

Dietary K and Ca effects on Mg absorption

Weiss (2004) used data from 8 experiments, 39 dietary treatments, and 162 individual cow mass balance collections to determine apparent digestibility of total dietary Mg. Basal diets had corn silage, corn grain, and soybean meal as predominant ingredients, along with alfalfa hay or silage, and orchardgrass silage in some studies. Original studies were designed to evaluate different feed byproducts, forages, and fat supplements, but the database allowed assessment of utilization of other mineral elements as well (Weiss and Wyatt, 2004). Supplemental dietary Mg came from MgO or magnesium sulfate, and total dietary

Mg ranged from 0.20 to 0.36% Mg, dry basis. Mean apparent digestibility of Mg was 18% with a range of -4 to 33%; this apparent mean digestibility was about 30% less than estimated by the NRC (2001) model. A very important factor in the analysis was the concentration of dietary K that averaged 1.60% (range = 1.07 to 2.65%). The authors stated that a main reason for the relatively low apparent Mg digestibility was the influence of high dietary K. At 1% dietary K, results agreed with NRC (2001); however, as dietary K concentration increased, the apparent digestibility of Mg declined 7.5-percentage units per each percentage increase in dietary K. To achieve the same amount of apparently digestible Mg at 1% K, cows had to consume an additional 18 g/day of Mg for every 1 percentage unit increase in dietary K above 1% to maintain the intake of apparently digestible Mg as consumed when fed a diet with 1% K.

Holtenius et al. (2008) studied the effects of 0.19, 0.28, and 0.37% dietary K factored with 0.19 and 0.43% dietary Mg on lactating cows fed a grass silage-based diet in Sweden. There was no effect of increasing dietary K (very low concentrations compared with those typically found in lactation rations in the TriState area and in the Weiss (2004) study) on apparent Mg absorption, urinary Mg absorption, or blood plasma Mg. Increasing dietary K or Mg did not improve milk yield. Research in the Netherlands explored effects of increasing dietary K (0.21, 0.48, and 0.75%, dry basis) on Mg absorption (Jittakhot et al., 2004). With high (~0.92% Mg of dietary DM) or low (~0.54% Mg) Mg absorption, urinary excretion of Mg was reduced with increasing dietary K and increased with increasing supplemental Mg intake. Their studies also demonstrated that increasing supplemental Mg (if from an available source) can effectively counteract the inhibitory effect of K on ruminal Mg absorption.

Work increasing dietary Ca prepartum (0.49, 0.93, and 1.36% of dietary DM) with 0.18% Mg across all treatments showed reduced apparent digestibility of Mg and daily urinary Mg excretion prepartum with 1.38% Ca (Kronqvist et al., 2011). Postpartum blood Mg was lowest at day 2, 4 and 7 for cows fed the 1.38% Ca diet prepartum. Varying prepartum dietary Ca did not affect Ca status, plasma Ca, parathyroid hormone, or marker of bone resorption (CTx) concentrations postpartum.

Vinegar Test of Reactivity of MgO Sources

Goff (2014) proposed a simple method to differentiate the reactivity and potential alkalizing properties of various MgO sources. Method is described as: *“If rumen alkalizing activity is valued, then the reactivity of MgO with acetic acid could give the nutritionist a simple test of the relative reactivity of a MgO being considered for use in lactating rations. Place 3 g of a MgO source in a container and slowly add 40 ml 5% acetic acid (white vinegar). Cap container and shake well for 15 seconds and let sit. Shake again at the 15-minute mark and check the pH at 30 minutes. Vinegar alone has a pH of 2.6 to 2.8. The best MgO sources will bring the pH up to 8.2; the worst to just 3.8 (Goff, 2014). pH is a log scale so this represents > 10,000-fold difference in the number of hydrogen ions neutralized. In an experiment with four cows with rumen fistulas, the solubility of MgO in vitro (tested in several ways) was found to parallel their solubility in the rumen and their urinary excretion (Schonewille et al., 1992).”*

This procedure and the alkalizing effect are an indication of the reactivity and solubilization of various MgO sources; it also could suggest that the Mg⁺² ion is released to a greater extent and might be available for ruminal absorption. However, this idea has not been evaluated in experiments with dairy cattle.

Nonetheless, it offers a way to differentiate the reactivity of various MgO sources that could be easily done with a calibrated pH meter or even pH paper strips.

Conclusion

When supplemental sources of Mg were tested in the laboratory for solubility, sometimes, but not always, improved lactational performance was detected. Unfortunately, determination and ranking of Mg sources by solubility as an indicator of apparent availability does not appear to be a very reliable test. The “vinegar test” proposed by Goff (2014) is a simple way to characterize the reactivity and alkalizing property of various MgO sources. It also could suggest that the Mg⁺² ion is released to a greater extent and might be available for ruminal absorption. Follow-up studies with animals are needed for proof of concept relative to apparent Mg availability using the vinegar test.

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