Magnesium absorption as influenced by the rumen passage kinetics in lactating dairy cows fed modified levels of fibre and protein

J.-L. Oberson1,2, S. Probst2 and P. Schlegel1†

1Agroscope, Ruminant Research Unit, 1725 Posieux, Switzerland; 2School of Agricultural, Forest and Food Sciences, Bern University of Applied Sciences, 3052 Zollikofen, Switzerland

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The potassium sensitive magnesium absorption through the rumen wall may be influenced by additional dietary properties, such as diet type, forage type or forage to concentrate ratio. These properties are likely associated to rumen passage kinetics modified by dietary fibre content. The study aimed to assess the effects of rumen passage kinetics on apparent Mg absorption and retention in lactating dairy cows fed modified levels of fibre. Six lactating Red-Holstein and Holstein cows, including four fitted with ruminal cannulas were randomly assigned to a 3 × 3 cross-over design. The experimental diets consisted of early harvested low NDF (341 g NDF/kg DM) and late harvested high NDF (572 g NDF/kg DM) grass silage (80% DM) and of concentrates (20% of DM). As the low-fibre diet was excessive in protein, a third high-fibre diet was formulated to be balanced in digestible protein with the low-fibre diet to avoid any eventual confounding effects of NDF and protein excess. All diets were formulated to contain iso-Ca, -P, -Mg, -K and -Na. Passage kinetics of solid and liquid phase of rumen digesta were evaluated using ruminal marker disappearance profiles. Cows fed the low-fibre diet had compared to the other diets, an up to 40% lower solid and 26% lower liquid phase volume of rumen digesta and a 10% numerically higher fractional rumen liquid passage rate. Rumen pH lost 0.6 units and Mg concentration in the rumen liquid phase tripled when cows were fed the low-fibre diet. Faecal Mg excretion was up to 14% higher in cows fed the low-fibre diet and Mg absorbability was 12% compared to up to 19% in other diets. Urinary Mg excretion in cows fed the low-fibre diet was half of the ones in the other treatments, but Mg retention was not affected. Dietary protein excess neither affected rumen passage kinetics nor Mg absorption and retention. Absorption of Mg was correlated with rumen liquid volume which both decreased with decreasing daily NDF intake (NDFi, 11.8 ± 2.4 l/kg NDFi). Consequently, daily Mg absorption decreased by 1.32 ± 0.28 g/kg decreasing NDFi. To conclude, in addition to the known antagonistic effect of dietary K, the present data indicate that Mg absorption was dependent from NDFi which modiﬁed rumen liquid volume, but was independent of dietary protein excess likely associated to low NDF herbages.

Keywords: mineral, herbage, rumen volume, rumen passage rate, NDF

Implications

Hypomagnesaemia remains an important topic in ruminant nutrition, especially in high yielding animals fed intensively produced herbage-based diets. Their potassium content is likely high and known to limit magnesium absorption. The provided data demonstrate that fibre intake is an additional antagonistic factor for magnesium absorption in dairy cows. Low-fibre intake reduces the rumen liquid volume, a possible reason for the observed limited magnesium absorption. Thus, in addition to dietary potassium, dietary fibre could be considered to formulate magnesium in dairy cattle diets.

Introduction

The risk for hypomagnesaemia occurrence, clinically diagnosed as grass tetany in lactating cows (Spilloma, 1930) is increased with dietary characteristics of intensively managed herbages, such as high concentrations in K and rapidly fermentable protein and low concentrations in Mg (Meschy, 2010). Increasing dietary K linearly decreases Mg absorbability in cows (Adediji and Suttle, 1999; Weiss, 2004; Schonewille et al., 2008), but the provided equations differ among authors resulting in relevant different Mg absorption rates for a given dietary K, especially when K is high. A K to diet type interaction (Suttle, 2010), a K to forage type interaction (Schonewille et al., 2008) and a contrasting forage to concentrate (F:C) ratio (Adediji and...
Suttle, 1999; Schonewille et al., 2002) were suggested as possible reasons for this lacking uniformity between equations. One common denominator of these suggestions is the modified rumen passage kinetics, namely rumen volumes (Vol) and passage rates (Kp). Modified diet type, forage type or F : C ratio influenced the solid phase Kp (Kps, Lopes et al., 2015), the solid phase Vol (VolS, Stensig and Robinson, 1997; Kuoppala et al., 2010), the liquid phase Kp (KpL, Stensig and Robinson, 1997; Schonewille et al., 2002) and the liquid phase Vol (VolL, Stensig and Robinson, 1997; Schonewille et al., 2002; Krämer et al., 2013). As the rumen epithelium is the main absorption site for Mg in ruminants (Tomas and Potter, 1976), it was hypothesized that the modified rumen passage kinetics (Kps, VolS, KpL and VolL) from herbage with modified fibre content would affect Mg absorption in lactating dairy cows. The protein excess in diets based on low fibre containing herbage may be associated to compromised Mg absorption as cows showed signs of tetany when fed intensively managed herbage (Kemp, 1960). As there is no clear evidence for a direct relation between protein excess and Mg absorption in cows (Weiss, 2004; Schonewille et al., 2008, Martens et al., 2018), especially under constant dietary K conditions, it was also hypothesized that Mg absorption would be independent from dietary protein excess associated to low-fibre herbage-based diets. If so, herbage fibre and its effect on rumen passage kinetics would be the explaining interaction for the various regressions associated to dietary K contents and this, independent from dietary protein.

Material and methods

Animals and experimental design
Six lactating Red Holstein and Holstein cows (697 ± 61 kg BW, 130 ± 60 days in lactation, 5 ± 2 lactations, mean ± SD), including four with ruminal cannulas used for rumen kinetics measures, were selected from the Agroscope dairy herd (Posieux, Switzerland) and randomly assigned to a 3 × 3 cross-over design with three treatment diets and three consecutive periods. One period consisted of 14 days (first period) or 21 days (subsequent periods) adaptation in a tiestall followed by 7 days of collection in metabolic tiestall allowing hourly feed intake recordings (Balreader, Mettler Toledo, Greifensee, Switzerland) and total quantitative collection of faeces, urine and milk.

Experimental diets
Herbages were moved on the 1st seasonal harvest when NDF concentration reached 350 (early harvest) and 550 g/kg DM (late harvest), respectively. The difference in NDF concentration aimed to be at least 200 g/kg DM to expect modified rumen passage kinetics (Colucci et al., 1990; Kuoppala et al., 2010). The two cuts were pre-wilted, pressed in square bales without chopping and without additive, wrapped with plastic for fermentation and stored inside until their use. The silages originated from the same plot (660 m a.s.l., 46°7712’N, 07°1055’E) which consisted of 76% and 87% of graminea (Lolium perenne) and of 24% and 13% of clover (Trifolium pratense and repens) of the fresh matter weight in the early and late harvest, respectively.

Three experimental diets were formulated by using the two silages and three concentrates. Diet Fibre− consisted of the early harvest and of concentrate Fibre− . Diet Fibre+ consisted of the late harvest and of concentrate Fibre+ to obtain potentially modified rumen passage kinetics with diet Fibre− . The third diet (Fibre+CP) consisted of Fibre− and of concentrate Fibre+CP to balance digestible protein concentration (PDIN) with diet Fibre− . The F : C ratio was set at 80 : 20 on DM basis. The relatively low proportion of concentrate is representative, under Swiss conditions, for dairy cows with such milk yields (Schmid and Lanz, 2013; Federal Office for Agriculture, 2017) and allowed to limit the dilution of NDF differences between Fibre− and Fibre+ or Fibre+CP considered as one major parameter to influence rumen Kp (National Research Council (NRC), 2001; Krizsan et al., 2010). Based on the analysed nutrients of silage and ingredients to be included in the concentrates, the experimental diets were formulated to reach or exceed nutrient requirements (650 kg BW, 22 kg/day DM intake (DMI) and 30 kg/day milk yield) according to the Swiss feeding recommendations (Agroscope, 2015), except in Mg set at a marginal level of 2.3 g/kg DM. Diets were balanced in Ca, P, Mg, K and Na concentrations and in PDIN between Fibre− and Fibre+CP by using the three pelleted concentrates, produced on the on-site feed mill according to the formulation shown in Supplementary Table S1.

Cows were fed the silage ad libitum during the adaptation periods and fed according to their previous 7 days mean DMI during the collection periods. The concentrate was offered in a separate container placed on top of silage and its amount was fixed per cow on a weekly basis. Cows were offered their diets at 0730 and 1700 h and had ad libitum access to water.

Marker preparation, labelling technique and data collection
Ytterbium-labelled fibre (Yb-NDF) and cobalt ethylenediaminetetraacetic acid (Co-EDTA) were used as marker for, respectively, the solid and liquid phase of rumen digesta. Fibre preparation and labelling technique (Supplementary Material S1) were adapted from Udén et al. (1980), Beauchemin and Buchanan-Smith (1989) and Ellis et al. (1994). Co-EDTA was prepared according to Udén et al. (1980).

Cows were weighted the day before and after each collection period. Intake of silage and concentrate was recorded as weight difference between offer and refusals on a daily basis. Water consumption was recorded daily during the collection period and after each rumen sampling. Samples of silages were collected daily, dried at 60°C for 24 h and pooled per collection period. Samples of concentrates were collected daily and pooled per collection period. Individual diet refusals were collected at 0700 h, prior feeding, dried at 60°C for 24 h and pooled per cow and collection period. At each milking (0600 and 1600 h), milk yields were determined and milk samples were taken. An aliquot of 0.7% (w/w) from each milking was pooled per cow and collection period and stored continuously at −20°C until analysis. Total faecal and
urine excretion were collected and weighted daily at 0900 and 0930 h, respectively, during the collection period. The faeces were collected in a container placed beneath the reproductive tie stall. The urine was collected via urinals attached around the vulva with Velcro straps glued to the shaved skin into 501 containers, whereas −2% of the 24 h collection was stabilized using 10% of sulfuric acid (2.5 mol/l). Daily homogenized aliquots of faeces (90 g, corresponding to −0.25% w/w) and urine (0.5% w/w) were pooled per cow and collection period and stored continuously at −20°C until analysis. Frozen faecal samples were lyophilized (Christ Delta 1to 24 LSD; Martin Christ, freeze-drying technology GmbH, Osterode am Harz, Germany) for 72 h. Silage, concentrate and faecal samples were milled in 1 mm screen (Brabender mill, Brabender, Duisburg, Germany) and stored in sealed jars at room temperature until analysis.

On day 3 of the collection period, shortly before the morning meal, 200 g of Yb-NDF was introduced into the dorsal rumen, via the cannula, using a plastic tube (68 × 70 cm). Subsequently, 50 g of Co-EDTA solubilized in 500 ml of water was introduced into the rumen via the cannula. Samples of rumen content were collected at 1, 2, 3, 5, 7, 10, 16 and 23 h after marker application. Sampling was timely enhanced compared to Schonewille et al. (2002) because of the expected slower Kp (NRC 2001). The rumen liquid phase was collected from the ventral rumen using a syringe equipped with a 40 cm long tube and a 2 mm pore size sieve. The pH was measured directly after collection ( Consort P902; Consort bvba, Turnhout, Belgium). Rumen liquid samples were centrifuged at room temperature for 1 min at 1000 g. The supernatant was centrifuged for 10 min at 12 000 g. The supernatant was stored continuously at −20°C until analysis. The rumen solid phase was collected per hand grabs taken in the dorsal, medial and ventral rumen. Each sample was rinsed six times under tap water using a sieve to remove eventual migrated residues around the vulva with Velcro straps glued to the shaved skin.

Calculation and statistical analysis
Data for rumen passage kinetic and mineral balances were analysed using R software (version 3.3.2; 2016-10-31). Cobalt concentrations in rumen liquid were logarithmically transformed and were subjected to a multiple linear regression using a mixed effect model (Bates et al., 2016). Differences among treatment intercepts and slopes were tested using the Type III Wald F tests (Fox and Weisberg, 2011) and treatment effects were assessed with the Posthoc interaction analysis PHIA (Rosario-Martinez, 2015) using Tukey’s contrasts. Calculations for Vol, and fractional and absolute Kp were conducted according to Schonewille et al. (1999) and are described along with Vol, and fractional and absolute Kp in the Supplementary Material S2. Absolute Kp and Kp treatment effects were assessed using Friedman χ2 test where animal (1 to 4) was set as block and diet (Fibre−, Fibre+CP and Fibre+) as factor.

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Data for mineral balances were averaged per cow and collection period defined as experimental unit, and were subjected to ANOVA (Fox and Weisberg, 2011) following the model

\[
y_{ijk} = \mu + \text{Diet}_i + \text{Period}_j + \text{Animal}_k + \varepsilon_{ijk},
\]

where \(y_{ijk}\) is the response, \(\mu\) the least-squares mean, \(\text{Diet}\), the fixed effect of the experimental diet (\(i = \text{Fibre}−, \text{Fibre}+\text{CP}, \text{Fibre}+)\), \(\text{Period}\), the fixed effect of the period (\(j = 1 \to 3\)), \(\text{Animal}_k\) the random effect of the animal (\(k = 1 \to 6\)) and \(\varepsilon_{ijk}\) the residual error.
the random error. Comparisons among means were calculated using the generalized linear hypothesis test GLHT (Hothorn et al., 2008) using Tukey’s contrasts. Differences were considered as significant when \( P \leq 0.05 \) and trends were noted at \( P < 0.10 \).

### Results

**Diet and production parameters**

Analysed and calculated nutrients in the consumed silages and concentrates are presented in Supplementary Table S2. The NDF concentrations in the two silages were sufficiently different (231 g NDF/kg DM) to expect modified rumen passage kinetics. Nutrient concentrations in the silages were according to expectations, except that K was slightly lower (2.2 g/kg DM) in the late silage than initially analysed for diet formulation. The nutrient contents and nutritive values of the effectively consumed experimental diets (Table 1) originate from the measured ingested quantities and the analysed contents of the sampled feedstuffs. The K and Mg concentrations were comparable among all consumed treatment diets, although they slightly differed by maximal 1.90 and 0.09 g/kg DM, respectively. The Fibre− and Fibre+CP diets were similar in PDIN as it only differed by 0.1 g/kg DM. The daily DMI of silage, concentrate and total diet did not differ (\( P > 0.10 \)) among treatments (Table 2). The concentrate intake represented 21.0%, 20.5% and 20.2% of the total intake (kg DM/day) in Fibre−, Fibre+CP and Fibre+, respectively. The VolL decreased by up to 26% (\( P < 0.05 \)) to lactating dairy cows compared to Fibre−, whereas the faecal NDF concentration (122 ± 4.5 g/kg) remained similar (\( P > 0.10 \)) among treatments. The urinary excretion differed (\( P < 0.001 \)) among treatments and the urinary urea concentration was higher (\( P < 0.001 \)) when Fibre+CP (18.2 g/l) was fed compared to Fibre− (11.1 g/l) and Fibre+ (7.75 g/l). The daily produced energy-corrected milk was 8.5% lower (\( P < 0.05 \)) in Fibre+ compared to Fibre+CP and Fibre−. Milk fat concentration was similar (\( P > 0.10 \)) among diets and milk protein concentration was higher (\( P < 0.01 \)) in cows fed Fibre− than Fibre+ and Fibre+CP. Milk urea concentration increased (\( P < 0.001 \)) by up to 83% in cows fed Fibre+CP compared to the other diets.

**Rumen volume, passage rate and mineral contents**

The VolL decreased by up to 26% (\( P < 0.05 \)) when cows were fed Fibre+−, but the fractional Kp was not affected (\( P > 0.10 \)) by the diets although it was numerically increased by 10% when cows were fed Fibre− (Table 3). The resulting absolute Kp was slower (\( P < 0.05 \)) in cows fed Fibre− than Fibre+CP and Fibre+. Similar to VolL, VolS decreased (\( P < 0.001 \)) by up to 40% when cows were fed Fibre−, but fractional Kp was not affected (\( P > 0.10 \)) by the diets. Finally, absolute Kps resulted in similar differences (\( P < 0.05 \)) among diets as observed for volume. The VolS and VolL were correlated with their respective absolute Kp (liquid: Pearson’s \( r = 0.68, \ df = 10 \), \( P = 0.02 \); solid: Pearson’s \( r = 0.88 \), \( P < 0.001 \)).

**Table 1 Nutrient composition of the consumed experimental diets fed to lactating dairy cows**

| Nutrients (g/kg DM) | Fibre− | Fibre+CP | Fibre+ |
|--------------------|--------|----------|--------|
| Organic matter     | 914    | 918      | 919    |
| CP                 | 210    | 209      | 142    |
| Crude fibre        | 149    | 265      | 266    |
| NDF                | 297    | 472      | 483    |
| ADF                | 163    | 288      | 291    |
| Crude fat          | 50.4   | 34.9     | 28.5   |
| Ash                | 85.8   | 81.9     | 81.5   |
| Ca                 | 6.61   | 6.63     | 6.73   |
| P                  | 3.82   | 4.20     | 4.07   |
| Mg                 | 2.32   | 2.34     | 2.41   |
| K                  | 27.6   | 26.3     | 25.7   |
| Na                 | 1.70   | 1.53     | 1.56   |
| NEt (MJ)           | 7.32   | 5.66     | 5.70   |
| PDIE               | 92     | 103      | 94     |
| PDIN               | 132    | 132      | 94     |

**Table 2 Dietary component intake and product excretion in lactating cows (\( h = 6 \) per treatment) fed the experimental diets**

| Parameters                  | Fibre− | Fibre+CP | Fibre+ | SEM | \( P \)-value |
|-----------------------------|--------|----------|--------|-----|---------------|
| Intake (kg DM/day)          |        |          |        |     |               |
| Grass silage                | 15.2   | 14.7     | 14.3   | 0.43 | 0.23          |
| Concentrate                 | 3.98   | 3.80     | 3.61   | 0.125| 0.14          |
| Total                       | 19.2   | 18.4     | 17.9   | 0.52 | 0.13          |
| Organic matter              | 17.5   | 17.1     | 16.5   | 0.55 | 0.43          |
| CP                           | 4.04a  | 3.89a    | 2.56b  | 0.198| < 0.001       |
| NDF                         | 5.70b  | 8.78b    | 8.67a  | 0.434| < 0.001       |
| Water (l/day)               | 90.4a  | 97.8a    | 82.4b  | 5.34 | 0.004         |
| Excretion (kg/day)          |        |          |        |     |               |
| Faeces (DM)                 | 4.21b  | 4.96a    | 5.07a  | 0.197| 0.04          |
| Urine                       | 36.2a  | 31.6b    | 24.9c  | 1.39 | < 0.001       |
| Energy-corrected milk       | 27.2a  | 26.9a    | 24.8b  | 1.12 | 0.02          |
| Milk fat (%)                | 4.24   | 4.32     | 4.39   | 0.123| 0.74          |
| Milk protein (%)            | 3.37a  | 3.25b    | 3.23b  | 0.062| 0.002         |
| Milk urea (mg/dl)           | 26.7b  | 43.1a    | 23.5b  | 2.26 | < 0.001       |
| Digestibility (% of intake) |        |          |        |     |               |
| Organic matter              | 79.2a  | 74.5b    | 73.4b  | 0.72 | < 0.001       |
| CP                           | 67.8b  | 75.6a    | 64.9b  | 1.24 | < 0.001       |
| NDF                         | 79.0a  | 72.4a    | 70.0b  | 1.05 | < 0.001       |

\( \text{NEt = net energy for lactation.} \)

Protein digestible in the small intestine (Vérite et al., 1979) calculated from its non-degradable N and degradable N contents (PDIN) or its rumen available energy content (PDIE).

Treatments consisted of 80% (DM basis) of early (Fibre−) or late (Fibre+CP, Fibre+) harvested grass silage and 20% of their respective concentrate.

Treatments consisted of 80% (DM basis) of early (Fibre−) or late (Fibre+CP, Fibre+) harvested grass silage and 20% of their respective concentrate.
Table 3 pH, mineral concentrations and passage kinetics of the liquid and solid phase of rumen digesta in lactating cows (fistulated; n = 4 per treatment) fed the experimental diets

| Parameters                          | Fibre− | Fibre+CP | Fibre+ | SEM  | P-value |
|-------------------------------------|--------|----------|--------|------|---------|
| Liquid phase volume (l)             | 116b   | 146a     | 156a   | 7.2  | 0.02    |
| Passage rate                        |        |          |        |      |         |
| Fractional %/h                      | 17.5   | 16.0     | 15.9   | 0.65 | 0.11    |
| Absolute (l/h)                      | 19.4b  | 23.3a    | 24.7a  | 1.10 | 0.04    |
| Solid phase volume (kg NDF)         | 3.69b  | 5.72a    | 6.20a  | 0.790| <0.001  |
| Passage rate                        |        |          |        |      |         |
| Fractional %/h                      | 1.50   | 1.57     | 1.46   | 0.030| 0.32    |
| Absolute (g/h)                      | 55.0b  | 88.0a    | 87.1a  | 0.33 | 0.05    |
| Rumen pH                            | 5.84b  | 6.50a    | 6.46a  | 0.034| <0.001  |
| Rumen liquid phase                  |        |          |        |      |         |
| K (mmol/l)                          | 34.8   | 32.5     | 28.9   | 0.88 | 0.07    |
| Mg (mmol/l)                         | 3.06a  | 0.60b    | 0.93b  | 0.021| <0.001  |
| Na (mmol/l)                         | 78.9b  | 90.1a    | 91.3a  | 1.89 | 0.01    |
| Rumen solid phase                   |        |          |        |      |         |
| K (g/kg DM)                         | 0.78   | 1.14     | 1.45   | 0.181| 0.60    |
| Mg (g/kg DM)                        | 0.72   | 0.73     | 0.68   | 0.032| 0.89    |

a,bValues within a row with different superscripts differ significantly at P < 0.05.

1Treatments consisted of 80% (DM basis) of early (Fibre−) or late (Fibre+CP; Fibre+) harvested grass silage and 20% of their respective concentrate.

2The model included a negative quadratic effect of time. Values represent the maximal slopes.

3Values represent the maximal slopes. P-value given by non-parametric Friedman test.

Nutrients digestibility and mineral balance

Diet Fibre− resulted in higher organic matter (OM) and NDF digestibility (P < 0.001; Table 2) and Fibre+CP resulted in higher CP digestibility (P < 0.001). Daily intake of Ca (124 ± 4.0 g/day), P (74.8 ± 2.5 g/day) and Mg were similar (P > 0.10) among diets, but daily intake of K (P < 0.01) and Na (P < 0.001) were slightly higher when Fibre− was fed compared to Fibre+CP and Fibre+. Faecal Mg excretion was up to 4.2 g/day higher (P < 0.01) in cows fed Fibre− than Fibre+CP and Fibre+. The Mg retention was 20% lower (P < 0.001) among treatments. The Mg retention was higher (P < 0.001) in cows fed Fibre− than Fibre+CP and Fibre+. The Mg retention was compared to Fibre− compared to Fibre+.

Although, the amount of daily urine excretion was higher (P < 0.001) in cows fed Fibre−, the urinary Mg concentration was half and one-third as high as in cows fed Fibre+CP and Fibre+, respectively (2.07, 4.38 and 5.88 mmol/l, respectively, P < 0.001), resulting in 49% lower (P < 0.001) urinary Mg excretion in cows fed Fibre− compared to Fibre+CP and Fibre+. Milk Mg excretion from cows fed Fibre+ was lower (P < 0.05) than Fibre+CP although milk Mg concentration was similar (P > 0.10) among treatments. The Mg retention was positive (P < 0.05) and similar (P > 0.10) among diets. Blood plasma Mg tended (P < 0.10) to be lower in cows fed Fibre− (0.87 mmol/l) than Fibre+ (0.97 mmol/l) and Fibre+CP (1.02 mmol/l). Although K intake was higher (P < 0.01) in cows fed Fibre− compared to Fibre+, their faecal K excretion was lower (P < 0.05) than those fed Fibre+CP diet. Apparent K absorbability was relatively high (91% to 94%) and higher (P < 0.001) in cows fed Fibre− than Fibre+CP and Fibre+. Urinary and milk K excretions were also higher (P < 0.001 and P < 0.05, respectively) in cows fed Fibre− than Fibre+CP and Fibre+. The Na absorbability was higher (P < 0.001) for Fibre− (85.4%) than Fibre+CP (76.3%) and Fibre+ (72.5%) and the Na retention was 49% lower (P < 0.001).
was also negative and comparable (data not shown; \( P > 0.10 \)) among treatments.

**Discussion**

**Rumen passage rate and volume**

The \( K_{ps} \) was comparable with the \( K_p \) of cell walls estimated by rumen evacuation (Huhtanen et al., 2007) and with the model correcting for forage type (Krizsan et al., 2010), but less with the model using DMI as percentage of BW, forage NDF and F : C ratio (NRC, 2001). The diet independent fractional \( K_{ps} \) support the findings of Kuoppala et al. (2010) who observed that \( K_{ps} \) of indigestible NDF was not affected between early and late harvested grass silage. With comparable dietary NDF, \( \text{Vol}_s \) from Fibre+CP and Fibre+ were similar to the NDF pool estimated by rumen evacuation method (Kuoppala et al., 2010). Although Krämer et al. (2013) observed similar \( \text{Vol}_s \) between maize and grass silage-based diets, the difference in \( \text{Vol}_s \) between Fibre− and Fibre+CP or Fibre+ are concordant with Stensig and Robinson (1997) and Kuoppala et al. (2010) who observed increasing pools of DM, OM, NDF and indigestible NDF, by feeding grass silages with increasing fibre content. Thus, the limited NDF intake (\( \text{NDF}_i \)) reduces the physical fill of the rumen, but not the \( K_{ps} \) (Kuoppala et al., 2010). The fractional \( K_p \) was within the range issued from lactating cows fed grass silage based diets (Krämer et al., 2013) and presenting similar DMI (Colucci et al., 1990). The constant F : C ratio and the similar DMI between treatment diets, known to influence \( K_p \) (Stensig and Robinson, 1997; Schonewille et al., 2002), allow the numerical differences in \( K_p \) to be attributed to the silages mainly differing in their NDF concentration. Nevertheless, the daily water consumption might have contributed to explain part of the \( K_p \) variability because they were correlated (Pearson’s \( r = 0.64 \), \( df = 10 \), \( P = 0.03 \)). The \( \text{Vol}_l \) was higher than found in studies with comparable milk yield or similar forages (Kuoppala et al., 2010; Krämer et al., 2013), which can be explained by the up to 200 kg heavier cows and the higher F : C ratio in the present study. Reported as % of BW, \( \text{Vol}_l \) was 16% to 21% of BW in the present study and 12% to 18% of BW according to Krämer et al. (2013). The dietary NDF concentration was however higher (484 v. 378 g/kg DM) in the present study than in Krämer et al. (2013). Reported per kilogram BW and at similar dietary NDF, the present \( \text{Vol}_l \) are thus consistent with other studies. Increasing the F : C ratio (Colucci et al., 1990; Stensig and Robinson, 1997) or feeding a grass compared to a maize silage-based diet (Krämer et al., 2013) increased the \( \text{Vol}_l \). Here, the constant F : C ratio and the similar DMI between treatments allow the observed differences in \( \text{Vol}_l \) to be attributed to the silages mainly differing in their NDF concentration. Furthermore, \( \text{Vol}_l \) was not related to the daily water intake (Pearson’s \( r = -0.12 \), \( df = 10 \), \( P = 0.72 \)), but was highly correlated with the daily \( \text{NDF}_i \) (Pearson’s \( r = 0.85 \), \( df = 10 \), \( P < 0.001 \)), which support previous data (Stensig and Robinson, 1997; Krämer et al., 2013). Adjusted by cow, \( \text{Vol}_l \) increased by 11.8 ± 2.4 l per kg daily \( \text{NDF}_i \) (\( R^2 \) marginal = 0.70, \( P < 0.001 \), Figure 1). Absolute \( K_p \) was affected by dietary

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**Table 4 Balance of Mg and K in lactating cows (n = 6 per treatment) fed the experimental diets**

| Parameters                 | Fibre− | Fibre+CP | Fibre+ | SEM | \( P \)-value |
|----------------------------|--------|----------|--------|-----|--------------|
| Magnesium (g/day)          |        |          |        |     |              |
| Intake                     | 44.6   | 43.0     | 43.2   | 1.21| 0.60         |
| Faecal excretion           | 39.2a  | 35.8ab   | 35.0b  | 1.28| 0.007        |
| Apparent absorption        | 5.24   | 7.60     | 8.30   | 0.584| 0.12         |
| % of intake                | 11.9   | 17.5     | 18.9   | 1.37| 0.08         |
| Urinary excretion          | 1.74b  | 3.31a    | 3.47a  | 0.249| <0.001       |
| Milk excretion             | 2.85ab | 2.94a    | 2.53b  | 0.140| 0.02         |
| Retention                  | 0.59   | 1.33     | 2.26   | 0.388| 0.56         |
| % of intake                | 1.26   | 3.04     | 4.86   | 0.924| 0.61         |
| Potassium (g/day)          |        |          |        |     |              |
| Intake                     | 536a   | 487ab    | 461b   | 16.0| 0.01         |
| Faecal excretion           | 32.6b  | 47.0a    | 40.6ab | 3.67| 0.02         |
| Apparent absorption        | 500a   | 439b     | 421b   | 13.5| <0.001       |
| % of intake                | 94.0a  | 90.6b    | 91.4b  | 0.62| <0.001       |
| Urinary excretion          | 477a   | 416b     | 403b   | 13.0| <0.001       |
| Milk excretion             | 43.3a  | 41.2ab   | 37.1b  | 2.64| 0.01         |
| Retention                  | −20.9  | −17.9    | −19.4  | 2.87| 0.95         |
| % of intake                | −3.90  | −3.57    | −4.57  | 0.915| 0.88         |
| Magnesium per K            |        |          |        |     |              |
| Apparent absorption (mg/g) | 10.5b  | 17.4a    | 19.5a  | 1.45| 0.01         |

\( ^a,b \)Values within a row with different superscripts differ significantly at \( P < 0.05 \).

\( ^1 \)Treatments consisted of 80% (DM basis) of early (Fibre−) or late (Fibre+CP; Fibre+) harvested grass silage and 20% of their respective concentrate.
treatments, because it was correlated with VolL but not with fractional KpL. Absolute KpL may thus be less appropriate than VolL and fractional KpL to evaluate rumen kinetics. Finally, the rumen kinetics were considered as sufficiently modified between diet Fibre− and the other diets to study the Mg balance according to the defined hypothesis.

Mineral balance, rumen mineral contents and their relation to rumen passage kinetics

According to the regression slopes to estimate Mg absorbability related to dietary K (Adediji and Suttle, 1999; Weiss, 2004; Schonewille et al., 2008; Meschy, 2010), the 27 g K/kg DM from the present study, result to a Mg absorbability between 12% and 22%. The lower range is attributed to Adediji and Suttle (1999) based on diets including concentrates and to Weiss (2004) using maize silage-based diets. The higher range is attributed to Adediji and Suttle (1999) based on diets without concentrates and to Schonewille et al. (2008) using herbage-based diets without concentrates. This wide range of Mg absorbability was covered by the cows fed the experimental diets formulated to be iso-K. The lower than initially analysed K concentration in the consumed late harvested silage and its numerically lower intake explain the slight lower dietary K concentration (1.9 g/kg DM) and the reduced daily K intake of cows fed Fibre− than Fibre+. This difference leads, according to the existing regressions for Mg absorbability (Adediji and Suttle, 1999; Weiss, 2004; Schonewille et al., 2008; Meschy, 2010) and Mg absorption (Schonewille et al., 2008) to a theoretical modification for diet Fibre− of, respectively, −0.6% to −1.0% units and +0.11 g/day. Absorption is improved as the proposed equation includes Mg intake. The potential impact on Mg absorbability of the slight difference in K content and intake between the experimental diets can thus be considered as irrelevant in relation to the modified 7% units between Fibre− and Fibre+. In addition, it has been suggested that the depressing effect of dietary K on Mg absorption may be attenuated with high dietary K levels (Martens et al., 2018) such as contained in the present study. The impaired Mg absorption in cows fed diet Fibre− lead to a compensated lower urinary Mg excretion with a concentration below the considered as normal physiological range of 5 to 10 mmol/l (Meschy, 2010). This homeostatic counter regulation capacity started to be limited as plasma Mg level tended to be lower in cows fed Fibre−.

Magnesium absorption was positively correlated with VolL (Pearson’s r = 0.79, df = 10, P = 0.002), but not with fractional KpL (Pearson’s r = −0.45, df = 10, P = 0.14). Furthermore, VolL (P = 0.001), rather than KpL (P = 0.82), pH (P = 0.92) or K in the rumen liquid phase (P = 0.56) contributed to the explained variance in Mg absorption. Finally, VolL was not correlated with K (Pearson’s r = −0.26, P = 0.35).
Magnesium absorption and rumen passage kinetics

when changing, for example, from a conserved maize-herbage-based diet to pasture in springtime, an eventual hypomagnesaemia is not to be attributed to dietary protein excess.

Conclusion
As NDFi was, independent from dietary K and protein, linearly related with the rumen liquid volume and with Mg absorption, the NDFi may be in addition to the known antagonistic effect of dietary K, the explanatory variable for modified Mg absorbability, so far, hypothesized as influence of diet type, forage type or contrasting F:C ratio. Further research is required to possibly implement dietary fibre into dietary K to Mg absorbability regressions.

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Declaration of interest
The authors declared no conflicts of interest.

Ethics statement
The experiment was approved by the Office for Food Safety and Veterinary Affairs (Authorization 2015_01_FR) and all procedures were conducted in accordance with the Ordinance on Animal protection and the Ordinance on Animal Experimentation.

Software and data repository resources
None.

Supplementary material
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