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Magnesium metabolism in sheep subjected to sodium or water loading

C. WACHIRAPAKORN1, A.R. SYKES AND A.B. ROBSON2

Animal and Veterinary Sciences Group, Lincoln University, Canterbury, New Zealand.

ABSTRACT

Six rumen-cannulated ewes, averaging 48±3.7 kg liveweight, were used to study the effects of sodium (Na) or water loading on magnesium (Mg) metabolism in sheep fed on a high potassium (K) diet (40 g K/kgDM). Animals were randomly allotted to receive one of three treatments: 1) high Na diet (15 g Na/d) (HNa), 2) low Na diet (1.3 g Na/d) + infusion of water (approx. 3 l/d) equivalent to the water intake of the HNa treatment (LNaHW) and 3) low Na diet (LNa) alone. A nutritional balance and renal clearance studies were used in two 3x3 Latin square change-over designs.

Apparent absorption of Mg was not different (p>0.05) between treatments, averaging 0.27±0.03 g/d, inspite of an increase in the rumen Na:K ratio from 0.7:1 to 1:1 with increasing Na intake. Urinary Mg excretion was significantly higher (p<0.01) on high Na intake (0.38±0.02 g/d), while water loading had no effect (0.30±0.02 g/d) when compared with the low Na diet (0.27±0.02 g/d).

Increasing Na intake, but not water loading, resulted in an increase in glomerular filtration rate (GFR) from 58.2±2.41 to 64.5±1.27 ml/min and, as a result total excretion (TE) and fractional excretion (FE) of Mg were increased from 12.9±1.10 to 17.4±1.83 mg/h and 21.3±2.26 to 26.4±2.04%, respectively.

Increasing Na intake to reduce the K:Na ratio in the rumen has been advocated to improve Mg absorption on tetany prone pasture. These data suggest that Na supplementation may, in fact, exacerbate an existing hypomagnesaemia.

Keywords: Sodium; potassium; magnesium; absorption; excretion; sheep.

INTRODUCTION

Spring pastures commonly contain high potassium (K) and low sodium (Na) concentrations (Reay and Grace, 1982), that may lower magnesium (Mg) absorption in grazing animals. Earlier studies (Martens et al., 1987; Johnson and Powley, 1990; Khorasani and Armstrong, 1990) have shown the importance of increasing the ratio of intake of Na to K for Mg absorption. Martens et al. (1987) advocated Na supplementation to improve Mg homeostasis. However, the addition of high levels of Na and K salts to ruminant diets can result in a marked increase in water consumption (Moseley and Jones, 1974).

Both water loading (Suttle and Field, 1966, 1967) and increase in water intake as a result of intraruminal infusion of NaCl (Godwin and Williams, 1986) have been observed to increase the urinary Mg excretion by up to 30%. This may be the result of an increase in glomerular filtration rate (GFR) which then could influence the loss of Mg from the extracellular Mg pool.

This experiment was designed to attempt to separate the effects of Na and water intakes on Mg metabolism and urinary losses.

MATERIALS AND METHODS

Experimental procedures

Animals and treatments

Six rumen-cannulated ewes, weighing c. 48±3.7 kg, were used. They were offered a diet which consisted of 600 g of chaffed meadow hay and 320 g of mixed pelleted concentrate at maintenance levels (50 g/d/kgW.75) (ARC, 1980). The diet provided 1.3 g Na, 1.5 g Mg and 15 g K per day.

Animals were placed on one of three treatments, low Na (1.3 g Na/d) (LNa), high Na (15 g Na/d) (HNa) and low Na + extra water (LNaHW) to match the same total water consumption as the HNa sheep. The K concentration of the diets was 40 g K/kgDM, a relatively high concentration but one which is representative of K levels in spring pastures in New Zealand. To achieve the required Na and K intake, NaCl and KCl were dissolved in (500 ml) distilled water and the solutions or water (LNaHW - approx. 3L/d) were infused into the rumen using a multi-channel peristaltic pump.

Two other sheep were used as a control group (CL) and were treated in all respects like the experimental sheep except that no KCl or NaCl infusion was used.

Balance study period

Animals were housed indoors in metabolism crates which permitted total collection and separation of faeces and urine. Intake of water was measured daily. Animals were offered the daily diet at 2-h intervals using automatic continuous feeders. They were accustomed to the diet and
brates for 14-d before the commencement of the experiment which consisted of a 14-d collection period and a 5-d transition period. The 14-d collection period included a 5-d preliminary period, a 2-d renal clearance study period and a 3-d recovery from bladder catheterisation followed by a 4-d balance study period. The collection and preparation of faeces, urine and digesta samples was discussed by Dalley et al. (1992).

Blood samples were withdrawn by jugular venipuncture after rumen fluid sampling was performed. Plasma was obtained by centrifugation at 1000 g for 15 min and then stored at -20°C until analysed.

Renal clearance study period

After the 5-d preliminary period, bladder catheters were inserted. Urine sampling commenced 12 hours later during 6-h intervals for 48 h.

Blood samples were taken at approximately the same time as urine collection.

After completion of each run, catheters were removed and the animal treated with 5 ml of Penstrep LA and allowed 3 d to recover before the next study period.

Chemical analyses

Creatinine in urine and plasma was measured by standard colorimetric techniques (Picric acid method) using a Multistat III Plus Centrifugal Analyser (Instrumentation Laboratory Inc., Mass., USA).

Feeds and faeces were wet ashed according to the procedure of Thompson and Blanchflower (1971). Magnesium was determined by atomic absorption spectrophotometry and potassium and Na by flame emission spectrophotometry.

Mineral clearances and fractional excretion were calculated according to Garry et al. (1990). Glomerular filtration (GFR) rate or endogenous creatinine clearance was calculated as:

\[
GFR = \frac{U_{cr} \times U_{vol}}{P_{cr} \times kgLW}
\]

where \(U_{cr}\) and \(P_{cr}\) represent urine and plasma creatinine (mg/l), respectively, \(U_{vol}\) urine flow rate (ml/min) and \(kgLW = \) liveweight (kg).

Total excretion (TE - g/h or mg/h) was calculated for an electrolyte \(Y\), as:

\[
TE_Y = U_{vol} \times U_Y
\]

where \(U_{vol}\) represents urine flow rate (l/h) and \(U_Y\) the concentration of \(Y\) in urine (g/l or mg/l).

Fractional excretion of an electrolyte \(Y\) (FE\(Y\)) was expressed as a percentage, without units as:

\[
FE_Y = \left(\frac{U_Y}{P_Y}\right) \times 100
\]

where \(U_Y\) and \(P_Y\) represent urine and plasma concentra-

tions of creatinine (mg/l), respectively, and the \(U_{cr}\) and \(P_{cr}\) = concentrations of \(Y\) in urine and plasma (g/l or mg/l).

Statistical analysis

Data were subjected to analysis of variance using the general linear model procedure (Proc GLM) (SAS, 1989) according to the extra-period Latin square change-over design (Ratkowsky et al., 1993). Mean comparisons were made using predicted difference (PDFF) option of least-squares means. Significance was accepted at 0.05 level of probability.

RESULTS

Dry matter intake averaged 831±11.0 g/d and was not affected by treatment.

Mean digestibilities of DM and OM, water intake and urinary excretion are given in Table 1. Mean DM intake averaged 831±11.0 g/d. DM and OM digestibilities for the HNa treatment were lower (p<0.05) than those for the LNa treatment, but did not differ (p>0.05) from the LNaHW treatment. Increasing Na intake (HNa treatment) increased (p<0.01) water consumption and urine excretion.

Mineral metabolism

The metabolism of Mg, is presented in Table 2. Urinary Mg excretion was increased (p<0.01) from 0.27±0.02 to 0.37±0.02 g/d by increasing dietary Na but not significantly (p>0.05) by water loading. Apparent Mg absorption was not different (p>0.05) between treatments, but was lower than in the control group. As a result, Mg retention in the HNa sheep was more negative than that in the LNaHW and the LNa treatments.

TABLE 1: Digestibilities of DM and OM, water consumption and urine excretion in sheep given extra Na or water (mean±sem, n=8).

<table>
<thead>
<tr>
<th></th>
<th>HNa(^1)</th>
<th>LNaHW</th>
<th>LNa</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM digestibility, %</td>
<td>65.0 ± 0.67</td>
<td>66.1 ± 0.60</td>
<td>67.0 ± 0.69</td>
<td>66.9 ± 1.02</td>
</tr>
<tr>
<td>OM digestibility, %</td>
<td>66.1 ± 0.71</td>
<td>66.9 ± 0.63</td>
<td>68.2 ± 0.75</td>
<td>67.9 ± 1.03</td>
</tr>
<tr>
<td>Water intake, l/d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>voluntary</td>
<td>2.98</td>
<td>1.17</td>
<td>1.87</td>
<td>2.79</td>
</tr>
<tr>
<td>infusion</td>
<td>0.50</td>
<td>2.64</td>
<td>0.46</td>
<td>–</td>
</tr>
<tr>
<td>total</td>
<td>3.46 ± 0.27</td>
<td>3.97 ± 0.50</td>
<td>2.33 ± 0.24</td>
<td>2.79 ± 0.21</td>
</tr>
<tr>
<td>Urine excretion, l/d</td>
<td>2.62 ± 0.23</td>
<td>3.11 ± 0.49</td>
<td>1.61 ± 0.23</td>
<td>1.94 ± 0.18</td>
</tr>
</tbody>
</table>

Mineral clearances and fractional excretion were calculated according to Garry et al. (1990). Glomerular filtration (GFR) rate or endogenous creatinine clearance was calculated as:

\[
GFR = \frac{U_{cr} \times U_{vol}}{P_{cr} \times kgLW}
\]

where \(U_{cr}\) and \(P_{cr}\) represent urine and plasma creatinine (mg/l), respectively, \(U_{vol}\) urine flow rate (ml/min) and \(kgLW = \) liveweight (kg).

Total excretion (TE - g/h or mg/h) was calculated for an electrolyte \(Y\), as:

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TE_Y = U_{vol} \times U_Y
\]

where \(U_{vol}\) represents urine flow rate (l/h) and \(U_Y\) the concentration of \(Y\) in urine (g/l or mg/l).

Fractional excretion of an electrolyte \(Y\) (FE\(Y\)) was expressed as a percentage, without units as:

\[
FE_Y = \left(\frac{U_Y}{P_Y}\right) \times 100
\]

where \(U_Y\) and \(P_Y\) represent urine and plasma concentra-

tions of creatinine (mg/l), respectively, and the \(U_{cr}\) and \(P_{cr}\) = concentrations of \(Y\) in urine and plasma (g/l or mg/l).

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where \(U_{vol}\) represents urine flow rate (l/h) and \(U_Y\) the concentration of \(Y\) in urine (g/l or mg/l).

Fractional excretion of an electrolyte \(Y\) (FE\(Y\)) was expressed as a percentage, without units as:

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\]

where \(U_Y\) and \(P_Y\) represent urine and plasma concentra-

tions of creatinine (mg/l), respectively, and the \(U_{cr}\) and \(P_{cr}\) = concentrations of \(Y\) in urine and plasma (g/l or mg/l).

Statistical analysis

Data were subjected to analysis of variance using the general linear model procedure (Proc GLM) (SAS, 1989) according to the extra-period Latin square change-over design (Ratkowsky et al., 1993). Mean comparisons were made using predicted difference (PDFF) option of least-squares means. Significance was accepted at 0.05 level of probability.
TABLE 2: Magnesium metabolism in sheep given extra Na or water (mean ± sem, n=8).

<table>
<thead>
<tr>
<th></th>
<th>HNa&lt;sup&gt;1&lt;/sup&gt;</th>
<th>LNaHW</th>
<th>LNa</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral intake, g/d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>1.39 ± 0.01</td>
<td>1.39 ± 0.01</td>
<td>1.39 ± 0.01</td>
<td>1.39 ± 0.01</td>
</tr>
<tr>
<td>Na</td>
<td>12.44 ± 0.27</td>
<td>1.25 ± 0.04</td>
<td>1.42 ± 0.07</td>
<td>1.25 ± 0.04</td>
</tr>
<tr>
<td>K</td>
<td>33.8 ± 0.86</td>
<td>36.0 ± 0.41</td>
<td>34.7 ± 0.82</td>
<td>17.9 ± 0.33</td>
</tr>
<tr>
<td>Mg metabolism, g/d</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faecal output</td>
<td>1.11 ± 0.03</td>
<td>1.14 ± 0.03</td>
<td>1.11 ± 0.03</td>
<td>0.90 ± 0.02</td>
</tr>
<tr>
<td>Urinary excretion</td>
<td>0.38 ± 0.02</td>
<td>0.30 ± 0.02</td>
<td>0.27 ± 0.02</td>
<td>0.41 ± 0.02</td>
</tr>
<tr>
<td>Apparent absorption</td>
<td>0.28 ± 0.03</td>
<td>0.25 ± 0.02</td>
<td>0.28 ± 0.03</td>
<td>0.49 ± 0.02</td>
</tr>
<tr>
<td>Retention</td>
<td>-0.08 ± 0.04</td>
<td>-0.05 ± 0.03</td>
<td>0.01 ± 0.02</td>
<td>0.09 ± 0.02</td>
</tr>
</tbody>
</table>

TABLE 3: Concentrations of Mg, Na, K in plasma and rumen fluid, rumen Na:K ratio and rumen digesta pH of sheep given extra Na or water (mean ± sem, n=8).

<table>
<thead>
<tr>
<th></th>
<th>HNa&lt;sup&gt;1&lt;/sup&gt;</th>
<th>LNaHW</th>
<th>LNa</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma, mmol/l</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>0.94 ± 0.12</td>
<td>1.00 ± 0.13</td>
<td>0.93 ± 0.06</td>
<td>1.07 ± 0.10</td>
</tr>
<tr>
<td>Na</td>
<td>144.0 ± 9.81</td>
<td>134.1 ± 7.70</td>
<td>141.4 ± 10.1</td>
<td>137.1 ± 7.47</td>
</tr>
<tr>
<td>K</td>
<td>5.78 ± 0.33</td>
<td>5.62 ± 0.23</td>
<td>5.85 ± 0.43</td>
<td>5.70 ± 0.27</td>
</tr>
<tr>
<td>Rumen fluid, mmol/l</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>2.41 ± 0.40</td>
<td>1.50 ± 0.25</td>
<td>2.02 ± 0.48</td>
<td>1.11 ± 0.18</td>
</tr>
<tr>
<td>Na</td>
<td>81.0 ± 10.1</td>
<td>57.1 ± 9.14</td>
<td>53.9 ± 7.65</td>
<td>81.2 ± 10.9</td>
</tr>
<tr>
<td>K</td>
<td>81.3 ± 7.28</td>
<td>75.9 ± 4.53</td>
<td>80.8 ± 5.52</td>
<td>46.6 ± 4.41</td>
</tr>
<tr>
<td>Rumen Na:K ratio</td>
<td>1.0:1</td>
<td>0.8:1</td>
<td>0.7:1</td>
<td>1.7:1</td>
</tr>
<tr>
<td>Rumen digesta pH</td>
<td>6.24 ± 0.07</td>
<td>6.29 ± 0.04</td>
<td>6.28 ± 0.05</td>
<td>6.38 ± 0.05</td>
</tr>
</tbody>
</table>

TABLE 4: Means of GFR and total excretion and fractional excretion of electrolytes in sheep given extra Na or water (mean ± sem, n=8).

<table>
<thead>
<tr>
<th></th>
<th>HNa&lt;sup&gt;1&lt;/sup&gt;</th>
<th>LNaHW</th>
<th>LNa</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine pH</td>
<td>7.60 ± 0.09</td>
<td>7.99 ± 0.05</td>
<td>8.14 ± 0.07</td>
<td>8.12 ± 0.88</td>
</tr>
<tr>
<td>Urine excretion rate, ml/min</td>
<td>1.95 ± 0.15</td>
<td>1.64 ± 0.10</td>
<td>1.06 ± 0.06</td>
<td>1.28 ± 0.22</td>
</tr>
<tr>
<td>GFR, ml/min</td>
<td>64.2 ± 2.70</td>
<td>52.5 ± 1.90</td>
<td>58.1 ± 2.09</td>
<td>50.9 ± 2.80</td>
</tr>
<tr>
<td>GFR, ml/min/kgLW</td>
<td>1.36 ± 0.05</td>
<td>1.09 ± 0.04</td>
<td>1.23 ± 0.05</td>
<td>1.02 ± 0.75</td>
</tr>
<tr>
<td>TE&lt;sub&gt;Mg&lt;/sub&gt;, g/h</td>
<td>0.59 ± 0.04</td>
<td>0.05 ± 0.01</td>
<td>0.06 ± 0.01</td>
<td>0.04 ± 0.06</td>
</tr>
<tr>
<td>TE&lt;sub&gt;Na&lt;/sub&gt;, g/h</td>
<td>1.26 ± 0.04</td>
<td>1.32 ± 0.02</td>
<td>1.18 ± 0.07</td>
<td>0.59 ± 0.09</td>
</tr>
<tr>
<td>TE&lt;sub&gt;Mg&lt;/sub&gt;, mg/h</td>
<td>17.4 ± 1.83</td>
<td>13.2 ± 0.96</td>
<td>12.9 ± 1.10</td>
<td>17.7 ± 2.50</td>
</tr>
<tr>
<td>FE&lt;sub&gt;Mg&lt;/sub&gt; %</td>
<td>4.91 ± 0.44</td>
<td>0.50 ± 0.08</td>
<td>0.57 ± 0.06</td>
<td>0.47 ± 0.28</td>
</tr>
<tr>
<td>FE&lt;sub&gt;Na&lt;/sub&gt; %</td>
<td>154.9 ± 9.59</td>
<td>202.1 ± 5.81</td>
<td>168.9 ± 18.5</td>
<td>105.6 ± 12.5</td>
</tr>
<tr>
<td>FE&lt;sub&gt;Mg&lt;/sub&gt; %</td>
<td>26.4 ± 2.04</td>
<td>23.7 ± 1.72</td>
<td>21.6 ± 2.26</td>
<td>30.2 ± 3.20</td>
</tr>
</tbody>
</table>

for urine pH, GFR, TE and FE for Mg, Na and K excretion are shown in Table 4. Urine pH was significantly decreased (P<0.05) when Na intake was increased. Glomerular filtration rate was significantly elevated (p<0.05) in sheep receiving the high Na treatment compared with sheep on all other treatments. The mean TE values for Na and Mg on the HNa treatment were significantly higher (P<0.05) than those for the LNaHW and LNa treatments. However, total excretion of K did not differ (p>0.05) between treatments.

Fractional excretion of Na for the HNa treatment was higher (p<0.01) than that for the LNaHW and LNa treatments while fractional excretion of K did not differ between the HNa and the LNa treatments. Increasing Na intake (HNa treatment) resulted in a 22% increase in FE<sub>Mg</sub> (p<0.05), but increasing water intake (LNaHW treatment) increased FE<sub>Mg</sub> by only 10% (p>0.05), when compared to the LNa treatment.

A highly positive correlation between TE and FE of Mg was observed (Figure 1).

**FIGURE 1:** Relationship between TE and FE for Mg in sheep given extra Na or water.
DISCUSSION

Addition of Na to a diet with high K concentration did not increase apparent Mg absorption. It did, unexpectedly, increase urinary Mg excretion by 37% and resulted in significant reduction in Mg balance. Water loading *per se* into the rumen, in volumes equivalent to that consumed voluntarily by the HNa sheep, had no effect on absorption and excretion of Mg. Renal clearance studies showed that increasing Na, but not water loading, resulted in an increase in the GFR resulting increase in urinary Mg excretion.

The finding that supplementation of Na did not alter net Mg absorption was surprising and contradicts the findings of Martens *et al.* (1987). In their study, a decrease in the concentration of K in rumen fluid with Na supplementation occurred whereas in the present work, although a change in rumen fluid Na:K was achieved, there was no change in rumen K concentration. The lack of effect of Na intake on Mg absorption without concomitant change in rumen K concentration does, however, indicate the overriding importance of rumen K concentration for the absorption of Mg from the reticulorumen (Martens *et al.*, 1988). In this study a greater Mg absorption occurred in control sheep which maintained lower rumen K concentrations but similar rumen Na concentrations to the HNa sheep.

Sodium infusion into the rumen markedly increased water consumption, GFR and fractional Mg excretion. These results are consistent with those reported by Godwin and Williams (1986) and Moseley and Jones (1974). Tomas *et al.*, (1973) observed increased urinary Mg excretion in association with increase in GFR in sheep drinking 1.3% saline water. The lack of increase in GFR in the water loaded sheep, even though their total water consumption was greater than that of HNa sheep, suggests that the increase in GFR in HNa sheep was Na-rather than water-intake induced. There are two possible reasons to explain how an excess Na may alter Mg excretion. Firstly, Mg reabsorption is a filtration-reabsorption process (Quamme and Dirks, 1985) and therefore an increase in the GFR would lead to increase in the filtered load within the kidneys. Magnesium shows a saturable maximum for reabsorption in the kidneys (Pitts 1970) and hence an increase beyond this maximum would lead to reduction in percentage reabsorbed. Secondly, there is evidence that the transepithelial and paracellular transport of Mg in the thick ascending limb of Henle’s loop are voltage-dependent (Sharegi and Agus, 1982). Change in Na concentration in tubular fluid would alter the transepithelial potential leading to change in Mg flux from the apical membrane to serosal membrane. High concentration of Na in the tubular fluid due Na loading leads to a decrease transepithelial potential resulting in Mg flux in a secretory direction and eventually a decrease in net reabsorption of Mg in the tubules.

The close relationship between $\text{TE}_{\text{Mg}}$ and $\text{FE}_{\text{Mg}}$ observed in the present work is important. While the $\text{TE}_{\text{Mg}}$ reflects the total amounts of Mg being excreted in urine and is highly correlated with apparent Mg absorption (Ammerman *et al.*, 1971), $\text{FE}_{\text{Mg}}$ is the proportion of Mg filtered through the glomerulus that is eventually excreted in urine and therefore reflects the tubular handling of the Mg in the filtrate (Garry *et al.*, 1990). An advantage of this relationship is that the Mg status of ruminants could be assessed from a urine sample. Sutherland *et al.* (1986) demonstrated in dairy cows that FE is a sensitive indicator and predictor of the need for Mg supplementation and suggested that herds with a mean $\text{FE}_{\text{Mg}} < 10\%$ are likely to benefit from Mg supplementation.

In summary, this study cautions against the use of Na supplementation for livestock to improve Mg homeostasis.

ACKNOWLEDGMENTS

We gratefully acknowledge the Dairy Research Corporation for financial support of this project, Dr A.S. Hamilton for his skilled surgery and P. Isherwood for his assistance with chemical analyses.

REFERENCES


