

MAGNESIUM METABOLISM IN SHEEP FED DIFFERENT LEVELS OF  
SOLUBLE CARBOHYDRATE AND POTASSIUM

by

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## Chapter I

### INTRODUCTION

Magnesium is recognized as one of the major minerals essential for both animals and plants. While it is a dietary requirement for all farm animals, the element appears to be especially critical for ruminants. A serious disorder accompanied by low blood serum magnesium levels known as grass tetany, hypomagnesemic tetany, lactation tetany and wheat pasture poisoning occurs quite frequently in ruminants and is responsible for a substantial financial loss to stockmen. In the United States, grass tetany is confined primarily to older lactating beef cattle, although the condition has also been reported in dry stock and ewes. Grass tetany becomes a problem in other countries when dairy cattle are maintained primarily on pasture with limited supplemental feed. Animals grazing cereal forages or lush pastures at immature stages of growth are most frequently affected. The main symptoms of hypomagnesemic tetany include nervousness, twitching and tetanic contractions of muscles, spastic abnormal gait, convulsions and death.

Research has indicated that an insufficient magnesium due to low levels in feeds and decreased availability at times of relatively high requirements, may be the major pre-

disposing factors of the disease. A common finding in affected animals is low serum magnesium levels, indicating that the disease is associated with a metabolic deficiency of magnesium. In ruminants, body reserves of magnesium often cannot be mobilized sufficiently to meet the needs of the animal for even short periods of time. Therefore, decreases in serum magnesium levels can occur rapidly when too little absorbable magnesium is present in the diet.

The levels of certain dietary components commonly found in tetany-prone forage have been reported as factors which may adversely affect the biological availability of magnesium. A variety of tetany-prone forages have been shown to be high in potassium and low in both magnesium and water soluble carbohydrates. Potassium levels in young, rapidly growing cereal forages may be as high as 5%, on a dry matter basis. In previous studies, high levels of dietary potassium have been shown to lower serum magnesium levels and depress magnesium absorption. Water soluble carbohydrate levels are sometimes low in immature cereal forages and grasses and then increase as plants mature. The lack of readily available carbohydrates has been suggested as contributing to high concentrations of ammonia-nitrogen in the rumen and an increased pH, thereby reducing the availability of magnesium. The beneficial effects of soluble carbohydrate

supplementation have been studied previously, but results have been inconsistent, and did not determine if magnesium availability could be improved in the presence of other detrimental factors, such as potassium.

The investigation reported here was designed to study the role of dietary soluble carbohydrate level on magnesium utilization in ruminants, and to ascertain the effect of soluble carbohydrate level when magnesium availability is decreased by a high potassium level.

## Chapter II

### REVIEW OF LITERATURE

#### MAGNESIUM HOMEOSTASIS

##### Distribution in Tissues.

Magnesium constitutes approximately .05% of the total animal body. Estimates indicate that about 60 to 70% of body magnesium is present in the skeleton, with the remainder in the soft tissues (Book and Storry, 1962). Wilson (1964) reported that only 1% of body magnesium is found in the extracellular fluid (plasma and interstitial fluid). However, this is the portion that is extremely important to the well-being of the animal.

In the bone, magnesium is present mainly as an ion and as magnesium hydroxide within the hydration shell of the hydroxyapatite crystal in a normal calcium:magnesium ratio of 55:1 (Allcroft and Burns, 1968). The highest concentrations of magnesium in the soft tissue are found in the heart, liver and skeletal muscle. Here magnesium is concentrated within the cell where it functions as a cofactor for numerous enzyme systems. Magnesium is required for oxidative phosphorylation and other reactions involving the splitting and transfer of phosphate groups, including reactions involved in glucose utilization; protein, fat and

nucleic acid synthesis; muscle contraction; and sulfate, acetate and formate activation (Wacker, 1969).

Normal concentrations of magnesium in the serum and plasma of ruminants were reported by Rook and Storry (1962) to range from 1.2 to 3.2 mg/dl. In the serum, magnesium is carried in a nondiffusible and diffusible form. Aikawa (1963) reported that an average of 25% of the total serum magnesium existed in the nondiffusible form and appeared to be nonselectively bound to serum proteins. Serum magnesium concentration is markedly reduced to values of .5 mg/dl or less in cases of grass tetany, but low serum magnesium levels are not invariably associated with clinical signs of tetany (Allcroft and Burns, 1968). They suggested tetany was more likely to develop when serum magnesium values fell rapidly.

Magnesium intake has been shown to influence serum magnesium in sheep (Chicco et al., 1972) and cattle (O'Kelley and Fontenot, 1969). Kemp (1960) showed a correlation between serum magnesium of lactating cows and the magnesium content of the diet. When forage magnesium concentrations were higher than .2% of the dry matter, hypomagnesemia did not develop. Factors in tetany-prone forage may reduce the availability of magnesium and contribute to the development of hypomagnesemia. Hemingway et al. (1965) reported a

rapid fall in plasma magnesium values and the occurrence of clinical signs of tetany after lactating ewes were transferred from wintering diets to spring forage.

In contrast to other animals, in ruminants the cerebrospinal fluid magnesium concentration is lower than the respective plasma magnesium concentration (Allsop and Pauli, 1975a). However, the percentage of cerebrospinal fluid magnesium that is in the diffusible or ionic form is much greater than in the plasma. Oppelt et al. (1963) observed that magnesium was actively transported from the blood into the spinal fluid against the ionized gradient present at the blood-brain barrier. Under normal conditions, the cerebrospinal fluid magnesium concentration remains relatively constant; however, Allsop and Pauli (1975a) reported cerebrospinal fluid magnesium decreased slowly at first then rapidly to approximately 60% of control values as clinical signs of tetany developed in hypomagnesemia-induced cows. Tetanic convulsions were observed in sheep ventriculary perfused with a low magnesium, artificial cerebrospinal fluid (Allsop and Pauli, 1975b). Meyer (1977) suggested that the clinical signs of hypomagnesemic tetany were central in origin and depended on a decrease in the cerebrospinal fluid concentration.

Milk has been reported to contain approximately 126 mg/kg of magnesium (Allcroft and Burns, 1968). Todd (1976) suggested that a high-yielding cow might therefore secrete into its milk in 1 d an amount of magnesium equivalent to the total magnesium in the extracellular fluid. Littledike and Cox (1979) reported a large percentage of intravenously injected  $^{28}$ magnesium was rapidly taken up by the mammary gland of both lactating and dry cows. When magnesium was injected into the mammary gland, only 10% of the total counts could be recovered 24 h later. They suggested the mammary gland may serve as a very large readily exchangeable pool of magnesium.

#### Tissue Exchange of Magnesium.

In young animals, bone can apparently serve as a major source of exchangeable magnesium. In calves consuming magnesium deficient diets, Blaxter and Rook (1954) found bone magnesium was depleted by 30% while no decline occurred in soft tissue magnesium. Blaxter and McGill (1956) suggested that in young animals on magnesium deficient diets there is a translocation of magnesium from the bone to supply the magnesium necessary for soft tissue growth and prevent a rapid fall in plasma magnesium concentration. However, using radioisotope techniques McAleese et al. (1961)

reported that soft tissue magnesium is also depletable. In magnesium deficient lambs, the rate of uptake of  $^{28}\text{Mg}$  by the soft tissues was much greater than that by the bone and the  $^{28}\text{Mg}$  content of soft tissues was greater than in normal animals, despite 80 to 90% of the bone magnesium being available for exchange. Therefore, Allcroft and Burns (1968) suggested that although there is no doubt that bone magnesium may serve as a source of labile magnesium in the young, part of the decrease in bone magnesium concentration might be attributable to the deposition of magnesium-poor bone rather than a net reabsorption of magnesium from the bone.

Skeletal reserves decline rapidly with age, so that in adult animals a rapid fall in serum magnesium may occur when insufficient amounts of magnesium are absorbed (Allcroft and Burns, 1968). In adult sheep, Field (1960) observed only .9 to 2.3% of bone magnesium was in equilibrium with the extracellular fluid magnesium 10 h after intravenous administration of  $^{28}\text{Mg}$ . Rook and Storry (1962) reported that only approximately 2% of the skeletal magnesium is available for release in adult cows. Therefore, apparently a comparatively large fraction of the total adult body magnesium is not readily exchangeable and available to meet physiological needs. Blaxter and McGill (1956) calculated that due to



this, old cows with 6 or more calves were 14 times more likely to develop grass tetany.

Care (1967) postulated that readily exchangeable magnesium was located in two pools in the animal (a central pool of bone and soft tissue vs an extracellular pool) and that a change in turnover rate was involved in hypomagnesemia. When hypomagnesemia was produced in adult sheep by a sudden change in diet from hay to lush grass the turnover rate of the central pool was reduced from 1.7 to 1.1 mEq/kg of body mass per day. The reduction in turnover rate was not accompanied by a redistribution of magnesium between the central and extracellular pool, but was attributed to a decrease in magnesium absorption.

Using magnesium isotope techniques, Larvor (1976) studied the magnesium kinetics in non-pregnant ewes fed normal and tetany-prone grass (.14% magnesium and 3.9% potassium). After switching to the tetany-prone grass, a drop in blood magnesium and urinary magnesium excretion occurred in conjunction with a decrease in the total output from the central magnesium pool. Since magnesium balance was not affected, he suggested that hypomagnesemia in adult animals may be associated with a shift of exchangeable body magnesium from the blood to other tissues in conjunction with a decrease in magnesium absorption.

## MAGNESIUM ABSORPTION AND EXCRETION

### Site of Absorption.

Early research indicated that the small intestine was the major site of magnesium absorption. Stewart and Moodie (1956) studied absorption in anesthetized sheep. Venous blood was sampled and the different sections of the digestive tract were drained after administration of large doses of magnesium salts. They reported magnesium absorption could apparently occur throughout the digestive tract, but, magnesium was absorbed most extensively from the duodenum. From a comparison of the distribution of <sup>24</sup>magnesium between the digesta and digestive tract epithelium after its oral or intravenous administration to sheep, Field (1961) reported that the main site of absorption was the middle third of the small intestine.

Magnesium flow was studied in vivo across isolated reticulo-rumen sacs and isolated loops of the duodenum, jejunum and ileum in anesthetized sheep by Phillipson and Storry (1965). They reported that the reticulum and rumen of sheep were relatively impermeable to both calcium and magnesium even when greater than normal amounts were present. Using isolated loops of the small intestine, they indicated magnesium can be absorbed along the entire length. However, endogenous secretions of a variable degree were also present along all sections.

From studies with sheep equipped with double re-entrant cannulae, Care and Van't Klooster (1965) concluded that the reticulo-rumen did not appear to be a main site of magnesium absorption when magnesium concentrations were within a normal range. They observed the upper ileum to be the primary site of magnesium absorption. It was shown that the rate of magnesium absorption increased as the magnesium concentration in the ileum increased, and that magnesium absorption occurred only when it was favored by concentration gradients.

Similar results were observed in calves. Using polyethylene glycol as a marker, Smith (1962) studied magnesium absorption in milk-fed calves cannulated in the lower small intestine. He reported that in calves 2 to 5 wk of age a net absorption of magnesium occurred up to the distal end of the small intestine, representing 25% of of the magnesium intake, and that through the large intestine 35% of the intake was absorbed. Magnesium absorption was lower in older calves, and he suggested this is due to a decrease in magnesium reabsorption from the large intestine. He estimated that in younger calves 40 to 70% of the magnesium not absorbed in the small intestine was available for absorption in the large intestine. Perry et al. (1967) reported that a net secretion of magnesium occurred in the proximal small

intestine of calves fed three different diets. A net absorption of magnesium occurred in the passage through the small intestine.

More contemporary research, however, indicate that the stomach is the primary site of magnesium absorption. Using a ruminal cannula, re-entrant cannulae in the small intestine and chromic oxide as a marker, Pfeffer et al. (1970) found that magnesium can be absorbed from the reticulo-rumen, omasum and abomasum in conscious sheep. A net secretion of magnesium was observed in the small intestine and a net absorption in the large intestine.

Grace and MacRae (1972) prepared sheep with a rumen cannula and re-entrant cannulae at the proximal and terminal small intestine and fed diets consisting of dried grass and casein either once daily or continuously. Using chromic oxide as a marker, they reported a net absorption of magnesium from the gut proximal to the duodenum in all sheep, and a net secretion of magnesium into and a net absorption of magnesium from the small and large intestine, respectively. However, they reported that feeding regimen altered the relative importance of the stomach and intestinal regions as sites of net absorption. Under continuous feeding, about 94% of the magnesium was absorbed in the stomach region but with once a day feeding only 50% was absorbed proximal to the duodenum.

The patterns of magnesium absorption were further studied by Grace et al. (1974). Sheep fitted with a rumen cannula and re-entrant cannulae in the duodenum and ileum were fed diets of either fresh perennial ryegrass, short-rotation ryegrass or white clover at two organic matter intakes. Within each herbage, increasing the organic matter and magnesium intakes increased the apparent absorption and retention of magnesium by the sheep. In all but one sheep, at the higher intake level there were significant net absorptions of magnesium from the stomach region and large intestine, and in all cases there were net secretions into the small intestine. At the lower intake level the amounts of magnesium entering or leaving the various regions did not differ significantly.

In cows equipped with duodenal cannula, Kemp et al. (1973) observed at normal magnesium intakes there were no significant differences in magnesium absorption between the stomach and intestine.

Greene (1981) studied magnesium absorption in both sheep and cattle equipped with abomasal and ileal cannulae. Feeding .2 vs .1% magnesium to sheep resulted in more magnesium being absorbed and retained in animals receiving the high level of magnesium. The increase in apparent magnesium absorption was primarily due to more magnesium being

absorbed prior to the duodenum. In both cattle and sheep, the preintestinal region was the primary site of magnesium absorption with smaller amounts absorbed in the large intestine. A net secretion of magnesium into the small intestine was observed for both cattle and sheep.

Tomas and Potter (1976) reported that the reticulo-rumen is the principal site of magnesium absorption in the sheep stomach. They found that magnesium infused into the omasum or abomasum was completely recovered at the duodenum. Significant absorption of magnesium occurred only when magnesium was infused into the rumen. The infusion of magnesium post-ruinally was associated with reduced plasma magnesium concentration and urinary magnesium excretion, and increased fecal excretion of magnesium. This indicated that post-ruinal absorption of magnesium was insufficient to maintain normal magnesium status in the animal.

Field and Monro (1977) also obtained evidence that the rumen was the primary site of magnesium absorption, however, they also found small amounts of magnesium were absorbed from the omasum in sheep. Magnesium absorption was found to be higher from ruminal than duodenal infusion. In addition, they indicated that the ruminal absorptive mechanism was an active process and could become saturated when high levels of magnesium are fed.

In contrast, Fitt et al. (1979) reported that the omasum was equally important as the reticulo-rumen as a magnesium absorptive site. When magnesium was provided through the feed, ruminal or omasal cannula, plasma magnesium levels were maintained, whereas, subsequent administration into the abomasum, proximal duodenum or terminal ileum resulted in steady falls in plasma magnesium levels.

In young steers approximately 26 wk of age, Horn and Smith (1978) reported only small amounts of magnesium were absorbed from the reticulo-rumen, and suggested the omasum is the primary site of magnesium absorption.

Dillon and Scott (1979) reported that a study of mineral absorptive sites before and after weaning indicates that the mineral absorptive capacity of the foregut is apparently related to the development of rumen function. Before weaning the small intestine was the major site for dry matter and water absorption and the small and large intestine were shown to be the primary sites of magnesium absorption. In the post-weaning period as the concentrate in the diet increased, they observed a gradual decrease in magnesium absorption by the large intestine and an increasing importance of the stomach. As magnesium absorbed prior to the duodenum exceeded that of the small intestine, magnesium availability also decreased from 90 to 51%.

### Magnesium Excretion.

Excretion of magnesium is mainly via the feces. Fecal magnesium includes the unabsorbed magnesium from the diet and the endogenous magnesium which enters the tract from desquamated epithelia cells, in the saliva, and other digestive secretions. Rook and Storry (1962) have suggested that in non-lactating mature animals the requirement for magnesium is limited to that needed to meet endogenous fecal loss. Blaxter and Rook (1954) reported that calves consuming liquid diets containing only .5 mg/dl of magnesium excreted 170 to 200 mg of magnesium per 100 g of feces. They suggested, therefore, that magnesium secreted into the intestine is not readily reabsorbed. Blaxter and McGill (1956) observed that the endogenous loss in old cows is similar to that of calves, with 3.5 mg of magnesium excreted per kilogram of body weight. Simsen et al. (1962), using tracer methods, reported values of 3.5 mg/kg of body weight for milk-fed calves and 1.5 mg for cows. Endogenous magnesium loss in non-lactating cows fed low magnesium diets was estimated by Storry and Rook (1963) to be 2 mg/kg of body weight per day.

In sheep, Smith (1959b) reported that fecal magnesium endogenous secretions increased per unit of body weight with increases in age. Values of .5 and 2.2 mg of magnesium per



kilogram of body weight were reported for 2- to 5-wk-old lambs and 26- to 32-wk-old lambs, respectively. Similar increases were seen in calves from 1 to 7 mo of age (Smith, 1959a). Using tracer methods, MacDonald et al. (1959) reported endogenous fecal loss to be approximately 5.0 mg/kg of body weight for a 20-mo-old wether. A value of 2.7 mg was reported by Hjerpe (1968) using artificial diets low in magnesium.

Rook and Storry (1962) have suggested that endogenous excretion may be increased due to greater saliva flow when the diet is composed of bulky roughages and grass. In a recent study by Allsop and Rook (1979), mature sheep were fed artificial diets differing greatly in fiber and low in magnesium content. A change in magnesium status was induced in the sheep by continuous infusion of different concentrations of magnesium. They reported small but significantly higher endogenous fecal losses for the diet containing the highest amount of fiber. Using regression techniques, they observed that an increase in the magnesium status of the animal resulted in unit increases in the endogenous fecal loss. The response was similar for all the diets and the average increase in fecal endogenous magnesium was .03 g/d for each increase of 1 mg/dl in plasma magnesium concentration. In a second study using natural diets containing .18%

magnesium, for each increase of 1 mg/dl in plasma magnesium the fecal loss increased by .515 g of magnesium per day. They concluded that the magnesium status of the animal may be an important factor controlling endogenous excretion of magnesium.

The kidney plays a key role in maintaining magnesium homeostasis. Rook and Storry (1962) reported that the urine is the major disposal route from the body for magnesium absorbed in excess of body requirements and suggested that urinary magnesium excretion, therefore, reflects the nutritional adequacy of the diet. The transfer of ruminants to low magnesium diets was reported to result in the progressive fall of plasma magnesium levels and urinary magnesium excretion. Field (1962) observed that a change in magnesium intake is quickly reflected in urinary magnesium excretion of sheep changed from a dry lot diet to spring grass. A high correlation of .95 between the amount of magnesium absorbed and urinary excretion of magnesium was reported by Chicco et al. (1972). Factors which lower the availability of magnesium and depress magnesium absorption have also been shown to decrease urinary magnesium excretion (Kemp et al., 1961; Newton et al., 1972; Larvor, 1976; and Greene, 1981).

In ruminants, magnesium acts as a threshold substance in the plasma with excretion controlled by a filtration-

reabsorption mechanism (Rook and Storry, 1962). When plasma magnesium values fall below the threshold little or no magnesium is excreted in the urine; above the threshold, the concentrations in the plasma and excreted urine are linearly related. Plasma and urinary magnesium concentrations were found by Chicco et al. (1972) to be positively correlated ( $r = .88$ ). Storry and Rook (1962) obtained a serum threshold value of 1.8 mg/dl of magnesium for grazing dairy cows. The renal threshold for two lactating ewes was determined to be 1.37 and 1.94 mg of magnesium/dl of serum by L'Estrange and Axford (1964).

#### READILY AVAILABLE CARBOHYDRATES AND MAGNESIUM METABOLISM

During periods when grass tetany is likely, early vegetative grasses are relatively low in total water-soluble carbohydrates (Waite and Boyd, 1953). Metson et al. (1966) observed soluble carbohydrate levels to range from 3.6 to 15% in the ryegrass-dominant pastures of New Zealand. Fertilization of pastures with nitrogen was also reported to further reduce the level of soluble carbohydrate in forage.

In the rumen, soluble carbohydrates are sources of readily available energy which may enhance rumen microbial activity and the utilization of forage. Other carbohydrate sources, such as cellulose and hemicellulose, are fermented

more slowly. Therefore, water soluble carbohydrate level has been taken as a relative measure of the energy producing constituents of a herbage. Since the greater part of the carbohydrate is converted to volatile fatty acids and absorbed from the rumen, a deficiency in soluble carbohydrate may give rise to an energy deficiency and lead to poor absorption of magnesium (Metson et al., 1966). Martens and Rayssiguier (1980) reported magnesium absorption was increased linearly in an artificial rumen when the acetic, propionic and butyric acid concentrations were raised from 15 to 45 mM, 5 to 15mM and 2.5 to 7.5 mM/l, respectively.

Dishington (1965) observed that dietary protein levels often were in excess of requirements and suggested that the imbalance between crude protein and readily soluble carbohydrates in young grass would increase the likelihood of grass tetany. He reported that if cows were fed a diet of grass containing 25 to 30% crude protein, their energy requirement would not be satisfied unless they consumed an amount of grass which would exceed their protein requirement by 200%. In a such situation in which energy substrates are inadequate for bacterial protein synthesis, protein deamination would exceed ammonia assimilation rates leading to elevated rumen ammonia levels and increased rumen pH.

Metson et al. (1966) indicated that the addition of readily fermentable carbohydrates would decrease ammonia concentration in the rumen and improve the utilization of protein. Also, volatile fatty acid synthesis would be enhanced. Both effects would lower pH values and increase the absorption and availability of magnesium and perhaps calcium. Storry (1961) indicated that a decrease in acidity of the digesta resulted in increased binding of magnesium in unavailable forms. Increased pH could also result in magnesium being partially precipitated as magnesium ammonium phosphate (Wilcox and Hoff, 1974).

Wilson and coworkers (1969) reported that the depression of plasma magnesium levels was significantly lessened by starch supplementation to mature lactating dairy cows grazing perennial ryegrass pastures. Older animals appeared much more sensitive than young animals to the treatment. In animals less than 5 yr of age, supplementation of 900 g of starch per day did not increase plasma magnesium above that of the control animals.

Okolo et al. (1976) found that energy supplementation was beneficial in reducing the grass tetany hazard in spring-calving beef cows. Three groups of eighteen cows were allowed to graze a tall fescue pasture previously fertilized with nitrogen and potassium. One group received no

supplement, the second group received fescue hay and a magnesium supplement and the third group were fed as those in group 2 with the addition of 3.6 kg of corn silage per day. The average serum magnesium levels were 1.24, 2.00 and 2.48 mg/dl and 8, 1 and 0 occurrences of grass tetany were observed during the 4 mo grazing period for groups 1, 2 and 3, respectively.

Using mature sheep, Madsen et al. (1976) studied the effect of the addition of 0, 50, 100 or 250 g of glucose per day to a diet of orchardgrass hay (1.14 kg/d). Magnesium absorption was linearly increased by glucose supplementation. However, plasma magnesium concentrations were not affected by the treatment. In a second study, although glucose supplementation to diets of vegetative ryegrass did not have an enhancing effect on magnesium absorption or retention, the plasma magnesium concentrations averaged 13% higher in the glucose-supplemented sheep. They proposed that the high moisture content of the forage may have increased magnesium excretion and the relatively high percentage of long chain fatty acids might have bound magnesium in a form unavailable for absorption.

Using a low magnesium, 25% crude protein, semi-purified diet, House and Mayland (1976) conducted two experiments in which the dietary levels of readily fermentable carbohydrate

were adjusted with either starch or sucrose to vary the ratio of total nitrogen to fermentable carbohydrate. Increasing the percent of corn starch in the diet from 1.9 to 18.5% had no effects on magnesium absorption or retention. Plasma magnesium concentrations were also not affected by the treatments. However, when lambs were fed a diet with sucrose as the main soluble carbohydrate source, urinary excretion, apparent absorption and retention of magnesium were higher than in those fed a diet without sucrose. They observed a trend for ruminal ammonia levels to increase as starch intake decreased, but no apparent relationship between ruminal ammonia level and plasma magnesium concentration was seen. Similar results were reported concerning the effect of ruminal ammonia by Moore et al. (1972) in a study with sheep fed two levels of crude protein and non-protein nitrogen. Ruminal ammonia levels increased as nitrogen intake increased, but magnesium absorption was similar for all treatments, as were plasma magnesium levels.

Using sheep equipped with duodenal and ileal cannulae and chromic oxide as a marker, Bayssiguier and Poncet (1980) studied the effect of lactose supplementation on the site of magnesium absorption. The addition of 400 g of lactose per day to a diet of alfalfa hay (800 g/d) significantly increased preintestinal absorption (40.8 vs 18.9% of the

amount ingested) and the retention of magnesium. Magnesium flow through the large intestine was not significantly altered. Plasma magnesium levels increased only slightly from 1.78 to 1.97 mg/dl when lactose was added. The addition of lactose to the diet was associated with decreases in rumen pH and ammonia, and increases in lactate concentration. The molar proportions of volatile fatty acids were altered by the addition of lactose. Acetate concentration was lower and propionate higher, but the total volatile fatty acid concentration was not affected.

#### DIETARY POTASSIUM LEVEL AND MAGNESIUM METABOLISM

Forages that are associated with a high incidence of grass tetany are frequently high in potassium. Dryerre (1932) and Nicholson and Shearer (1938) observed an increase in the occurrence of hypomagnesemic tetany when animals were grazed in pastures fertilized with potassium. Many experimental studies have since shown that pastures can become tetany-prone after fertilization with nitrogen and potassium (Barlet et al., 1954; Hvidsten et al., 1959; Kemp, 1958, 1960, 1961). These studies also reported high levels of potassium fertilization resulted in lowered serum magnesium levels. Kemp and t'Hart (1957) found a positive correlation between the  $K/(Mg + Ca)$  ratio in forages and the incidence



of grass tetany. When the value of this ratio was less than 2.2, there were few cases of grass tetany, and when it was greater, grass tetany occurred much more frequently. Similar observations were reported by Butler (1963).

Grunes et al. (1970) reported nitrogen fertilized ryegrass contained an average of 3.9% potassium and a  $K/(Mg + Ca)$  ratio of 2.8. The addition of 121 kg/ha of potassium increased potassium levels to 4.5% and the  $K/(Mg + Ca)$  ratio to 3.8.

Eaton and Avampato (1952) observed that serum magnesium levels were significantly lower in lambs fed a diet of high potassium hay (3.2%) as compared to a diet of normal alfalfa hay (1.6%). However, Daniel et al. (1952) reported that the addition of 7.7% potassium chloride to a dry lot ration had no effect on serum magnesium in ewes.

Fontenot et al. (1960) observed that feeding a high protein and potassium diet to lambs significantly reduced apparent magnesium absorption and urinary excretion of magnesium. Throughout the trial, plasma magnesium values were lower for the animals receiving the high protein and potassium diet.

Kemp et al. (1961) reported that when dairy cows were fed a diet of fresh cut grass plus 400 g of potassium chloride the magnesium availability was reduced from 18.5 to

16%. Using sheep, Suttle and Field (1967) found that the addition of 4.2% of potassium chloride in the feed or via a rumen fistula with 7.5 liters of water per day significantly increased fecal magnesium excretion and decreased urinary output of magnesium. Infusion of water alone increased urinary output of magnesium, but fecal magnesium excretion was not affected. The authors suggested that high potassium levels in the diet might decrease the true absorption of magnesium by increasing the potential difference across the wall of the rumen.

Newton and coworkers (1972) reported that feeding a high potassium diet (4.9 vs .6%) resulted in a consistent reduction in apparent magnesium availability over eight-3 d trials (26.4 vs 49%). In a second experiment, wethers were given an injection of  $^{28}$ magnesium intravenously and the magnesium turnover rate was measured. In animals receiving the high potassium diets, central pool magnesium turnover rate was lower, indicating that high potassium levels increase fecal magnesium by interfering with magnesium absorption rather than increasing the endogenous excretion.

Powley et al. (1977) observed no difference in endogenous fecal magnesium excretion in sheep fed ryegrass which contained either 1.5 to 3.12% potassium and .15 or .73% sodium. However, the availability of magnesium was lower for the high potassium grass than the high sodium grass.

Tomas and Potter (1976b) observed that a continuous ruminal infusion of potassium chloride at a level equivalent to 3.9% of the diet depressed magnesium absorption in sheep. Duodenal infusion had no significant effects on magnesium absorption. MacGregor and Armstrong (1979) fed four levels of potassium to sheep (.62, 1.36, 2.12, and 3.87%) and found that magnesium availability was depressed only at the highest level. At this level, magnesium absorption from the stomach was reduced.

Greene (1981) conducted studies in sheep and cattle to determine the minimal level of potassium that depresses magnesium absorption and the effects of different potassium levels on magnesium flow throughout the digestive tract. In sheep when .6, 1.2, 2.4 and 4.8% potassium were fed, magnesium absorption was linearly depressed when expressed as percent of intake (51.2, 50.4, 40.7 and 35.3%, respectively). Serum magnesium levels were depressed at the higher potassium intakes. In sheep and steers equipped with abomasal and ileal cannulae, the preintestinal region was the primary site of magnesium absorption. Increasing potassium level in the diet resulted in smaller amounts of magnesium absorbed from the preintestinal region.

It was suggested that potassium also directly depresses the circulating levels of magnesium (Suttle and Field,

1969). They observed a decrease in plasma magnesium levels when a high potassium-low magnesium diet was fed to ewes. Hypomagnesemic tetany developed in several animals on this diet. In cattle, the oral administration of potassium chloride in combination with either citric acid or trans-aconitic acid produced a tetany similar to that of grass tetany (Bohman et al., 1969).

House and Van Campen (1971) reported feeding a 4% potassium diet to lambs intravenously injected with  $^{28}$  magnesium elevated fecal magnesium excretion and depressed magnesium absorption, urinary magnesium excretion and lowered endogenous fecal magnesium excretion. The total exchangeable magnesium pool was not affected by potassium treatment, however, they observed an alteration in the magnesium flux between rapidly exchanging compartments and more slowly exchanging compartments. House and Bird (1975) suggested that high levels of dietary potassium may act to enhance the rate of magnesium disappearance from the plasma and decrease urinary magnesium excretion by increasing cellular uptake. In their study, the plasma magnesium concentration of goats fed high levels of potassium declined more rapidly upon intravenous magnesium injection (176 vs 239 min) and urinary magnesium excretion decreased to 80% of previous levels. However, in a recent study by Rahnama and Fontenot (1981),

the continuous, intravenous infusion of 25 g of K<sup>+</sup>/d had no effect on serum magnesium levels in sheep. Absorption, retention and urinary excretion of magnesium also were not affected by potassium infusion. The authors suggested that the depression in serum magnesium levels and in magnesium absorption that have been observed when potassium intake was excessive result from a decrease in preintestinal magnesium absorption due to the presence of potassium in this region.

The effects of ruminal or intravenous infusions of potassium chloride were studied in normal and magnesium deficient cows by Lentz et al. (1976). Elevated plasma potassium levels resulted from both intravenous and ruminal potassium infusion and were accompanied by a significant increase in immunoreactive insulin levels in both groups. However, in magnesium-deficient animals, a significantly greater insulin response was observed without a concomitant decrease in glucose levels as was observed in normal cows. They suggested that an increase in potassium for prolonged periods may lead to metabolic disturbances in intermediary magnesium metabolism, especially since tissue exchange of magnesium has also been shown to be affected by alterations of carbohydrate metabolism in nonruminants by Aikawa (1963). Aikawa reported that plasma magnesium levels decreased significantly faster in rabbits injected with

insulin and glucose in conjunction with an increase in the uptake of magnesium by the soft tissues and bone.

## Chapter III

### OBJECTIVES

The objectives of this experiment were to study:

1. The role of dietary soluble carbohydrate level on magnesium metabolism and on site of magnesium absorption in sheep fed low magnesium diets; the effect of increased dietary soluble carbohydrate level when magnesium availability is depressed by high potassium levels.
2. The effect of soluble carbohydrate and potassium level on the site of absorption and utilization of potassium, calcium, sodium and phosphorus.

## Chapter IV

### EXPERIMENTAL PROCEDURE

Two metabolism trials were conducted with 12 crossbred wether lambs (average initial weight - 41.4 kg). The lambs were surgically equipped with abomasal and ileal cannulae approximately 6 mo prior to the start of the experiment as described by Greene (1981). The experimental design was a randomized block with a 2 x 2 factorial arrangement of treatments. Dietary levels of 3 and 23% soluble carbohydrate and .6 and 4% potassium, dry basis, were evaluated. Prior to the beginning of the first trial the lambs were placed into three blocks of four animals, based on initial weight and apparent breeding and randomly allotted to the four experimental diets. For the second trial the lambs within each block were reallocated to the four diets by incomplete randomization, the restriction being that no lamb would receive the same treatment as in the first trial.

The ingredient composition of the experimental diets is shown in table 1. The orchardgrass hay (Dactylis glomerata, L.) and corn cob fraction were ground through a 3.8 cm screen prior to feeding. Chromic oxide was incorporated at the level of .5% to measure the flow of dry matter and minerals through the segments of the digestive tract. Supple-



TABLE 1. INGREDIENT COMPOSITION OF DIETS<sup>a</sup>

Ingredient	Soluble carbohydrate level			
	Low		High	
	.6%k	4%k	.6%k	4%k
	g/d			
Orchard grass hay (IFN 1-02-438)	180	180	180	180
Corn cob fraction <sup>b</sup>	177	177	177	177
Cellulose <sup>c</sup>	180	180	60	60
Cerelose <sup>d</sup>	0	0	120	120
Isolated soy protein <sup>e</sup>	51	51	51	51
Potassium bicarbonate	0	56	0	56
Dicalcium phosphate (IFN 6-01-080)	6	6	6	6
Trace mineralized salt	3	3	3	3
Chromic oxide	3	3	3	3

<sup>a</sup>As fed basis.

<sup>b</sup>Corn cob fraction #4, The Andersons, Maumee, Ohio.

<sup>c</sup>Solka-floc, BW-20, Brown Co., Berlin, N.H.

<sup>d</sup>Corn sugar, Corn Products Refining Co., New York, N.Y.

<sup>e</sup>Assay Protein, RP #101, Ralston Purina, St. Louis, Missouri.

mentary levels of potassium were provided as potassium bicarbonate and the levels of soluble carbohydrate were achieved by altering the ratio of cerelose (glucose) to cellulose. Premixes were made prior to each trial containing all of the diet ingredients except the hay and supplementary potassium bicarbonate. The three parts of the diet were mixed by hand prior to feeding. All the lambs were fed 600 g per day of their respective diet in equal portions at 0600 and 1800 hours. Just prior to feeding, 100 g of water were mixed with each diet to improve palatability and reduce dustiness. Each lamb was given an intramuscular injection of 500,000 IU of vitamin A and 75,000 IU of vitamin D prior to the start of the experiment.

The area surrounding the abomasal and ileal cannulae of each wether was sheared and cleaned of any dirt and fecal matter 1 wk before the beginning of the experiment and the animals were placed in false bottom metabolism stalls similar to those used by Briggs and Gallup (1949). The lambs were introduced to the low potassium experimental diets over a 5-d transition period. The supplementary potassium bicarbonate was then introduced during a subsequent 2-d transition period. Approximately 16 d were required to get the lambs to consume appreciable amounts of the diets at a constant rate for the first trial, after which the preliminary

period was started. For the second trial, the preliminary period started following the 7-d transition period.

Each trial consisted of a 10-d preliminary period followed by a 7-d collection of feed, feces, and urine and a 6-d sampling period of feed, abomasal and ileal contents, and feces. Feed samples were collected once daily at the time of the evening feeding beginning 2 d prior to the start of the collection period and ending 2 d before the end of the sampling period. Feed samples were maintained separately for each of the collection and sampling periods. Total fecal collections were placed in metal pans at a constant time once daily and then dried for 24 h in a forced air oven at a maximum of 60C. After removal from the oven, the dried feces were composited and stored in metal cans with loose-fitted lids and allowed to equilibrate with the moisture of the atmosphere. Fecal collections were made for each collection and sampling period. At the end of each period, the dried feces were weighed, sampled and stored for analysis.

Urine was collected in plastic containers via a plastic funnel under the metal grid of the stall floor. To each urine container, 15 ml of a 1:1 (v/v) sulfuric acid and water solution were added and diluted with approximately 500 ml of water. The urine was collected once daily at a con-

stant time and tested for acidity. Additional sulfuric acid mixture was added as needed to acidify the urine. The daily urine collections were diluted to a constant weight, mixed, and a 2% aliquot (by volume) was placed in a 1 liter polypropylene container and stored under refrigeration until analysis.

Abomasal and ileal samples were simultaneously collected twice daily at 12-h intervals (appendix table 1). The even hours of the clock were randomly assigned to one of the six sampling days to determine the time of sampling (Potter et al., 1969). At each sampling time, approximately 80 ml of abomasal contents were collected in 120 ml plastic containers and 30 ml of ileal contents were collected in plastic bags. All samples were frozen immediately after collection at -20 C. At the end of the trial, digesta samples were composited for each animal by using 25 ml of abomasal fluid from each sampling time and 20 g of ileal fluid from each sampling time. The pH was determined on composited abomasal and ileal samples and the samples were dried in a forced air oven at a maximum of 60 C.

On the last day of each trial rumen fluid samples were collected via a stomach tube at 2 h postfeeding and blood samples were taken by jugular puncture at 3 h postfeeding. Rumen samples were strained through 4 layers of cheesecloth

and the pH of the strained fluid was determined. A 5 ml sample was acidified with 1 ml of 25% metaphosphoric acid and frozen until analyzed for volatile fatty acids using a gas-liquid chromatograph by the method of Erwin et al. (1961). Blood samples were centrifuged and the serum was separated and frozen at -20 C until analysis.

The day following the end of each trial, blood samples were collected for determination of plasma glucose, insulin and glucagon. Three blood samples were taken from each animal by jugular puncture at 15 min intervals beginning 1 h prior to feeding and three samples were again collected at 15 min intervals beginning 1 h after feeding. Approximately 10 ml of blood were collected into syringes previously prepared with Na-EDTA and placed on ice until the blood was centrifuged. Plasma samples were separated and frozen until analysis. Glucose<sup>1</sup> was determined on deproteinized plasma by enzymatic assay. Immunoreactive insulin<sup>2</sup> was determined using a double antibody radioimmunoassay. Plasma glucagon was measured by radioimmunoassay according to the method of Harris et al. (1979) using antiserum 30K (purchased from R. H. Unger, Dept. of Internal Medicine, University of Texas Southwestern Medical School, Dallas, Texas). The assay was

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<sup>1</sup>Sigma Chemical Company, St. Louis, Missouri.

<sup>2</sup>Immuno Nuclear Corporation, Stillwater, Minnesota.

modified to a double antibody immunoassay. The second antibody was produced in sheep against rabbit gamma globulin as described by Yalow (1976).

Feed, feces, abomasal and ileal samples were ground through a 1 mm screen and wet ashed according to the method of Sandell (1950). Feed, feces, urine, blood serum, abomasal and ileal samples were analyzed for magnesium and calcium by atomic absorption and potassium and sodium by emission spectrophotometry with a Perkin-Elmer 403 Atomic Absorption Spectrophotometer. Phosphorus was determined by the method of Fiske and Subbarow (1925). Chromic oxide was determined on feed, feces, abomasal and ileal samples using a modification of the procedure of Hill and Anderson (1958).

Data were statistically analyzed using the General Linear Models Procedure of SAS (1979).

## Chapter V

### RESULTS AND DISCUSSION

#### RUMEN, ABOMASAL AND ILEAL FLUID PH

The pH values of samples of rumen contents taken 2 h after feeding are given in table 2. Ruminal fluid pH values were decreased ( $P < .05$ ) by the high level of soluble carbohydrate. The pH values averaged 7.11 and 6.61 for lambs fed the low and high soluble carbohydrate diets, respectively. Davis et al. (1964) reviewed results that indicated saliva output is reduced when soluble carbohydrates are fed, which lowers the buffering capacity of the rumen, resulting in a lower pH. In the present study, while the decrease in pH was significant, the addition of soluble carbohydrate was expected to lower pH values to a greater degree than the observed values.

The addition of potassium bicarbonate to the diet increased ( $P < .05$ ) rumen fluid pH from 6.8 to 7.4 and from 6.4 to 6.8 at the low and high levels of soluble carbohydrate, respectively. Moore (1971) reported significant increases in rumen fluid pH of sheep when 106 g of potassium bicarbonate were added to a diet of hay, corncobs and and shelled corn. Greene (1981) observed similar increases in the rumen fluid pH of steers supplemented with 196.0 and 244.0 g of potassium bicarbonate daily.

TABLE 2. RUMINAL, ABOMASAL AND ILEAL pH VALUES FOR WETHERS  
FED DIFFERENT LEVELS OF SOLUBLE  
CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4.0% K	.6% K	4.0% K	
Rumen <sup>a,b</sup>	6.81	7.41	6.39	6.84	.03
Abomasum	2.73	2.81	2.76	2.59	.03
Ileal <sup>a</sup>	8.00	8.04	7.87	7.85	.02

<sup>a</sup>Affected by soluble carbohydrate level (P < .05).

<sup>b</sup>Affected by K level (P < .05).



Level of soluble carbohydrate or potassium had no effect on abomasal fluid pH. Ileal pH decreased ( $P < .05$ ) when high levels of soluble carbohydrate were included in the diet. High levels of potassium had no effect on ileal pH.

#### RUMINAL VOLATILE FATTY ACIDS

From the rumen fluid volatile fatty acid data presented in table 3, it is clear that the addition of readily available carbohydrate resulted in higher ( $P < .05$ ) concentrations of propionic and butyric and lower ( $P < .05$ ) concentrations of isobutyric and isovaleric acids. The total volatile fatty acids concentration in the rumen was also higher ( $P < .05$ ) when readily available carbohydrate was fed, primarily due to an increase in propionate and butyrate. These changes were accompanied by a decrease ( $P < .05$ ) in the acetic to propionic ratio (2.5 vs 4.3) for diets containing the high level of soluble carbohydrate. Decreases ( $P < .05$ ) in molar proportions of acetic, isobutyric and isovaleric acids were associated with increases ( $P < .05$ ) in propionic and butyric acids. Hungate (1966) reviewed literature which indicated a tendency for lower ratios of acetic to propionic and butyric acids with increased soluble carbohydrate feeding. Chappell and Fontenot (1968) reported a tendency for total volatile

TABLE 3. RUMEN FLUID VOLATILE FATTY ACIDS IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Micromoles/ml					
Acetic <sup>a,b</sup>	51.87	52.47	45.57	60.41	.99
Propionic <sup>c</sup>	13.15	11.66	20.69	23.20	.96
Isobutyric <sup>a,b,c</sup>	.84	.83	.48	.71	.02
Butyric <sup>c</sup>	6.30	5.02	10.45	12.44	.43
Isovaleric <sup>b,c</sup>	1.28	1.20	.76	1.05	.03
Valeric <sup>b</sup>	.84	.68	.62	1.03	.04
Total <sup>a,b,c</sup>	74.28	71.86	78.55	98.84	1.50
Moles/100 moles					
Acetic <sup>a,c</sup>	69.77	72.87	57.80	61.08	.70
Propionic <sup>c</sup>	17.73	16.37	26.43	23.20	.93
Isobutyric <sup>c</sup>	1.13	1.16	.62	.72	.03
Butyric <sup>c</sup>	8.52	6.98	11.74	12.64	.54
Isovaleric <sup>c</sup>	1.72	1.20	.96	1.07	.04
Valeric	1.12	.68	.78	1.04	.07
Acetic: propionic ratio <sup>c</sup>	3.96	4.56	2.42	2.67	.13

<sup>a</sup>Affected by potassium level (P < .05).

<sup>b</sup>A potassium x soluble carbohydrate interaction was observed (P < .05).

<sup>c</sup>Affected by soluble carbohydrate level (P < .05).

fatty acid concentration in the rumen to be higher when readily available carbohydrates were fed, and that this increase was primarily due to increased levels of propionate and butyrate. When lactose was added to a diet of alfalfa hay, Rayssiguier and Poncet (1980) observed a decrease in acetate and an increase in propionate levels. However, the total volatile fatty acid concentration was similar for both diets.

A significant potassium x soluble carbohydrate interaction was observed for acetic, isobutyric, isovaleric and valeric acid concentrations. It appears that the effect due to the potassium bicarbonate level is dependent upon the level of soluble carbohydrate in the diet. At the low level of soluble carbohydrate, supplementation of potassium to the diet was associated with a small increase in acetate and valerate levels, when expressed as either  $\mu\text{M}/\text{ml}$  or moles/100 moles. Propionate and butyrate levels were slightly depressed, as was total volatile fatty acid concentration when potassium was added to the low soluble carbohydrate diet. The addition of potassium to the high soluble carbohydrate diet was associated with increased levels of all fatty acids and a large increase in the total concentration ( $98.84$  vs  $78.55$   $\mu\text{M}/\text{ml}$ ), primarily due to the large increase in acetic acid concentration. However, when expressed as

moles/100 moles the addition of potassium had no significant effect on the volatile fatty acid levels, with the exception of acetic acid. There was an increase in moles of acetate/100 moles and a trend for decreased moles of propionate/100 moles for both high potassium diets.

The trend for increased acetate to propionate ratios has been reported in many studies in which bicarbonates were fed to animals on high soluble carbohydrate diets. In dairy cows, Davis et al. (1964) reported that feeding 3% sodium and potassium bicarbonate increased the acetic to propionate ratios. Miller et al. (1965) observed that moles of acetate/100 moles was higher and moles of propionate and valerate/100 moles were lower when cows on high grain diets were supplemented with sodium and potassium bicarbonate and magnesium carbonate. In steers fed either 10% starch, .7% calcium carbonate or both, Varner and Woods (1972) reported that calcium carbonate supplementation increased the concentrations of acetate and butyrate. Concentrations of propionate were increased by the addition of starch and decreased by the addition of calcium carbonate. In steers receiving both starch and calcium carbonate, acetate, butyrate and isovalerate levels were higher than in animals only receiving starch.

A change in rumen fermentation patterns is thought to occur because of changes in rumen pH. Emery and Brown (1961) suggested that the rate of volatile fatty acid absorption is altered by changes in rumen pH. Esdale and Satter (1972) reported that when labeled acetate and butyrate were incubated with rumen fluid, the movement of butyrate carbon to acetate is increased as pH increases. These authors suggested that in short term fluctuations of pH, the existing population simply alters their pattern of fermentation. However in long term alterations of pH, they suggested that changes in volatile fatty acid levels reflect changes in the microbial population. Since in the present study, the pH of the rumen was not frequently measured nor was the rumen contents cultured to determine changes in the microbial population, it is not known whether the changes in the fermentation pattern resulted from changes in absorption rate, changes in the microbial population or whether the existing species simply altered their fermentation patterns.

#### MAGNESIUM BALANCE AND ABSORPTION

Magnesium balance data are shown in table 4. Fecal excretion, urinary excretion, absorption and retention of magnesium were not significantly different between sheep fed the different levels of soluble carbohydrate. Increasing

TABLE 4. MAGNESIUM BALANCE IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	.65	.65	.62	.62	
Excretion, g/day					
Fecal <sup>a</sup>	.52	.60	.49	.56	.02
Urinary <sup>a</sup>	.22	.08	.23	.09	.01
Total <sup>a</sup>	.74	.68	.72	.65	.02
Absorption					
Grams/day <sup>a</sup>	.13	.05	.13	.06	.01
Percent of intake <sup>a</sup>	20.18	7.74	20.96	8.79	1.22
Retention, g/day <sup>a</sup>	-.09	-.03	-.10	-.03	.01

<sup>a</sup>Affected by potassium level (P < .05).

the dietary soluble carbohydrate level did not have an enhancing effect on magnesium availability. Expressed as a percent of intake, apparent magnesium absorption averaged 13.9 and 14.8% for sheep fed the low and high soluble carbohydrate diet, respectively. Similar results were reported by House and Mayland (1976). Using crossbred, 9 month-old wether lambs, they observed that increasing the dietary soluble carbohydrate level from 4.6 to 20.5% by increasing the starch in the diet had no effect on magnesium absorption or retention. Madsen et al. (1976) found the addition of 130 g of glucose to a diet of vegetative grass (2.14 kg of dry matter per day) had no effect on magnesium absorption in mature wethers. When hay-fed sheep were given increasing increments of glucose, magnesium absorption increased linearly. They suggested that the high ether extract content of the grass might have resulted in the binding of magnesium in unavailable forms, and caused alterations in the reabsorption of endogenous magnesium. The low dry matter intake of the grass in combination with the high water intake were also theorized to promote greater passage rates through the digestive tract, thereby lowering absorption.

Fecal magnesium excretion was increased ( $P < .05$ ) and apparent magnesium absorption, expressed as grams per day or percent of intake, was lower ( $P < .05$ ) for the lambs consuming

both high potassium diets. Magnesium absorption was depressed approximately 58% when the high level of potassium was fed. The average absorption values, expressed as a percent of intake, were 20.6 and 8.3% for the low and high level of potassium, respectively. Urinary magnesium excretion was lowered approximately 62% in the high potassium fed lambs. Rook and Storry (1962) suggested that urinary excretion is the major route for disposal of magnesium absorbed in excess of body requirements. Chicco et al. (1972) reported a high correlation ( $r = .95$ ) between the amount of magnesium absorbed and the amount excreted in the urine. The decrease observed in urinary magnesium levels probably reflects the depression in magnesium absorption noted in these animals. Magnesium retention was negative for all animals, but was higher for lambs fed the high level of potassium ( $P < .05$ ). This is attributable to the large decrease in urinary magnesium excretion. A slight increase in magnesium retention when 4.9% potassium was fed to lambs was reported by Newton et al. (1972). These results are generally in agreement with those of others. Fontenot et al. (1960) found absorption and urinary excretion of magnesium was significantly depressed when a high-protein, high potassium diet was fed to sheep. Newton et al. (1972) observed a 46% decrease in apparent magnesium absorption due



to high potassium intake. In studies with  $^{28}$ magnesium, they showed that the increase in fecal magnesium excretion is due to a decrease in magnesium absorbed rather than an increase in endogenous losses. Greene (1981) reported linear decreases in magnesium absorption in sheep and steers when increasing amounts of potassium up to 4.8% of the diet were fed.

There were no significant soluble carbohydrate x potassium interactions. The effects of high potassium intake were similar at both levels of carbohydrate. In the study by House and Mayland (1976), magnesium availability was only 1 to 2% of the intake for all treatments and they suggested that certain dietary factors, such as potassium level (2.4%), made it difficult to demonstrate any effects soluble carbohydrate level might have on magnesium absorption. In the present study, magnesium availability ranged from 21.0 to 7.7% and the response to soluble carbohydrate level was not affected by potassium level.

Magnesium flow and absorption along the different regions of the digestive tract are presented in table 5. In all sheep the quantity of magnesium leaving the preintestinal area was lower than in the diet. Magnesium flow was similar for both soluble carbohydrate treatment groups, except in the large intestine. Here, the high soluble car-

TABLE 5. MAGNESIUM INTAKE, FLOW AND ABSORPTION IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	.70	.70	.61	.61	
Flow, g/day					
Preintestinally <sup>a</sup>	.37	.40	.38	.41	.02
Small intestine <sup>a</sup>	.53	.59	.49	.61	.01
Large intestine <sup>a</sup>	.52	.65	.48	.58	.01
Absorption					
Preintestinal					
Grams/day	.33	.30	.23	.20	.02
Percent of intake	47.07	43.19	38.08	32.74	3.53
Small intestine					
Grams/day	- .16	- .19	- .11	- .20	.03
Percent of amt. entering	- 49.62	- 91.71	- 30.97	- 67.98	18.09
Large intestine					
Grams/day	.01	- .06	.01	.03	.01
Percent of amt. entering	1.93	- 4.67	.78	6.00	1.16
Total					
Grams/day <sup>a</sup>	.18	.05	.13	.03	.01
Percent of intake <sup>a</sup>	25.54	6.99	19.40	5.45	1.16

<sup>a</sup>Affected by potassium level (P < .05).

bohydrate treatments tended to result in smaller amounts flowing through the large intestine and excreted in the feces. Generally, magnesium flow through the preintestinal region, small intestine ( $P < .05$ ) and large intestine ( $P < .05$ ) was increased in lambs consuming the high potassium diets.

The primary site of magnesium absorption for all animals was the preintestinal region (table 5). A net secretion and both a net secretion and absorption of magnesium were observed in the small and large intestines, respectively. Expressed as a percent of intake, approximately 45 and 35% of the magnesium was absorbed in the stomach area for the low and high soluble carbohydrate diets, respectively. Smaller amounts of magnesium tended to be absorbed in the preintestinal region in lambs fed the high soluble carbohydrate diet, but the difference was not significant. Substantial amounts of magnesium were secreted in the small intestine by lambs fed both levels of soluble carbohydrate. Level of soluble carbohydrate did not affect magnesium absorption in the small intestine. There was a trend for a net secretion of magnesium in the large intestine of lambs fed low soluble carbohydrate diets and a net absorption for animals fed the high soluble carbohydrate diets.

These results do not agree with those of Rayssiguier and Poncet (1980). In their study, the addition of 400 g of

lactose per day to a diet of alfalfa hay increased preintestinal absorption of magnesium by 34% and increased the secretion of magnesium into the small intestine (.03 vs .25 g/d). The addition of lactose was associated with a decrease in rumen fluid pH to approximately 5.2. They suggested the addition of lactose may have influenced magnesium absorption by lowering pH in the rumen, thus increasing magnesium availability. In the present study, rumen fluid pH ranged from 6.31 to 7.41 (table 3). The addition of soluble carbohydrate caused only a relatively small decrease in rumen pH compared to the decreases reported by Rayssiquier and Poncet (1980). A greater modification of pH might be required before magnesium availability or solubility is significantly affected. Horn and Smith (1978) reported that magnesium absorption was significantly increased from control values when 800 ml of .2M hydrochloric acid was infused in the rumen of steers over an 8 h period, as rumen pH decreased from 5.6 to 5.3. They showed that ruminal pH was negatively correlated to the proportion of dietary magnesium absorbed. Absorption was greatest when rumen pH was 6 or lower. In vitro research by Grace et al. (1977) suggested the binding of magnesium in insoluble forms was greatly increased as the pH of the rumen, duodenal and ileal digesta were raised from 5 to 6.

When 4% potassium was fed (table 5) smaller amounts of magnesium tended to be absorbed in the preintestinal region. Expressed as percent of intake, preintestinal absorption was depressed from 42.6 to 38.0% when .6 and 4% potassium were fed, respectively. Flow of magnesium through the small and large intestine was increased ( $P < .05$ ) when high levels of potassium were fed, and more magnesium appeared to be secreted into the small intestine. It is unlikely that the small increase in rumen pH observed in animals supplemented with potassium bicarbonate is totally responsible for the decrease in magnesium absorption, since ruminal pH was similar for the low-soluble carbohydrate, low-potassium diet (6.81) and the high-soluble carbohydrate, high-potassium diet (6.84), with only the latter affecting magnesium absorption.

Greene (1981) reported similar results in sheep. In lambs, feeding .6, 2.4 and 4.8% potassium depressed magnesium absorption linearly in the preintestinal region (49.2, 44.7 and 38.1%, respectively). He reported similar results in steers.

#### POTASSIUM BALANCE AND ABSORPTION

Dietary soluble carbohydrate level did not affect the absorption or retention of potassium (table 6). Increasing

TABLE 6. POTASSIUM BALANCE IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	3.52	25.43	3.46	25.37	
Excretion, g/day					
Fecal <sup>a</sup>	.50	1.09	.49	.79	.04
Urinary <sup>a</sup>	2.44	12.22	2.35	11.85	.81
Total <sup>a</sup>	2.94	13.31	2.84	12.64	.81
Absorption					
Grams/day <sup>a</sup>	3.02	24.34	2.97	24.58	.03
Percent of intake <sup>a</sup>	85.70	95.72	85.83	96.87	.75
Retention, g/day <sup>a</sup>	.58	12.12	.62	12.73	.81

<sup>a</sup>Affected by potassium level (P < .05).

potassium in the diet increased ( $P < .05$ ) fecal excretion of potassium (.50 vs .94 g/d). When 4% potassium was fed, absorption was increased from approximately 3.0 to 24.4 g/d. As a percent of intake, potassium absorption averaged 85.5% at the low potassium level and 95.8% at the high potassium level. Despite dietary potassium level, the urine appeared to be the primary site of potassium excretion. When high levels were fed approximately 50% of the absorbed potassium was excreted in the urine. Urinary potassium excretion increased ( $P < .05$ ) from 7.6 to 12.0 g/d when .6 and 4% potassium were fed, respectively. Animals receiving higher levels of potassium also retained more ( $P < .05$ ) than those on the low potassium diets (12.4 vs .6 g/d).

Suttle and Field (1967) reported that feeding 4.2% potassium or infusion of equivalent amounts into the rumen with 7.5 liters of water increased fecal potassium excretion by 88% and urinary excretion of potassium (33.5 vs 7.74 g/d). Addition of potassium to the diet increased retention (4.41 vs 1.41 g/d); whereas, infusion of potassium into the rumen with water significantly increased urinary excretion and decreased retention of potassium (-1.62 g/d). Newton et al. (1972) reported that lambs consuming 4.9 vs .6% potassium consistently absorbed a higher percentage of potassium and excreted more potassium in the urine. Potassium reten-

tion tended to be higher in lambs fed the high potassium diet. Thus, high dietary levels of potassium have generally been reported to increase absorption and urinary excretion of potassium, while inconsistent effects on fecal excretion and retention have been reported.

Abomasal and ileal samples collected during the sampling period showed that a net absorption of potassium occurred in all three regions of digestive tract (table 7). However, the main site of absorption was altered by the potassium level. At the low level of potassium, the primary site of absorption was the small intestine (2.91 g/d) with smaller amounts absorbed in the large intestine (1.17 g/d). A net secretion of potassium occurred in the preintestinal region at the low potassium level. In sheep fed high potassium diets, the stomach was the main site of absorption ( $P < .05$ ). In the small intestine, an increase in dietary potassium resulted in higher amounts ( $P < .05$ ) absorbed when expressed as either g/d (7.60 vs 2.70) or the percent of the mineral entering the region (67.0 vs 61.4%). Potassium absorption in the large intestine was similarly affected, although the difference was not significant. The increase in the apparent availability of potassium ( $P < .05$ ) for the high potassium diets appears to be a result of increased potassium absorption along all segments of the digestive



TABLE 7. POTASSIUM INTAKE, FLOW AND ABSORPTION IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	4.04	25.93	3.78	25.69	
Flow, g/day					
Preintestinally <sup>a</sup>	4.63	11.70	4.19	11.05	.50
Small intestine <sup>a</sup>	1.72	4.17	1.66	3.39	.14
Large intestine <sup>a</sup>	.55	1.08	.54	.87	.03
Absorption					
Preintestinal					
Grams/day <sup>a</sup>	-.59	14.23	-.41	14.64	.51
Percent of intake <sup>a</sup>	-14.97	54.85	-11.11	57.00	2.36
Small intestine					
Grams/day <sup>a</sup>	2.91	7.53	2.53	7.65	.56
Percent of amt. entering <sup>a</sup>	62.54	64.81	60.29	69.11	3.47
Large intestine					
Grams/day <sup>a</sup>	1.17	3.09	1.12	2.52	.12
Percent of amt. entering	66.07	72.76	65.39	72.50	1.61
Total					
Grams/day <sup>a</sup>	3.49	24.85	3.24	24.82	.03
Percent of intake <sup>a</sup>	86.48	95.82	85.69	96.61	.42

<sup>a</sup>Affected by potassium level ( $P < .05$ ).

tract, the effect being most pronounced in the preintestinal region.

Other researchers have reported similar results. Grace et al. (1974) reported considerable variation in the amount of potassium absorbed in the stomach region of sheep when potassium intake ranged from 3.14 to 4.95% of the diet. Usually, a net absorption of potassium occurred in the stomach region. Using sheep and steers, Greene (1981) observed that increasing dietary potassium from .6 to 4.8% caused an increase in the absorption of potassium from all segments of the digestive tract. At the higher levels, the preintestinal region became an important site of potassium absorption.

#### CALCIUM BALANCE AND ABSORPTION

Calcium balance data are presented in table 8. Apparent absorption and retention of calcium tended to be higher for the animals consuming the high soluble carbohydrate diet, but the differences were not significant. Madsen et al. (1976) indicated apparent calcium absorption tended to be higher when glucose was supplemented to hay-fed sheep, but no effects were observed when glucose was supplemented to sheep receiving grass. House and Mayland (1976) reported calcium absorption and retention in sheep were not affected by either starch or sucrose supplementation.

TABLE 8. CALCIUM BALANCE IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	3.06	3.07	2.83	2.83	
Excretion, g/day					
Fecal	3.09	2.95	2.58	2.60	.07
Urinary <sup>a</sup>	.19	.06	.18	.07	.01
Total	3.28	3.01	2.76	2.67	.06
Absorption					
Grams/day	-.03	.12	.25	.23	.07
Percent of intake	-.99	3.72	8.92	8.32	2.30
Retention					
Grams/day	-.22	.06	.07	.16	.06
Percent of intake	-7.37	1.73	2.40	5.76	2.23

<sup>a</sup>Affected by potassium level (P < .05).

Urinary excretion was depressed ( $P < .05$ ) and retention tended to be higher for the sheep receiving the high potassium diets. The effects of increased potassium intake on calcium utilization have been inconsistent. Fontenot et al. (1960) found that calcium absorption and retention were higher when lambs were fed a high protein, high potassium diet. Suttle and Field (1967) reported that fecal calcium excretion and retention were not significantly affected when high potassium diets were fed to sheep. A trend for increased calcium absorption and retention in sheep fed 4.9% potassium was observed by Newton et al. (1972).

Neither soluble carbohydrate nor potassium level affected the flow of calcium along any segment of the digestive tract (table 9). In the present study, the primary site of calcium absorption was the preintestinal region, with an average of 1.26 g/d or 38.8% of the amount ingested absorbed in this region. A net secretion of calcium into the small intestine was followed by a smaller secretion into the large intestine. The amount secreted tended to be proportional to the amount of calcium absorbed in the preintestinal region. Similar results were observed by Grace et al. (1974). In their study using sheep fed various types of herbage, calcium was absorbed mainly in the preintestinal region, followed by a net secretion into and a small absorp-

TABLE 9. CALCIUM INTAKE, FLOW AND ABSORPTION IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	3.40	3.40	2.95	2.94	
Flow, g/day					
Preintestinally	1.94	1.88	2.01	1.80	.10
Small intestine	2.68	2.85	2.52	2.35	.07
Large intestine	3.19	3.19	2.87	2.75	.05
Absorption					
Preintestinal					
Grams/day	1.46	1.52	.94	1.14	.11
Percent of intake	42.25	43.64	31.03	38.15	3.27
Small intestine					
Grams/day	-.74	-.97	-.51	-.55	.12
Percent of amt. entering	-39.30	-121.23	-28.05	-49.40	24.24
Large intestine					
Grams/day	-.51	-.34	-.35	-.40	.06
Percent of amt. entering	-20.85	-11.93	-13.91	-21.07	2.90
Total					
Grams/day	.21	.21	.08	.19	.06
Percent of intake	6.22	6.22	3.42	5.97	1.84

tion from the small and large intestines, respectively. Greene (1981) reported conflicting results using sheep and steers. In sheep, when dietary calcium was supplied mainly by limestone, calcium was secreted into the stomach and large intestine and absorbed from the small intestine. In steers receiving a diet similar to the sheep with the addition of hay and dicalcium phosphate, calcium was absorbed primarily from the preintestinal region and large intestine. Rayssiguier and Poncet (1980) observed that the addition of lactose to a diet of hay altered the primary site of calcium absorption in sheep. When hay was fed alone, calcium was absorbed primarily in the small intestine. When supplemented with lactose, preintestinal calcium absorption increased from .13 to 2.37 g/d and a net excretion of calcium was observed in the small and large intestine.

#### SODIUM BALANCE AND ABSORPTION

Soluble carbohydrate level did not affect the total amount of sodium absorbed or retained (table 10). When expressed as a percent of intake, sodium availability tended to be higher (78.5 vs 72.8%) for lambs receiving the high soluble carbohydrate diet. Grace et al. (1974) observed that apparent availability of sodium ranged from 84 to 96% when sheep were fed various types of herbage. They reported

TABLE 10. SODIUM BALANCE IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	1.88	1.87	1.65	1.64	
Excretion, g/day					
Fecal <sup>a</sup>	.78	.23	.51	.20	.03
Urinary <sup>a</sup>	1.13	1.66	1.07	1.55	.04
Total	1.91	1.89	1.58	1.74	.03
Absorption					
Grams/day <sup>a</sup>	1.10	1.64	1.13	1.44	.04
Percent of intake <sup>a</sup>	58.32	87.12	69.23	87.71	1.90
Retention, g/day	-.03	-.02	.07	-.10	.03

<sup>a</sup>Affected by potassium level (P < .05).

that the type of diet had a more pronounced effect on sodium flow than sodium intake level.

Increasing dietary potassium level to 4% resulted in less ( $P < .05$ ) sodium fecal excretion. This resulted in an increase ( $P < .05$ ) in apparent sodium absorption (1.54 vs 1.12 g/d) when high potassium levels were fed. However, retention was similar for all treatments due to an increase in urinary sodium excretion ( $P < .05$ ) with the high potassium level. These results are in agreement with those of Fontenot et al. (1960) when a high protein, high potassium diet was fed to sheep, and Newton et al. (1972) when 4.9% potassium was fed to lambs.

In all animals the quantity of sodium entering the intestinal region was greater than that in the diet (table 11). McDougall (1948) reported that sodium is the major cation in mixed ruminant saliva which normally contains about 180 mEq/liter of sodium and that the potassium concentration is approximately 1/10 that of the sodium concentration. In the present study, small amounts of sodium were secreted into the small intestine, with the large intestine being the primary site of sodium absorption. Sodium absorption was between 93 to 96% complete in the large intestine. Perry et al. (1967) observed a net secretion of sodium into the upper small intestine of calves. They estimated that an



TABLE 11. SODIUM INTAKE, FLOW AND ABSORPTION IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	2.19	2.19	1.79	1.79	
Flow, g/day					
Preintestinally <sup>a</sup>	8.99	4.65	8.04	4.33	.26
Small intestine <sup>b</sup>	9.11	8.56	6.88	6.94	.18
Large intestine <sup>a</sup>	.65	.33	.49	.24	.11
Absorption					
Preintestinal					
Grams/day <sup>a</sup>	-6.80	-2.46	-6.25	-2.54	.26
Percent of intake <sup>a</sup>	-316.11	-104.67	-354.55	-144.38	14.16
Small intestine					
Grams/day <sup>a,b</sup>	-.12	-3.91	1.16	-2.61	.24
Percent of amt. entering <sup>a</sup>	-3.01	-129.13	14.92	-71.73	13.45
Large intestine					
Grams/day <sup>b</sup>	8.46	8.23	6.39	6.70	.18
Percent of amt. entering	92.83	96.39	92.58	96.38	.41
Total					
Grams/day <sup>a</sup>	1.54	1.86	1.30	1.54	.03
Percent of intake <sup>a</sup>	71.31	86.11	72.34	86.98	1.49

<sup>a</sup>Affected by potassium level (P <.05).

<sup>b</sup>Affected by soluble carbohydrate level (P <.05).

average of 133 g of sodium were secreted into this region daily. Approximately 87% of this was absorbed during passage through the lower gut.

Increasing the dietary soluble carbohydrate level had no effect on preintestinal sodium flow. A net absorption of sodium in the small intestine and a decrease in the amount secreted were observed in animals fed the high soluble carbohydrate diets ( $P < .05$ ). Consequently, less sodium entered the large intestine and less was absorbed ( $P < .05$ ) there (6.5 vs 8.35 g/d). When expressed as a percent of intake, total sodium absorption was similar for both soluble carbohydrate levels.

When 4% potassium was fed, there was a marked decrease ( $P < .05$ ) in the sodium flowing through the preintestinal region (2.5 vs 6.5 g/d). Hungate (1966) indicated that sodium levels in the saliva decrease reciprocally with an increase in potassium levels to maintain a combined constant concentration of about 190 mEq/liter. Greater amounts of sodium were secreted into the small intestine ( $P < .05$ ) as a result of increased potassium intake, and a higher percentage of sodium entering the large intestine tended to be absorbed there. The increase in apparent sodium absorption ( $P < .05$ ) from 71.8 to 86.5% of the intake when .6 and 4% potassium were fed, respectively, appears to result primar-

ily from a decrease in the amount of sodium secreted into the saliva and preintestinal secretions.

Grace et al. (1974) reported that considerably less sodium was secreted into the preintestinal region in sheep consuming a white clover diet (4.9% potassium). Sodium availability as a percent of intake was not influenced by the potassium level of the herbage.

In sheep and steers fed .6, 2.4 and 4.8% potassium, Greene (1981) observed that less sodium was secreted into the preintestinal region, and absorbed in the small intestine at the higher levels of potassium.

#### PHOSPHORUS ABSORPTION

Phosphorus absorption data are shown in table 12. Due to the dilution of the urine the phosphorus content was too low to be determined, and therefore retention could not be calculated. Increasing the soluble carbohydrate or potassium level of the diet had no significant effects on apparent phosphorus absorption (table 12). An average negative absorption of 3.2 g of phosphorus occurred in the preintestinal region (table 13). The small intestine was the primary site of phosphorus absorption, with smaller amounts absorbed in the large intestine. Grace et al. (1974) also reported considerable net secretion of phosphorus into the

TABLE 12. PHOSPHORUS ABSORPTION IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	1.97	1.96	1.89	1.89	
Excretion, g/day					
Feces	1.99	1.77	1.75	1.60	.05
Absorption					
Grams/day	-.02	.19	.13	.29	.05
Percent of intake	-1.18	9.72	7.05	14.97	2.64

TABLE 13. PHOSPHORUS INTAKE, FLOW AND ABSORPTION IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Intake, g/day	1.92	1.90	1.86	1.84	
Flow, g/day					
Preintestinally	5.70	4.28	5.34	5.19	.29
Small Intestine	2.02	1.85	1.92	1.67	.06
Large Intestine	1.73	1.74	1.61	1.52	.04
Absorption					
Preintestinal					
Grams/day	-3.78	-2.38	-3.48	-3.35	.29
Percent of intake	-198.09	-123.54	-187.25	-183.66	15.48
Small intestine					
Grams/day	3.68	2.43	3.43	3.52	.31
Percent of amt. entering	63.75	45.92	63.38	66.22	4.17
Large Intestine					
Grams/day	.29	.11	.31	.15	.06
Percent of amt. entering	13.21	5.30	15.91	4.00	1.51
Total					
Grams/day	.19	.16	.25	.32	.04
Percent of intake	10.01	8.58	13.53	17.55	2.24

stomach and a large net absorption from the small intestine. Rayssiguier and Poncet (1980) observed an average increase in apparent phosphorus absorption of .26 g/d when sheep were supplemented with lactose. Phosphorus absorption in the small and large intestine tended to be increased in these animals.

In lambs consuming high potassium diets, less phosphorus tended to be excreted in the feces, and apparent phosphorus absorption tended to be higher (12.3 vs 4.1%). The amount of phosphorus entering the preintestinal region was decreased slightly and flow through the small intestine was less in lambs receiving 4% potassium. Greene (1981) reported that absorption was increased in steers fed high levels of potassium. The increase in absorption appeared primarily due to smaller amounts of phosphorus secreted into the preintestinal region.

#### SERUM MINERALS

The concentrations of magnesium, calcium, potassium and sodium in the serum are shown in table 14. There were no significant soluble carbohydrate x potassium interactions for any of the reported serum minerals.

Serum magnesium and calcium levels were not significantly affected by soluble carbohydrate level of the diet.

TABLE 14. SERUM MINERALS OF WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
	mg/dl				
Magnesium	2.14	1.95	2.04	1.98	.03
Calcium	9.37	9.11	9.25	9.10	.10
Potassium <sup>a,b</sup>	15.72	17.19	14.37	15.02	.35
Sodium	325.00	320.80	329.00	307.50	5.27
Phosphorus	8.56	8.01	8.34	8.99	.11

<sup>a</sup>Affected by soluble carbohydrate level (P < .05).

<sup>b</sup>Affected by potassium level (P < .05).

Inconsistent results of carbohydrate supplementation on serum magnesium levels have been reported. Boling et al. (1979) reported serum magnesium levels were only slightly increased from 1.9 to 2.1 mg/dl when cows were supplemented with a carbohydrate source. House and Mayland (1976) observed no effect on plasma magnesium and calcium levels in wethers supplemented with 18.5% starch or sucrose. Lactose supplementation increased plasma magnesium levels from 1.78 to 1.97 mg/dl in adult sheep (Rayssiguier and Poncet, 1980).

The addition of 4% potassium to the diet tended to depress serum magnesium and calcium levels. Serum magnesium levels averaged 2.09 and 1.96 mg/dl and calcium levels were 9.31 and 9.10 mg/dl when .6 and 4% potassium were fed, respectively. High levels of dietary potassium have been reported to result in lowered magnesium levels by Fontenot et al. (1960) and Suttle and Field (1967). In the present study, it is likely that the magnesium intake was sufficient to meet the animals' requirements. Since excess magnesium is excreted rather than stored in mature ruminants, a decrease in the amount of magnesium absorbed is reflected by a decrease in urinary excretion instead of a drop in serum magnesium levels, unless the level absorbed is critical.

Increased dietary soluble carbohydrate level was associated with reduced ( $P < .05$ ) potassium levels in the serum.



Madsen et al. (1976) observed a general trend for plasma potassium levels to be lowered as the amount of glucose added to the diet increased. Plasma levels were 18.28, 16.67, 17.35 and 16.37 mg/dl when 0, 50, 100 and 250 g of glucose were fed, respectively. Serum potassium levels were increased ( $P < .05$ ) when potassium intake was increased (15.0 vs 16.1 mg/dl). Newton et al. (1972) reported a trend for an increase in serum potassium when 4.9% potassium was fed. Suttle and Field (1967) observed an average increase of 4.9 mg/dl of potassium when lambs were fed 4.2% potassium.

Serum sodium and phosphorus levels were not significantly affected by the soluble carbohydrate or potassium treatments. Similar results were reported by Newton et al. (1972) and Greene (1981).

#### PLASMA GLUCOSE, INSULIN AND GLUCAGON

Table 15 shows the concentrations of plasma glucose, insulin and glucagon in sheep prior to and after feeding. The glucose levels in the present study are similar to those reported by Trenkle (1978). Glucose levels were not affected by the soluble carbohydrate level of the diet. However, after feeding, glucose levels generally increased ( $P < .05$ ) from pre-feeding values, with the increase tending to be higher for the animals receiving the high soluble car-

TABLE 15. PLASMA GLUCOSE, INSULIN AND GLUCAGON LEVELS IN WETHERS FED DIFFERENT LEVELS OF SOLUBLE CARBOHYDRATE AND POTASSIUM (K)

Item	Soluble carbohydrate level				S.E.
	Low		High		
	.6% K	4% K	.6% K	4% K	
Glucose, <sup>a</sup> mg/dl					
Prefeeding <sup>b</sup>	61.25	63.54	59.51	63.45	.68
Postfeeding	68.55	66.94	68.76	69.34	1.38
Insulin, <sup>a</sup> ng/ml					
Prefeeding <sup>b</sup>	.168	.037	.084	.062	.02
Postfeeding	.114	.297	.323	.327	.04
Glucagon, <sup>a</sup> ng/ml					
Prefeeding	.224	.180	.167	.168	.02
Postfeeding <sup>b</sup>	.197	.354	.283	.319	.02
Percent change					
Glucose	11.96	4.92	15.72	9.84	1.97
Insulin	35.03	3631.32	812.18	2714.43	98.40
Glucagon	-6.16	359.77	145.49	142.49	73.72
Insulin: glucagon ratio	.67	.68	.95	.80	.08

<sup>a</sup>Prefeeding values are different from postfeeding values across treatments ( $P < .05$ ).

<sup>b</sup>Affected by potassium level ( $P < .05$ ).

bohydrate diets. When expressed as percent of change between pre- and post-feeding values, the glucose levels increased 8.5 and 12.8% for the low and high soluble carbohydrate diets, respectively. Trenkle (1970) reported that plasma glucose levels depended upon the feed and feeding regimen. The concentrations of blood glucose were higher in sheep fed 30% grain diets as compared to 100% hay diets and in sheep fed unlimited amounts of corn-based diets. In cows, Jenny and Polan (1975) also observed that substitution of roughage with concentrate resulted in higher plasma glucose levels.

Pre-feeding or basal plasma glucose levels were elevated ( $P < .05$ ) in sheep fed 4% potassium. After feeding, glucose levels were increased in animals fed high potassium, but the amount of increase was proportionally less (7.4 vs 13.4%). Allcroft and Burns (1968) noted that blood glucose levels were often high in cases of grass tetany. Since elevated plasma glucose levels were observed in magnesium-deficient calves infused intravenously with potassium chloride by Lentz et al. (1976), high dietary levels of potassium may be responsible for disorders in carbohydrate metabolism that often accompany the grass tetany syndrome.

Correlations between plasma glucose and insulin concentrations in ruminants are usually low (Trenkle, 1978). In the present study, pre- and post-feeding insulin levels were

not significantly affected by the soluble carbohydrate level of the diet. Insulin levels were higher ( $P < .05$ ) after feeding, which is similar to what Trenkle (1970) reported. However, the postprandial increase tended to be greater when readily available carbohydrates were present in the diet (.325 vs .205 ng/ml). The trend for higher postfeeding insulin levels could be due to higher levels of ruminal propionic acid (table 15). Trenkle (1970) observed that intrajugular injection of propionate and butyrate caused marked increases in plasma insulin levels of sheep. Plasma insulin and glucose levels were also significantly increased up to 12 h after feeding when sheep were fed a hay and grain diet, as compared to an all hay diet.

The trend for higher insulin levels when high carbohydrate diets are fed may explain the decrease in serum potassium levels (table 14) observed in this study for the high soluble carbohydrate diet. The plasma potassium-reducing action of insulin has been reported in nonruminants (Hiatt et al., 1974). In dogs, insulin was shown to be necessary for the transfer of excess potassium into the intracellular fluid.

Animals consuming high potassium diets had lower ( $P < .05$ ) prefeeding levels of plasma insulin. The cause for this effect is not apparent. The postprandial increase in

plasma insulin tended to be greater in animals fed high potassium levels (.312 vs .213 ng/ml). Increased insulin levels were accompanied by elevated potassium concentrations in calves (Lentz et al., 1976).

Glucagon levels in the present study are similar to those reported by Deetz and Wangness (1981) in wether sheep. Prefeeding concentrations of glucagon generally increased after feeding. Trenkle (1978) reported that feeding may or may not affect the concentration of glucagon in the plasma. In the present study, the amount of soluble carbohydrate in the diet did not affect the glucagon levels, whereas, postfeeding glucagon levels were increased ( $P < .05$ ) in sheep consuming the high potassium diets (.336 vs .240 ng/ml). Lentz et al. (1976) suggested that the elevated plasma insulin levels observed when calves were infused with potassium chloride could stimulate glucagon secretion.

The tendency for higher insulin levels with increased dietary soluble carbohydrate in the present study is also reflected by the slightly higher insulin to glucagon ratio observed in these animals (.87 vs .68). Basset (1978) has summarized studies that point toward the insulin to glucagon ratio and their subsequent interactions as the main factor in the control of gluconeogenesis in ruminants. Therefore, alterations in this ratio or prolonged elevations of insulin

and glucagon levels in the blood associated with increased potassium ingestion could be involved in the triggering metabolic disturbances often observed in cases of grass tetany.

## Chapter VI

### SUMMARY

Two metabolism trials were conducted with 12 wether lambs surgically equipped with abomasal and ileal cannulae to study the effects of dietary soluble carbohydrate and potassium level on magnesium metabolism in ruminants. A 2 x 2 factorial arrangement was used with diets containing 3 and 23% soluble carbohydrate and .6 and 4% potassium, dry basis. Each trial consisted of a 10-d preliminary period followed by a 7-d collection of feed, feces and urine and a 6-d sampling of feed, abomasal and ileal fluid and feces. Chromic oxide was used as an indicator to measure the flow of minerals along the digestive tract.

The pH of the rumen and ileal fluid was decreased ( $P < .05$ ) by high levels of soluble carbohydrate. Increased dietary potassium increased ( $P < .05$ ) ruminal pH. Abomasal fluid pH was not affected by soluble carbohydrate or potassium level.

Magnesium absorption and retention were not affected by the level of dietary soluble carbohydrate. High potassium levels decreased ( $P < .05$ ) magnesium absorption, expressed a g/d or percent of intake. The primary site of magnesium absorption in all animals was the preintestinal region. A

net secretion of magnesium into the small intestine was followed by a small net absorption in the large intestine. High levels of dietary potassium tended to depress preintestinal magnesium absorption and increase flow through the small and large intestine.

Soluble carbohydrate level had no effect on potassium absorption or retention. Increased potassium intake increased ( $P < .05$ ) apparent absorption, retention and urinary excretion of potassium. In animals fed the low potassium diet, potassium was absorbed primarily in the small intestine, whereas at the high level, a large net absorption occurred in the stomach region.

The addition of soluble carbohydrate had no consistent effects on calcium and phosphorus balance and absorption. Sodium absorption in the small intestine was increased ( $P < .05$ ) by the high level of soluble carbohydrate. Increased dietary potassium depressed ( $P < .05$ ) urinary calcium excretion and increased sodium availability and urinary excretion of sodium ( $P < .05$ ). Calcium was absorbed primarily in the preintestinal region. Sodium and phosphorus were secreted into the preintestinal region and absorbed primarily in the large and small intestine, respectively.

Serum magnesium and calcium levels were not affected by soluble carbohydrate level, but tended to be depressed at



the high potassium level. High dietary potassium increased serum potassium level ( $P < .05$ ), whereas high soluble carbohydrate intake decreased the level ( $P < .05$ ).

Plasma glucose, insulin and glucagon levels generally increased ( $P < .05$ ) after feeding. Feeding high levels of potassium decreased ( $P < .05$ ) prefeeding glucose and insulin concentrations and increased postfeeding insulin and glucagon ( $P < .05$ ) levels.

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**APPENDIX TABLES**

TABLE 1. SAMPLING TIME OF ABOMASAL AND ILEAL CANNULAE

Trial	Day	Time	
		A.M.	P.M.
1	1	1200	2400
	2	0400	1600
	3	0600	1800
	4	1000	2200
	5	0800	2000
	6	0200	1400
2	1	1200	2400
	2	1000	2200
	3	0800	2000
	4	0400	1600
	5	0600	1800
	6	0200	1400

APPENDIX TABLE 2. EXAMPLE OF ANALYSIS OF VARIANCE FOR METABOLISM TRIAL DATA - MAGNESIUM ABSORPTION, G/DAY

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General Linear Models Procedure

Dependent variable: MGABS - I

Source	DF	Sum of squares	Mean Square	F value	PR>F	R-square	C.V.
Model <sup>a</sup>	6	2946.29656711	491.04942785	15.99	.0001	.849439	38.6390
Error	17	522.22537739	30.71913985				
Corrected total	23	3468.52194450			STD DEV 5.54248499	MGABS - I Mean 14.34426922	

  

Source	DF	Sum of squares	F value	PR>F
Trial	1	1180.71146110	38.44	.0001
Block	2	61.25954357	1.00	.3895
CHO	1	88.41142119	2.88	.1080
K	1	1584.28782871	51.57	.0001
CHO x K	1	31.62631253	1.03	.3245

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<sup>a</sup>Components under "Model".

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MAGNESIUM METABOLISM IN SHEEP FED DIFFERENT LEVELS  
OF SOLUBLE CARBOHYDRATE AND POTASSIUM

by

SHARON A. GIDUCK

(ABSTRACT)

Two metabolism trials were conducted with 12 wethers surgically equipped with abomasal and ileal cannulae. A 2 x 2 factorial arrangement was used with diets containing 3 and 23% soluble carbohydrate and .6 and 4% potassium, dry basis. Each trial consisted of a 10-d preliminary period followed by a 7-d collection of feed, feces and urine and a 6-d sampling of feed, abomasal and ileal contents and feces. Chromic oxide was used as an indicator to measure the flow of minerals along digestive tract. The pH of the rumen and ileal fluid was decreased ( $P < .05$ ) by high levels of soluble carbohydrate. Increased dietary potassium increased ( $P < .05$ ) ruminal pH. Magnesium absorption and retention were not affected by the level of dietary soluble carbohydrate. High potassium levels decreased ( $P < .05$ ) magnesium absorption, expressed a g/d or percent of intake. The primary site of magnesium absorption in all animals was the preintestinal region. A net secretion of magnesium into the small intestine was followed by a small net absorption in the large intestine. High levels of dietary potassium tended to



depress preintestinal magnesium absorption and increase flow through the small and large intestine. Soluble carbohydrate level had no effect on potassium absorption or retention. Increased potassium intake increased ( $P < .05$ ) apparent absorption, retention and urinary excretion of potassium. In animals fed the low potassium diet, potassium was absorbed primarily in the small intestine, but at the high level the stomach was also important. The addition of soluble carbohydrate had no consistent effects on calcium and phosphorus balance and absorption. Sodium absorption in the small intestine was increased ( $P < .05$ ) by the high level of soluble carbohydrate. Increased dietary potassium increased sodium availability and urinary excretion ( $P < .05$ ). Calcium was absorbed primarily in the preintestinal region. Sodium and phosphorus were secreted into the preintestinal region and absorbed from the large and small intestine, respectively. Serum magnesium and calcium levels were not affected by soluble carbohydrate level, but tended to be depressed at the high potassium level. High dietary potassium increased serum potassium level ( $P < .05$ ), whereas high soluble carbohydrate intake decreased the level ( $P < .05$ ).