SOME EFFECTS OF FEEDING POTASSIUM, SODIUM AND CALCIUM UPON GROWTH OF LAMBS RECEIVING A POTASSIUM DEFICIENT DIET

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ABSTRACT

SOME EFFECTS OF FEEDING POTASSIUM, SODIUM AND CALCIUM UPON GROWTH OF LAMBS RECEIVING A POTASSIUM DEFICIENT DIET

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A 56-day feeding trial was conducted with 128 Western range lambs to study the effect upon growth and various plasma electrolytes of adding dietary cations (K, Na, Ca) to a potassium deficient ration (0.1% K). In addition, a 28-day equalized group feeding trial (0.3% K and 0.6% K fed to two groups of 8 lambs each) and an appetite trial (KCl administered by intraruminal injection or addition to the drinking water) were conducted to study the effect of potassium upon growth and appetite behavior of lambs. Semi-purified rations containing dried brewers grains, cornstarch, solka floc, beet pulp, and animal tallow were fed in each trial.

Data from the feeding trial showed that dietary potassium markedly affected appetite in growing lambs. Feeding 0.1% K resulted in decreased feed consumption, loss of weight, listlessness, pica and hypertrophied kidneys. Feed consumption decreased rapidly within 24 hours in lambs receiving 0.1% K. Conversely feed consumption increased markedly within 24 hours when these lambs were switched to 0.6% K

in the ration. A decrease in plasma potassium concentration was associated with the decrease in appetite.

The addition of sodium or calcium, or a metabolizable anion ($CO_3^=$) was not significantly effective in alleviating the potassium deficiency symptoms.

Potassium deficient lambs exhibited a pica of wool biting to the extent that some lambs were partially devoid of wool.

Dietary level of potassium greater than 0.6% of the ration did not adversely affect lamb growth when 0.21% sodium was fed. However 0.7 and 1.2% sodium in the ration adversely affected lamb growth when fed in conjunction with 0.6% K.

Potassium levels in the ration did not significantly affect plasma concentrations of sodium, calcium, magnesium and phosphorus. Plasma chloride level was significantly ($P < 0.01$) decreased by high dietary potassium (1.1% K).

The equalized group feeding trial indicated that potassium affects growth but not volatile fatty acid production in lambs receiving equal quantities of rations containing 0.3 and 0.6% K.

Lambs receiving potassium by intraruminal injection consumed more feed and gained more weight than lambs fed a potassium deficient diet. However lambs receiving potassium in the drinking water gained more weight than the lambs intraruminally injected.

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INTRODUCTION

Potassium is unique among the major dietary elements required by man and animal because deficiencies of this element under normal conditions are very rare. Any natural diet consumed by ruminants would probably never be deficient in potassium and presumably for this reason very little consideration has been given to potassium as a dietary constituent. In recent years, there has been much interest in high concentrate rations for fattening cattle and sheep. Differences in physiological and biochemical responses to these diets have been extensively investigated in terms of physical form, fibre content, rate of digestion and rate of passage. However, one of the most striking differences between high-roughage and high-concentrate rations is that the potassium intake may be as much as fourfold higher in animals consuming mostly forage.

The potassium requirement for sheep has been shown to be about 0.5% of the air-dry ration and it is thought that some high-concentrate rations may contain a level of potassium less than 0.5%. The responses of sheep to feeding potassium deficient rations have been demonstrated; however, there is still a dearth of information on potassium function and the dietary factors which may influence the potassium requirement of ruminants.

The objectives of this study were (1) to investigate the effects upon growth of lambs of supplying various dietary cations (K, Na, Ca) to a potassium deficient ration: (2) to determine if potassium per se affects the production of volatile fatty acids in the rumen and (3) to study the appetite behavior of lambs when supplemented with potassium by various methods.

LITERATURE REVIEW

Functions of Potassium Within the Animal Body

Potassium and sodium, the major monovalent cations within the body, are usually discussed in relation to one another. Potassium exists primarily intracellularly and exerts most of its effects at the cell level, while sodium is found primarily in the extracellular fluid. The explanation for preferential concentrating of potassium within the cell relates basically to the minimal free energy required for the maintenance of the "balanced state" in cells having easily distensible membranes (17). Since cell membranes are not ideally semipermeable, sodium ions would slowly "leak" into the cell and potassium ions would "leak" out. This situation necessitates the presence of sodium and potassium pumps to maintain the "balanced state." Several models for coupled transport of sodium and potassium between the intracellular and extracellular space have been proposed (77). The coupled transport is thought to be facilitated through a potassium carrier X, and a sodium carrier Y. Outside the cell, X combines with a potassium ion to form KX which moves into the cell. Inside the cell, X is changed to Y in an endergonic reaction. This carrier then combines with a sodium ion to form NaY which moves out of the cell. The carrier Y then undergoes a reverse reaction to form carrier X.

Active transport of potassium and sodium across the cell membrane plays an important part in certain potassium dependent phenomena. These include the electrical activity of nerve and muscle cells and synaptic transmission (32), electrolyte and water distribution between various body fluid compartments, intra- and extracellular pH (31), cellular respiration (1, 6), gastrointestinal function (61) and urine formation.

Metabolically, potassium has been shown to affect the activity of at least ten enzymes (70). Rendi and Uhr (58) identified the properties of adenosine triphosphatase by isolating and purifying this enzyme from calf liver homogenate. It was found that ATPase hydrolyzes the terminal phosphate group of ATP and its activity is dependent upon concentrations of sodium and potassium ions. Sodium has been shown to be antagonistic to several of the potassium activated enzymes (70). Thus, an influx of sodium into the cell during potassium depletion could result in irregularities of intermediary metabolism, particularly glycogen synthesis and protein anabolism.

In vitro studies, utilizing liver slices (24) and rabbit brain slices (1), have shown that deposition of glycogen in the liver was accompanied by deposition of potassium and that glycogenesis decreased during potassium depletion. It is probable that the role of potassium in carbohydrate metabolism is as an enzyme activator. Boyer (7, 8) observed that potassium was required for the transfer of phosphate from 2-phosphopyruvate to creatine, resulting in the formation of ATP.

Data from _in vivo_ studies on the effect of potassium on carbohydrate metabolism have been inconsistent (76). The work of Fuhrman (28) has shown that during potassium depletion in rats, liver glycogen levels increased. On the other hand, Gardner _et al_ (29) observed that rats depleted of potassium for 120 days had extremely low levels of liver glycogen. The discrepancies of the _in vivo_ data are probably due to factors other than potassium _per se_. Since a lack of potassium markedly depresses appetite (13) the low liver glycogen levels are likely due to starvation.

The consistency of the potassium to protein ratio in muscle suggests a relationship between potassium and protein metabolism. In muscle, this relationship is 3 mM of potassium for 1 g of nitrogen (31). One of the specific effects of potassium on protein anabolism is active transport of amino acids. Yunis and Arimura (79) observed that the level of Na- K-dependent ATPase (58) was considerably higher in immature erythrocytes (reticulocytes) than in mature erythrocytes. They observed that decrease in enzyme activity of red cell upon maturation occurs concomitantly with loss of capacity to concentrate amino acids. This supports the hypothesis that Na- K-dependent ATPase plays an important role in transport and intracellular distribution of amino acids (76).

Experiments have indicated that poor growth resulting from potassium deficiency is related to protein metabolism. Cannon _et al_ (14) fed two groups of rats a basal ration adequate in all respects except potassium. One group received potassium and the other did not. The group receiving potassium gained significantly more weight, even though feed intake was quite similar in both groups. Muntwyler et al (51) reported that rats consuming a low potassium ration exhibited poor growth and lower nitrogen retention than rats fed adequate potassium. They suggested that the poor growth was due to an impairment of nitrogen anabolism caused by a potassium deficiency. Leach et al (41) observed a definite interrelationship between potassium requirement and protein level in the diet of chicks. When chicks were fed increasing levels of protein, the potassium requirement of the chick for growth and survival increased, but not in proportion to the protein increase. Campbell and Roberts (13) showed that relatively less nitrogen was retained by lambs fed a low potassium (13.7 mEqK) ration than those fed medium (56.1 mEqK) and high potassium (94.4 mEqK) rations. However, since they were unable to maintain equal feed intake among groups, due to the appetite effect of the low potassium treatment, it is difficult to ascertain whether the lowered nitrogen retention was a potassium effect or the result of a marked reduction in nitrogen intake. St. Omer (64), on the other hand, observed that nitrogen balance in heifers was not affected by levels of potassium in the ration.

Potassium Depletion

Potassium depletion is accompanied by compositional changes in body tissues. In most cases, intracellular potassium is transferred to the extracellular fluid and then excreted by the kidney. This condition results not only in changes of intra- and extracellular potassium concentrations, but also in alterations in acid-base balance and changes in cellular structure and activities. Since potassium is involved in protein and glycogen anabolism, as previously mentioned, it is necessary to consider potassium depletion in terms of "potassium capacity", a concept developed by Scriber and Burnell as cited by Welt et al (76). Protein and glycogen are the major determinants of "potassium capacity". Although potassium may be lost from the body in absolute quantities, there is no cell deficit in terms of concentration if equivalent quantities of protein or glycogen are likewise dissipated. On the other hand, if protein is fed to an animal deficient in both protein and potassium, the "potassium capacity" is increased, resulting in potassium deficiency in terms of tissue and serum potassium content. Thus when inadequate protein was fed with a low potassium diet (51) rats grew slowly, but did not go into potassium deficiency, the reason being that the potassium from metabolized tissue replaced the extracellular potassium lost in the urine. However, when a protein supplemented potassium deficient diet was fed to protein-starved animals (9), they grew but developed a potassium deficiency presumably because of the increase in "capacity".

Potassium deficiency is generally measured by determining serum levels of potassium. However, Welt et al (76) reported that a low correlation between body potassium deficit and serum potassium level. This was observed when potassium deficit was estimated by either muscle analysis or by determining the total exchangeable body potassium, utilizing potassium 40. Recently Kaul et al (39) observed close agreement between balance trials and whole-body potassium 40 for determining potassium deficiency in man. Telle et al (68) suggested that plasma potassium concentrations may be of importance in diagnosing potassium deficiency in sheep. This suggestion was corroborated in part by the data of Campbell and Roberts (13). Similarly, St. Omer (64) observed a significant decrease in serum potassium levels in steers fed low potassium diets.

Dietary factors, other than lack of potassium, may also cause potassium deficiency. Recently, Nesheim et al (52) have shown that potassium deficiency in chicks can result from an anion-cation imbalance. Two groups of chicks received a purified diet containing high levels of chloride, supplied as glutamic hydrochloride. Potassium was supplied to one group as KCl and to the other as K_2CO_3. The group supplemented with the potassium salt containing an anion metabolizable to carbon dioxide and water (K_2CO_3) grew better than the other group. The workers concluded that the high chloride intake caused an acidosis, which in turn resulted in a potassium or sodium deficiency. Thacker (69) observed that a basal diet consisting of 50% timothy hay did not support growth or normal hemoglobin and bone ash levels in rabbits. Supplementing the diet with sodium, potassium, calcium or magnesium salts which carried an anion (acetate, carbonate, bicarbonate) capable of being oxidized to CO_2 and water by the animal body, resulted in superior body weight gains, efficiency of feed utilization, blood hemoglobin levels and bone ash levels. However, when these cations were fed as chloride or sulfate salts, no improvement was noted in performance over that shown by rabbits fed the basal diet. He concluded that under some dietary conditions the rabbit was forced to draw on its body stores of certain mineral cations (Ca and K) to excrete the physiological excess of anions produced (SO_4, Cl), thereby creating a potassium or calcium deficiency.

Potassium deficiencies have also been induced by gastric losses such as diarrhea, vomiting and gastric fistulas, and renal losses caused by kidney disfunction, administration of hormones and metabolic or respiratory alkalosis (22).

The consequences of potassium depletion in animals have been extensively reviewed by Welt _et al_ (76) who presented data through 1960. More recently there has been much interest in studying the consequences of potassium deficiency in ruminants. Telle _et al_ (68) reported that lambs fed less than 0.3% potassium in the ration developed potassium deficiency. Loss of appetite, listlessness, muscular weakness and death were among the symptoms observed. Histological observation showed kidney lesions and muscle fibre degeneration. The work of Campbell and Roberts (13) in general agreed with these observations. In addition they found that potassium deficient lambs exhibited a peculiar pica characterized by wool biting. Low potassium intake also resulted in low serum levels of potassium and phosphorus (13, 64, 65, 68). St. Omer (64) observed that wound healing (gluteal incisions) was significantly delayed in steers fed a 0.25% potassium ration in comparison to those fed 0.47% potassium. In contrast to the observations made by Telle et al (68) and Campbell and Roberts (13) on lambs, St. Omer found increased serum magnesium levels in steers fed a diet deficient in potassium. Similarly, Seta et al (62) and Forbes (27) observed an increase in serum magnesium of rats fed a potassium deficient diet. These contrasts may only represent species differences.

Effect of Potassium on Production and Absorption of Volatile Fatty Acids in the Rumen

Dietary minerals can influence volatile fatty acid production in the rumen. Several workers have conducted in vitro experiments to study the mineral requirements of rumen microorganisms. Hubbert et al (36, 37) using cellulose digestion and McNaught et al (45) using a decrease in non-protein nitrogen as criteria have established the optimum and toxic levels of a number of mineral elements for rumen microorganisms. It was found that a minimum concentration of 100 mcg of potassium per ml of fermentation medium was essential for satisfactory in vitro cellulose digestion (36) and for the production of VFA's.

Burroughs et al (11) were the first to observe that the addition of alfalfa hay or an equivalent amount of alfalfa ash to rations containing a high percentage of corn cobs, or poor quality forage, greatly improved the digestibility of fibre. The alfalfa ash effect has now been generally ascribed to its "trace mineral" content (3). Nicholson _et al_ 1960 (54) found that the addition of 5% alfalfa ash to a ration of corn cobs and timothy hay increased the rumen fluid concentration of total VFA's. The percentage of acetic acid tended to increase, and propionic acid to decrease, when the rations were supplemented with alfalfa ash; in addition, rumen pH values were higher for the alfalfa ash supplemented rations. More recently, Nicholson _et al_ (53) found that the addition of buffers (3% $NaHCO_3$ or 3% $NaHCO_3$ plus 2% limestone plus 1% K_2CO_3) to all concentrate rations caused a consistent decrease in dry matter per cent and total VFA concentration of rumen digesta. The percent acetic acid and the acetic to propionic acid ratio were reduced.

MacKay (42) observed that Na- or K_2HCO_3 had no effect on rumen VFA production under _in vitro_ conditions. However, _in vivo_, the concentrations of VFA's in rumen fluid and the total VFA's in the rumen of lactating cows were increased when $NaHCO_3$, Ca salts, or Na + K phosphate were added to the drinking water. The pH of rumen ingesta was lower when these minerals were added to the drinking water. This latter observation is not in agreement with other findings (53, 54). MacKay suggested that with some apparent exceptions, minerals probably exert their effects on VFA production indirectly rather than through direct action on the microbial population.

The indirect effects are on water consumption, rumen dry matter content, rumen liquid volume, rumen pH and transport of VFA's from the rumen.

Matrone _et al_ (43, 44) have found that the addition of Na- and $KHCO_3$ to purified diets caused a beneficial effect on lamb growth. They suggested that since the diets were readily fermentable, the rumen acids would be formed more quickly than when a normal diet is fed, thus requiring more rumen buffering capacity at certain times. When the purified diets were fed rumination was decreased and the flow of saliva was probably also reduced which would further decrease the total buffering capacity of the rumen. The physiological role played by Na- and $KHCO_3$ in the rumen environment may induce both quantitative and qualitative changes in the population of rumen microorganisms, as well as rate of transport of VFA's across the ruminal epithelium which in turn may affect net energy of the diet (44).

Van Campen and Matrone (71) studied the _in vivo_ and _in vitro_ incorporation of labelled carbon into individual VFA when $NaHC^{14}O_3$ was added to two purified diets in which the only difference was the presence or absence of Na- and $KHCO_3$. With both diets it was found that the propionate contained a major portion of the labelled carbon, followed in order by valerate, butyrate and acetate. The maximum incorporation of labelled carbon in propionate and valerate was reached at one and three hours, respectively, after administration of added bicarbonates. In diets containing no added bicarbonates maximum labelling of the two acids occurred at one-half and two hours, respectively. Percent incorporation of labelled carbon was more than doubled in diets containing added bicarbonates. Total VFA concentrations per ml of rumen fluid of sheep fed the bicarbonate-free diet were lower and decreased more rapidly with time after feeding than that in the rumen fluid of sheep fed Na- and $KHCO_3$. When the Na- and $KHCO_3$ were fed, the propionate level in the rumen approached or exceeded the level of acetate, whereas with the bicarbonate-free diet the level of propionate in the rumen fluid was consistently less than one-half that of the acetate.

The use of $C^{14}O_2$ in <u>in vitro</u> studies with rumen ingesta from sheep fed purified diets suggests that CO_2 plays a major role as a precursor of propionate and valerate (71). Similarly using acetate -2-C^{14}, it was found that acetate is a major precursor of butyrate and valerate. All of these reactions were apparently enhanced by the presence of Na- and $KHCO_3$ in the diet.

Feeding semipurified diets to lambs, Telle <u>et al</u> (68) found that increasing levels of $KHCO_3$ and K_2CO_3 (0.2 to 0.81% K) resulted in an increase in rumen fluid K and Mg and a decrease in rumen fluid Na. The authors suggested that the depressed growth displayed by the low potassium groups was due to a decreased action and/or number of rumen microorganisms caused by the higher Na:K ratios. The observations of Campbell and Roberts (13) agree only in part with this hypothesis. They found that increasing the potassium level of a semi-purified ration from 0.3 to 0.7% K resulted in an increase in rumen fluid K. However, they observed no significant changes in sodium concentration and pH of rumen fluid or microbial activity of rumen ingesta. St. Omer (64) found non-significant increases in pH and concentrations of sodium and potassium in rumen fluid of steers fed semi-purified rations containing 0.25 to 0.79% K. The microbial activity of rumen ingesta increased, but not significantly, as ration potassium increased.

Parathasarathy and Phillipson (55) studied the effect of potassium on the absorption of other ions and fatty acids from the rumen of sheep. They observed that the presence or absence of potassium in the rumen did not affect the absorption of acetate or propionate. Dobson (18), on the other hand, suggested that hydrogen ions derived from the conversion of carbon dioxide to bicarbonate transform the fatty acid anions into the unionized form. However, only half of the total fatty acids absorbed could leave as the free acid because the other half is equivalent to the net movement of strong electrolytes such as **sodium** and potassium from the rumen. Thus half the fatty acid is taken up as anions in conjunction with cation absorption from the rumen. Barnett and Reid (3) suggested that since the rumen wall may have an active role in the selective absorption of VFA into the blood stream, it is probable that the rumen epithelium may perform a similar function with mineral elements.

If this is the case, minerals might be expected to influence either the production of VFA's within the rumen or the absorption of VFA's from the fore-stomach.

Effect of Potassium on Appetite of Ruminants

The literature on regulation of appetite in ruminants has been reviewed by Balch and Campling (2), and Conrad (16). In summary the experimental evidence indicates that appetite is probably controlled by chemostatic mechanisms, thermoregulation and/or the presence of undigested food particles in the digestive tract (16).

Potassium has been shown to affect appetite in ruminants. Various experiments (12, 13, 59, 68, 64, 65) have shown that daily feed consumption of lambs and steers was decreased by inadequate potassium. The effect of potassium on appetite does not appear to be mediated solely via the oral cavity. St. Omer (64) observed that steers receiving a potassium deficient ration in conjunction with intraruminal injections of potassium (25 g K as K_2CO_3 daily) maintained normal serum potassium levels, displayed superior appetite and gained significantly more body weight than steers receiving the same ration but intraruminally injected with only deionized water. Roberts and Campbell (59) fed a potassium deficient diet (0.046% K) to two groups of lambs. One group of lambs received potassium (K_2CO_3) in its drinking water and the other group received tap water only. They observed that the potassium supplemented group consumed 0.60 kg of feed daily as compared to 0.24 kg for the other group.

These workers also observed that when normal and potassium deficient groups of lambs were supplied ad libitum with both tap water and potassium supplemented water in separate containers, both groups consumed equal amounts of tap water, but the normal group of sheep consumed more potassium supplemented water. The experiments of St. Omer (64) and Roberts and Campbell (59) indicate that appetite of steers and sheep is not greatly affected by the route of potassium supplementation, be it via the feed, drinking water or intraruminal injection.

Denton and Sabine (19) and Beilharz et al (5) have shown that sheep depleted of sodium by parotid fistula, showed preference and remarkably accurate adjustments to requirement in selecting solutions with high amounts of sodium. The sheep preferred $NaHCO_3$ over NaCl and varied the amount drunk to corresponding changes in sodium concentration in the drinking solution so that sodium intake remained relatively constant and approximated fistula losses (19). Sodium deficient sheep rarely consumed KCl when offered as a choice along with $NaHCO_3$ and NaCl. This work indicates that sheep can preferentially select among salts offered free choice; it is verified in part by the observations of Roberts and Campbell (59) whose normal sheep selected potassium supplemented water.

Some observations have also been made on the effects of feeding potassium deficient rations on appetite of monogastric animals. Hughes (37) observed that reduced appetite was one of the first indications of potassium deficiency in growing pigs fed a purified diet low in potassium. The pigs readily resumed eating when potassium was included in the ration. Bell and Erfle (4) determined the potassium requirement for mice and found that a potassium deficient diet reduced feed intake. On the other hand, Miller (49) observed that rats on a potassium deficient diet did not display reduced appetite and Scott _et al_ (60) reported that potassium deficient rats showed no preference for potassium containing diets in which the deficient element was supplied as potassium dihydrogen phosphate. Similarly, Sullivan (67) failed to observe a definite appetite effect in turkeys fed a potassium deficient purified diet. In light of the literature reviewed, it seems that the effect of potassium on appetite varies among species of animals.

EXPERIMENTAL PROCEDURE

Experiment 1

A 56-day feeding trial was conducted with 128 western range wether lambs. The lambs, averaging 34.2 kg each, were ear tagged and randomly allotted to 8 pens of 16 lambs each. They were adjusted for 25 days to a semi-purified ration (Table 1) containing 0.6% potassium. The basal ration supplied 0.1% K and the remaining potassium was supplied as KCl. During adjustment the amount of hay was gradually decreased, and the amount of basal ration increased until hay was eliminated and *ad libitum* consumption of the semi-purified ration was attained by all pens. Some of the lambs began to scour quite severely and ten died; thus this ration was discontinued after 25 days. A different semi-purified ration was mixed in which the KCl was replaced by K_2CO_3 and a new adjustment period was started. This time no complications were observed, and the lambs were fed *ad libitum* for 12 days. Each group was then abruptly changed to one of the eight dietary treatments shown in Table 2. *Ad libitum* feeding was continued by adding feed twice daily and the quantity of feed uneaten at the end of each week was measured. The lambs were weighed at the beginning of the experiment and at weekly intervals thereafter. Tap water, containing 2.2 ppm K and 2.4 ppm Na, was available *ad libitum*. The lambs were kept in pens located in an open fronted steel structure. The feed bunks were located in the shed, while the exercise area of the pens

TABLE 1

BASAL RATION**

Ingredient	Per cent
Brewers grains	68.9
Solka floc (cellulose)	10.0
Corn starch	8.0
Beet pulp	6.0
Animal tallow	5.0
Dehydrated alfalfa meal	1.0
Mineral-vitamin mix*	1.1

*The mineral-vitamin mix contained (in g/kg): tricalcium phosphate 648.4; sodium chloride (cobalt-iodized) 351.6; and vitamins A and D to supply 3000 and 300 I.U. respectively, per kilogram of feed.

**Contained 0.1% K, 0.21% Na and 0.33% Ca, air dry basis.

was in the open. Wood shavings were used for bedding in the feeding area. The mean temperature throughout the trial was about -18°C except for the last week during which the temperature was less than -34°C. In the remainder of the text the lambs receiving the various ration treatments (Table 2) are referred to as Groups 1 to 8, respectively.

At initiation of the trial venous blood samples were taken from six lambs randomly selected from each treatment group. Blood samples were obtained from the same lambs at subsequent times. The blood was collected in tubes containing 200 U.S.P. units of sodium heparin. After collection, 3 ml of blood were removed from each sample and the remainder centrifuged at 2000 rpm for 20 minutes. The plasma was decanted into vials and both the samples of plasma and whole blood stored at -18°C until analyzed.

Daily visual observations of the lambs were made for signs of deficiency symptoms, and any lambs considered in moribund condition were removed from the experiment. Autopsies were performed on all lambs that died.

After receiving the experimental rations for 35 days the lambs in treatment 1 were changed to treatment 2 (adequate potassium supplied as KCl). Whole blood and plasma samples were obtained from all groups at this time. Likewise, at 42 days, lambs in groups 4 and 5 were changed to treatment 2.

TABLE 2

EXPERIMENTAL TREATMENTS

Group No.	Treatment
1	basal*
2	basal + 0.5% K as KCl
3	basal + 0.5% K as K_2CO_3
4	basal + 0.5% Na as Na_2CO_3
5	basal + 0.5% Ca as $CaCO_3$
6	basal + 0.5% K as K_2CO_3 + 0.5% Na as Na_2CO_3
7	basal + 0.5% K as K_2CO_3 + 1.0% Na as Na_2CO_3
8	basal + 0.5% K as K_2CO_3 + 0.5% K as KCl

*The basal ration contained 0.1% K, 0.21% Na and 0.33% Ca, air dry basis.

At conclusion of the 56-day feeding trial 48 lambs from groups 1, 2, 4 and 5 were selected for other experiments and the remaining lambs were sold as fat lambs. The lambs kept for other experiments were sheared and moved to a heated barn where the temperature was about 10^{o}C. They were allotted to 6 pens of 8 lambs each, and all were fed the basal ration (Table 1) plus 0.5% K as K_2CO_3 for eight days.

Experiment 1b

Two pens of 8 lambs each selected from Experiment 1 were used in a 28-day equalized feeding trial to determine if lack of dietary potassium influences lamb growth. One group (A) of lambs had ad libitum access to the basal ration plus 0.2% K as K_2CO_3 and the other group (B) was fed ration 3 (basal + 0.5% K as K_2CO_3) in amounts to equal the intake of lambs in group A. Tap water was offered ad libitum. The lambs were weighed at weekly intervals during the trial, and blood and plasma samples were obtained at beginning and end of the trial. Rumen contents were collected from all lambs on the 28th day. The feed was removed in the evening prior to sampling. The following morning both groups were fed the same amount at the same time. Rumen contents were collected 3 hours later by stomach tube and a suction pump. The samples were strained through 4 layers of cheesecloth and stored at -18^{o}C until analysis for sodium, potassium and VFA's.

Experiment 2b

The remaining four groups of lambs from Experiment 1 were used to study effects of various methods of potassium supplementation upon feed consumption. All groups were switched to a ration containing 0.3% K for the remainder of the experiment. The four groups were offered water *ad libitum* and were treated as follows:

A - control

B - intraruminal injection of 10 g K as KCl per lamb every two days

C - addition of KCl to the water to supply 5 g K per lamb per day

D - a choice of one container filled with tap water and a second filled with the same KCl-water as supplied in treatment C.

Daily water and feed intake was measured during a 28-day period. The lambs were weighed once a week.

Analytical Methods

The feed, whole blood, plasma, rumen fluid and tap water samples were analyzed for sodium and potassium by flame photometry. A "Hitachi" Perkin-Elmer spectrophotometer with a flame attachment was used (33). The feed samples were dried at 60°C for 70 hours, equilibrated to room conditions, and then ground in a Wiley mill. Approximately 1.0 g samples of dried feed were wet-ashed in micro-Kjeldahl flasks with concentrated HNO_3 and 70% $HClO_4$. After digestion the samples were filtered through Whatman #40 filter paper and diluted with deionized water.

Whole blood samples were wet ashed in a similar manner. For potassium determinations, the bracketing technique was used, and also an artificial serum (30) was used in the working standards to overcome the interference caused by other cations, mainly sodium.

Plasma chloride and inorganic phosphorus were determined by the method of Schales and Schales (63) and Fister (25), respectively.

Whole blood iron and plasma calcium and magnesium were determined with a Perkin-Elmer Model 303 atomic absorption spectrophotometer according to the method of the manufacturer (56).

Volatile fatty acid of the rumen fluid was determined by gas-liquid chromatography, using the flame ionization detecting unit of a Burrel Kromotog KO gas chromatograph. Rumen fluid samples were prepared and analyzed according to the method of Erwin _et al_ (23).

Statistical methods were analysis of variance and Duncan's multiple range test as described by Steel and Torrie (66).

RESULTS

Experiment 1

Lamb Feedlot Performance. There was a marked treatment effect on lamb feedlot performance. Average body weights are illustrated in Figure 1. Over the 35-day period, lambs receiving the potassium deficient rations lost weight, the average weight loss per lamb being 7.3, 3.6 and 4.4 kg for groups 1, 4 and 5, respectively (Table 3). The weight lost by lambs fed the basal ration (group 1) was significantly greater ($P < 0.05$) than that of groups 4 and 5. After 35 days lambs in group 1 were exceptionally thin and rapidly becoming debilitated: after they were switched to the feeding regimin of group 2 they gained 5.5 kg (21 day period). Lambs in groups 4 and 5 gained 0.43 and 2.3 kg, respectively, during the 14 days on the recovery ration. Throughout the experiment, the ration containing potassium as K_2CO_3 (group 3) supported significantly ($P < 0.01$) greater weight gains than the ration containing potassium as KCl (group 2). As shown in Tables 3 and 4, lambs in group 3 gained 12.7 kg over the 56-day period while lambs in group 2 gained only 7.6 kg. Lambs receiving 1.2% Na and adequate potassium (group 7) gained significantly ($P < 0.01$) less than its control group (group 3). Lambs receiving 0.7% Na (group 6) also gained non-significantly less weight than lambs in group 3 which received no added sodium over that of the basal ration (0.2% Na). The total average

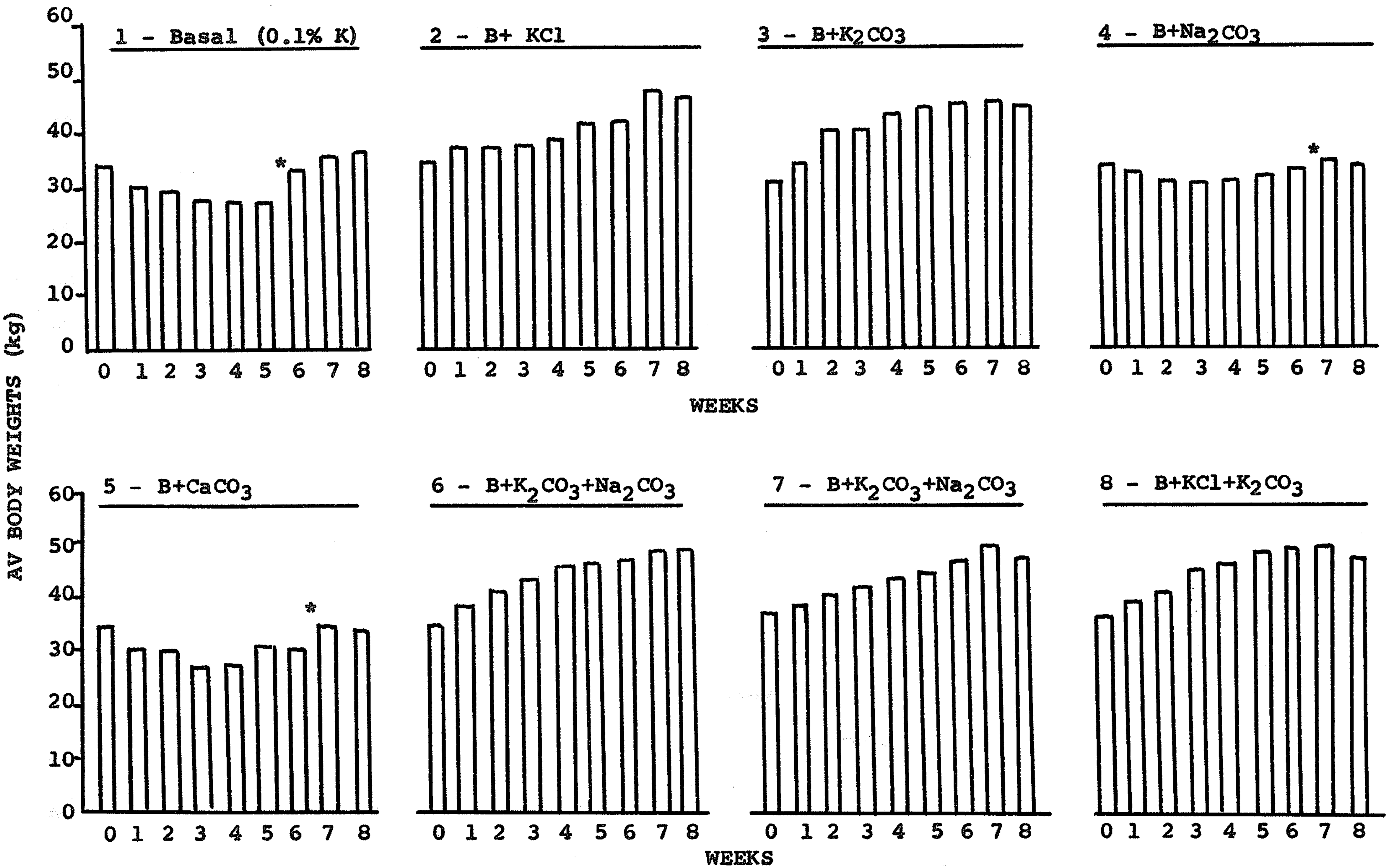


Figure 1. Average body weights of lambs fed the experimental rations.

*ration changed to B+KCl

TABLE 3

EFFECT OF ADDING K, Na, Ca TO A POTASSIUM DEFICIENT DIET UPON GROWTH OF LAMBS OVER 35 DAYS

Treatment**	No. of Lambs	Av wt Change kg	Av Daily Feed kg	Av Daily Feed/ kg Gain kg
1	16	-7.3^{A*a1}	0.42	-
2	16	5.4^{Cb}	1.12	0.21
3	16	10.9^{Db}	1.35	0.12
4	16	-3.6^{Ba}	0.56	-
5	16	-4.4^{ABa}	0.59	-
6	16	8.2^{CDb}	1.35	0.16
7	16	6.4^{Cb}	1.21	0.19
8	16	8.4^{CDb}	1.38	0.16

*A,B,C,D Treatment means within an item not showing the same superscript letter are significantly different ($P < 0.01$)

1a,b Treatment means within an item not showing the same superscript letter are significantly different ($P < 0.05$)

**1 - Basal (0.1% K); 2 - B + KCl; 3 - B + K_2CO_3; 4 - B + Na_2CO_3; 5 - B + $CaCO_3$; 6 - B + K_2CO_3 + Na_2CO_3; 7 - B + K_2CO_3 + Na_2CO_3; 8 - B + K_2CO_3 + KCl weight gains over 56 days for groups 7, 6 and 3 were 7.9, 9.7 and 12.7 kg, respectively (Table 4). This same relationship in weight gains was also observed during the initial 35 days of the trial (Table 3). High potassium in the ration (1.0% K added) did not significantly affect weight gains over the 35 or 56 day periods. Average total weight gains for animals in groups 3 and 8 at the end of the experiment were 12.7 and 11.1 kg, respectively (Table 4).

The average daily feed consumption data revealed a very marked effect of ration potassium upon appetite (Figure 2). Average feed consumption at the end of the adjustment period was about 1.15 kg for all lambs. When fed the experimental diet, feed consumption of the group 1 lambs dropped sharply within 24 hours, and that of groups 4 and 5 within 36 hours. Average feed consumption during the initial 35 days of the experiment for groups 1, 4 and 5 was approximately one third that of the other groups. Lambs in groups 4 and 5 consumed slightly more feed (0.56 and 0.59 kg/head/day, respectively) than those in group 1 (0.42 kg). When group 1 and groups 4 and 5 were changed to the ration containing 0.5% KCl at 35 and 42 days, respectively, a sudden increase in feed consumption was apparent within 24 hours. During the remainder of the experiment average daily feed consumption of lambs switched to the KCl ration was equal to that of lambs in group 2 which had been fed this ration throughout the experiment (Table 4).

TABLE 4

EFFECT OF ADDING K, Na, Ca TO A POTASSIUM DEFICIENT DIET UPON GROWTH OF LAMBS OVER 56 DAYS

Treatment*	Av Wt Change kg	Av Daily Feed kg (35-56 day)
2	7.6^{A1}	1.07
3	12.7^{B}	1.28
6	9.7^{AB}	1.23
7	7.9^{A}	1.24
8	11.1^{AB}	1.36

[1]Treatment means within an item not showing the same superscript letter are significantly different ($P < 0.01$)

*2 - B + KCl; 3 - B+K_2CO_3; 6 - B+K_2CO_3+Na_2CO_3; 7 - B+K_2CO_3+Na_2CO_3; 8 - B+K_2CO_3+KCl

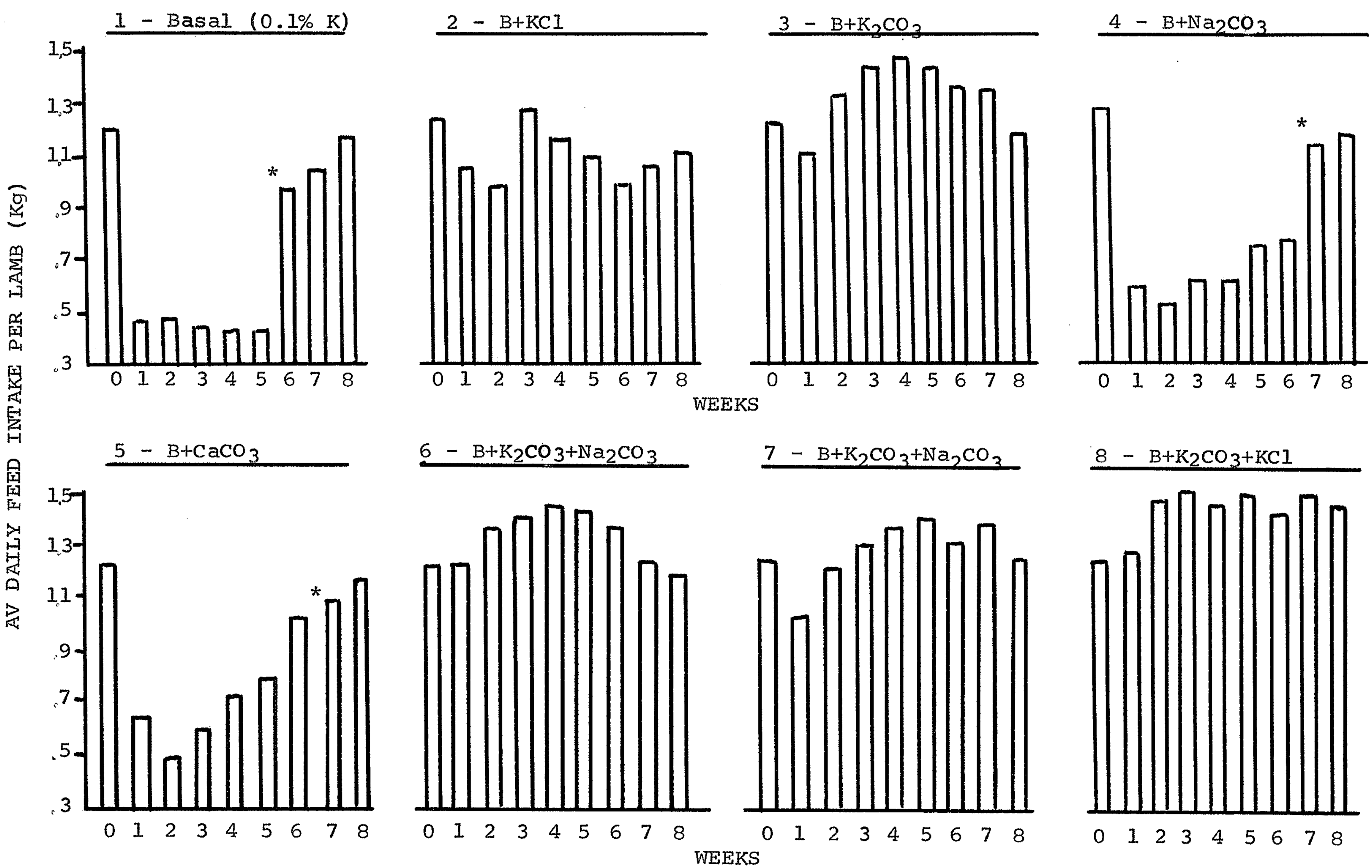


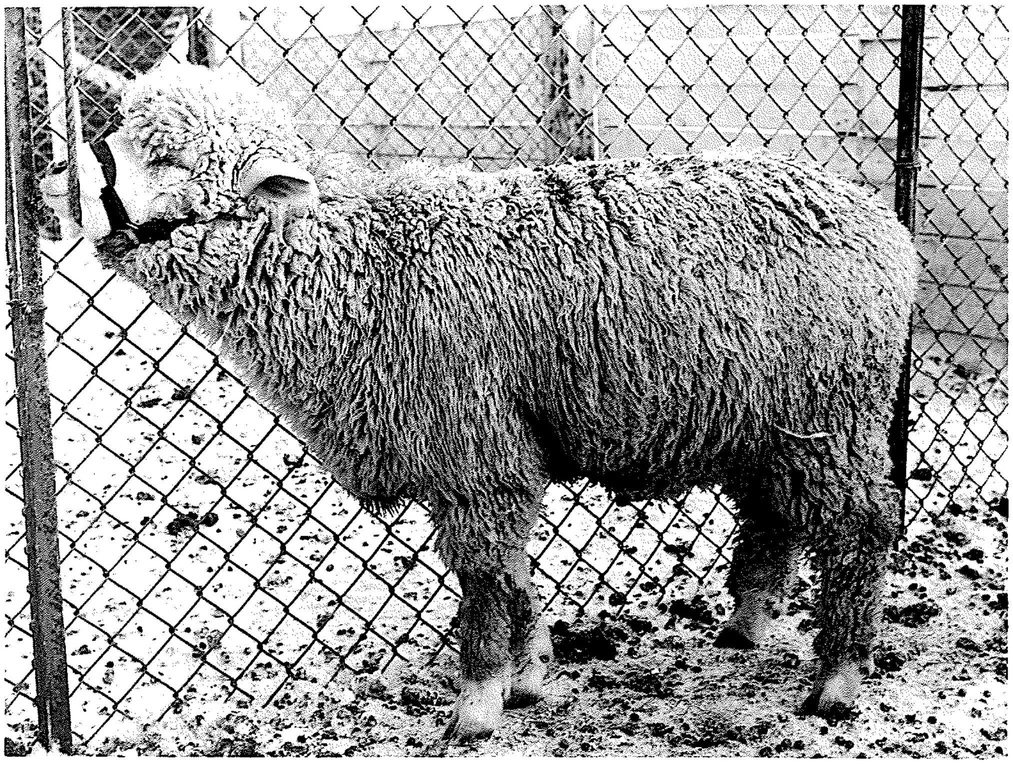
Figure 2. Average daily feed consumption of lambs fed the experimental rations.

*ration changed to B+KCl

Throughout the experiment lambs fed KCl consumed less feed than those fed K_2CO_3. At the end of the experiment, average daily feed consumption of group 2 was 1.07 kg as compared to 1.28 kg of group 3 (Table 4). High level potassium in the ration did not affect feed consumption of lambs in group 8.

Potassium Deficiency Symptoms. The lambs in groups 1, 4 and 5 exhibited poor appetite, listlessness and emaciation. The peculiar pica of wool biting was observed among these lambs, with several of the weaker individuals being almost devoid of wool at the end of 35 days (Figure 3). In addition a reddish color was observed on the snow in the pens of these lambs. This condition was probably caused by blood being excreted in the urine (hematuria).

At the end of 35 days 4, 3 and 1 lambs in groups 1, 4 and 5, respectively, were severely debilitated, displayed muscle stiffness and were unable to rise. These lambs on being removed from the experiment readily consumed hay and drank large quantities of water. After a week, about half of them had recovered sufficiently to be able to walk. Autopsies of all lambs that died showed pale, hypertrophied kidneys. However, no other gross abnormalities were observed.



Normal (0.6% K)

Potassium Deficient (0.1% K)

Figure 3. Pictures of lambs taken at 35 days showing a normal lamb in comparison to one that was fed a potassium deficient ration and had lost a portion of body wool from wool biting.

<u>Electrolyte Concentrations of Plasma and Whole Blood</u>. The plasma and whole blood electrolyte concentrations at 35 and 56 days are presented in Tables 5, 6, 7 and 8. Within one week after initiation of the experiment, the plasma potassium level of lambs in group 1 was 3.76 mEq/l compared to 5.26 mEq/l of lambs in group 3 (Figure 4); this decrease being concomitant with loss in weight and appetite. At 35 days, all lambs receiving low levels of potassium in the diet (groups 1, 4 and 5) had significantly ($P < 0.01$) lower plasma and whole blood potassium levels (Tables 5 and 7). However, at 56 days, after adequate potassium had been fed to group 1 for 21 days and to groups 4 and 5 for 14 days, plasma and whole blood potassium levels were not significantly ($P > 0.01$) different from the other groups (Tables 6 and 8). High levels of potassium in the ration (Group 8) did not significantly affect plasma potassium levels but whole blood potassium was significantly ($P < 0.01$) increased at 35 days (Table 7). No significant treatment effects upon whole blood were found at 56 days.

Whole blood sodium levels were not significantly affected by treatment (Tables 7 and 8). However, at 35 days, the plasma sodium level of group 4 (Na_2CO_3 treatment) was significantly higher ($P < 0.01$) than the other treatments (Table 5). Level of potassium did not significantly affect plasma calcium levels (Tables 5 and 6). However, sodium sup-

TABLE 5

EFFECT OF ADDING K, Na, Ca TO A POTASSIUM DEFICIENT DIET UPON VARIOUS MEAN PLASMA COMPONENTS IN LAMBS AT 35 DAYS

Treatment**	PLASMA COMPONENT					
	Potassium mEq/l	Sodium mEq/l	Calcium mg/100 ml	Magnesium mg/100 ml	Chloride mEq/l	Inorganic Phosphorus mg/100 ml
1	4.20^{A*} ± .07[1]	147.2^{AB} ± 5.6	9.9^{B} ± .2	2.39^{ABC} ± .1	114.6^{DE} ± 1.8	6.3^{A} ± .4
2	5.74^{B} ± .36	146.4^{AB} ± 4.9	9.4^{B} ± .2	2.61^{BC} ± .1	114.26^{CDE} ± 2.3	6.9^{AB} ± .4
3	5.01^{B} ± .15	136.9^{A} ± 0.4	8.6^{AB} ± .5	2.41^{ABC} ± .17	117.2^{E} ± 1.4	6.6^{A} ± .9
4	3.81^{A} ± .11	165.0^{C} ± 1.4	9.4^{B} ± .1	2.47^{ABC} ± .21	109.7^{ABC} ± 1.2	6.0^{A} ± .7
5	3.78^{A} ± .27	146.0^{AB} ± 1.9	9.7^{B} ± .1	2.80^{C} ± .11	110.7^{BCD} ± 1.8	6.2^{A} ± .1
6	5.51^{B} ± .06	152.8^{B} ± 1.5	7.2^{A} ± .8	2.13^{A} ±.15	106.6^{A} ± 0.9	10.3^{C} ±1.2
7	5.26^{B} ± .04	148.0^{AB} ± 1.2	7.3^{A} ± .4	2.28^{AB} ± .10	107.9^{AB} ± 0.9	9.4^{BC} ±1.2
8	5.37^{B} ± .06	148.5^{AB} ± 1.8	8.6^{AB} ± .3	2.40^{ABC} ± .08	110.4^{ABCD} ± 0.6	7.6^{AB} ± .3

*A,B,C,D,E Treatment means within an item not showing the same superscript letter are significantly different ($P < 0.01$)

**1 - Basal (0.1% K); 2 - B + KCl; 3 - B + K_2CO_3; 4 - B + Na_2CO_3; 5 - B + $CaCO_3$; 6 - B + K_2CO_3 + Na_2CO_3; 7 - B + K_2CO_3 + Na_2CO_3; 8 - B + K_2CO_3 + KCl

[1] Standard error

TABLE 6

EFFECT OF ADDING K, Na, Ca TO A POTASSIUM DEFICIENT DIET UPON VARIOUS MEAN PLASMA COMPONENTS IN LAMBS AT 56 DAYS

Treatment***	PLASMA COMPONENT					
	Potassium mEq/l	Sodium mEq/l	Calcium mg/100 ml	Magnesium mg/100 ml	Chloride mEq/l	Inorganic Phosphorus mg/100 ml
1	4.75^{AB*} ± .17[1]	149.2^{ab**} ± 1.6	9.1 ± .7	2.42^{ab} ± .13	118.2^{C} ± 1.3	5.5^{A} ± .4
2	4.95^{AB} ± .32	151.3^{ab} ± 0.8	8.5 ± .2	2.40^{ab} ± .06	112.8^{BC} ± 2.5	5.9^{AB} ± .7
3	4.98^{AB} ± .17	149.8^{ab} ± 0.2	8.5 ± .9	2.40^{ab} ± .03	108.5^{AB} ± 2.3	7.6^{C} ± .6
4	4.81^{AB} ± .18	154.2^{c} ± 1.3	10.0 ± .5	2.72^{b} ± .09	118.1^{C} ± 0.8	6.1^{AB} ± .2
5	4.07^{A} ± .21	151.9^{abc} ± 1.8	10.3 ± .3	2.74^{b} ± .12	115.5^{BC} ± 2.2	5.7^{AB} ± .3
6	5.02^{AB} ± .37	149.8^{ab} ± 1.4	8.9 ± .9	2.11^{a} ± .04	103.9^{A} ± 2.0	7.1^{ABC} ± .5
7	4.64^{AB} ± .37	148.2^{a} ± 0.8	8.6 ± .8	2.30^{ab} ± .03	101.9^{A} ± 2.4	8.8^{C} ± .6
8	5.54^{B} ± .16	152.7^{bc} ± 0.9	8.3 ± .1	2.35^{ab} ± .13	111.3^{BC} ± 1.5	6.8^{AB} ± 1.2

*A, B, C, Treatment means within an item not showing the same superscript letter are significantly different ($P < 0.01$)

**a, b, c Treatment means within an item not showing the same superscript letter are significantly different ($P < 0.05$)

***1 - Basal (0.1% K); 2 - B + KCl; 3 - B + K_2CO_3; 4 - B + Na_2CO_3; 5 - B + $CaCO_3$; 6 - B + K_2CO_3 + Na_2CO_3; 7 - B + K_2CO_3 + Na_2CO_3; 8 - B + KCl + K_2CO_3

[1] Standard error

TABLE 7

EFFECT OF ADDING K, Na, Ca TO A POTASSIUM DEFICIENT DIET UPON VARIOUS MEAN WHOLE BLOOD COMPONENTS IN LAMBS AT 35 DAYS

Treatment**	Whole Blood Component		
	Potassium mEq/l	Sodium mEq/l	Iron mg/100 ml
1	5.9^{AB*} ±0.1	122.9 ± 2.7	44.0^{AB} ± 3.1
2	6.7^{BC} ±0.3	123.0 ± 2.9	44.0^{AB} ± 6.4
3	7.5^{C} ±0.3	123.7 ± 3.5	50.9^{ABC} ± 3.3
4	5.4^{A} ±0.2	122.7 ± 3.6	60.4^{BC} ± 2.0
5	6.0^{A} ±0.2	113.7 ± 2.5	63.2^{C} ± 0.9
6	7.4^{C} ±0.2	116.5 ± 2.2	51.7^{ABC} ± 4.3
7	7.8^{CD} ±0.2	120.3 ± 2.5	45.6^{ABC} ± 5.5
8	8.9^{D} ±0.6	122.3 ± 1.8	33.6^{AC} ± 5.9

*A,B,C,D Treatment means within an item not showing the same superscript letter are significantly ($P < 0.01$) different

**1 - Basal (0.1% K); 2 - B + KCl; 3 - B + K_2CO_3; 4 - B + Na_2CO_3; 5 - B + $CaCO_3$; 6 - B + K_2CO_3 + Na_2CO_3; 7 - B + K_2CO_3 + Na_2CO_3; 8 - B + K_2CO_3 + KCl

[1] Standard error

TABLE 8

EFFECT OF ADDING K, Na, Ca TO A POTASSIUM DEFICIENT DIET UPON VARIOUS MEAN WHOLE BLOOD COMPONENTS IN LAMBS AT 56 DAYS

Treatment**	WHOLE BLOOD COMPONENT		
	Potassium mEq/l	Sodium mEq/l	Iron mg/100 ml
1	9.7	139.3	52.1[abc*]
	±0.7[1]	± 4.2	± 4.0
2	8.5	135.4	43.6[a]
	±0.4	± 0.5	± 5.6
3	9.5	137.0	47.5[ab]
	±1.2	± 4.0	± 2.7
4	8.7	133.8	52.6[abc]
	±0.3	± 1.2	± 1.7
5	8.8	132.0	59.2[c]
	±0.5	± 1.5	± 3.9
6	8.8	134.2	54.3[bc]
	±0.4	± 1.0	± 3.0
7	8.2	132.9	47.8[ab]
	±0.4	± 1.2	± 1.9
8	9.9	134.3	47.3[ab]
	±0.7	± 1.6	± 1.8

*a,b,c Treatment means within an item not showing the same superscript letter are significantly ($P < 0.05$) different

**1 - Basal (0.1% K); 2 - B + KCl; 3 - B + K_2CO_3; 4 - B + Na_2CO_3; 5 - B + $CaCO_3$; 6 - B + K_2CO_3 + Na_2CO_3; 7 - B + K_2CO_3 + Na_2CO_3; 8 - B + K_2CO_3 + KCl

[1] Standard error

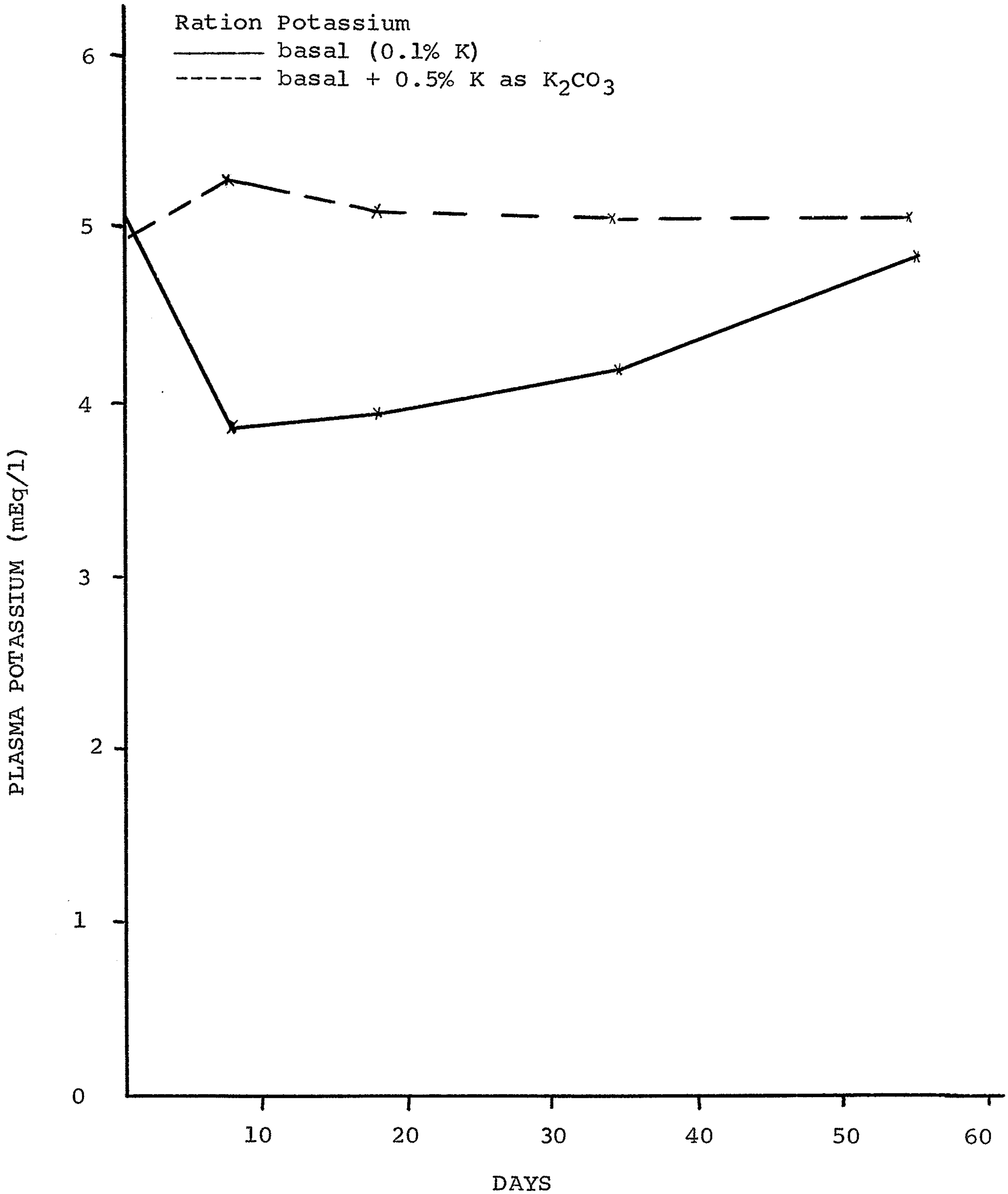


Figure 4. Plasma potassium concentrations of lambs fed rations containing 0.1 and 0.6% potassium.

plementation of potassium adequate diets (groups 6 and 7) significantly ($P < 0.01$) decreased plasma calcium as compared to the potassium deficient groups (Table 5). Plasma magnesium was lowest for lambs fed adequate potassium plus 0.5% added sodium and highest for those fed $CaCO_3$ in conjunction with the potassium deficient diet (group 5). These two treatments differed significantly ($P < 0.01$) (Table 5). At 35 days, plasma chloride levels of group 3 were significantly ($P < 0.01$) higher than those receiving adequate potassium plus added levels of sodium (groups 6 and 7). At 56 days the plasma chloride levels of these three groups were not significantly different. Also at 35 days, lambs receiving the potassium-deficient ration plus 0.5% Na (group 4) had significantly lower plasma chloride levels than lambs on the basal ration (group 1). Plasma chloride levels of lambs in groups 1 and 3 were not significantly different at 35 days, however at 56 days the plasma chloride level of group 1 was significantly higher than that of group 3.

Plasma phosphorus levels, at 35 days, were significantly ($P < 0.01$) higher for lambs in groups 6 and 7 which received adequate potassium plus 0.5 and 1.0% Na, respectively, than those of group 3 which received no added sodium. There was no difference at 56 days. At 56 days, groups of lambs receiving 0.5% KCl (groups 1, 2, 4 and 5) did not differ significantly in plasma phosphorus levels, although there was a significant ($P < 0.01$) difference between these groups and group 3 which received 0.5% K_2CO_3.

Whole blood iron levels were highest for lambs in groups 4 and 5 and lowest for lambs in group 8. Lambs in group 4 and 5 had significantly ($P < 0.05$) higher whole blood iron levels than lambs on group 1 at 35 days (Table 7). Whole blood iron levels of lambs receiving added levels of sodium (groups 5 and 6) did differ significantly from those receiving no added sodium (group 3) throughout the experiment. High potassium intake (group 8) did not affect whole blood iron levels when compared to lambs receiving a diet either adequate or deficient in potassium (groups 3 and 1, respectively).

<u>Experiment 1b</u>

Results of this experiment are presented in Table 9. During the 28-day experiment, 2 lambs on the high potassium (0.6% K) and 4 lambs on the low potassium (0.3% K) treatment died. These animals displayed the same symptoms and anatomical abnormalities as the potassium deficient lambs that died in Experiment 1.

An attempt was made to equalize feed intake between treatments by limiting feed consumption of lambs fed the adequate potassium ration to that consumed <u>ad libitum</u> by lambs fed the potassium deficient ration. Prior to the experiment,

TABLE 9

EFFECT OF POTASSIUM ON GROWTH, PLASMA AND RUMEN FLUID SODIUM AND POTASSIUM CONCENTRATIONS AND RUMEN FLUID VFA'S

	Treatment	
	High	Low
Ration potassium %	0.6	0.3
No of animals	8	8
No of animals removed from experiment	2	4
Av wt change kg	3.2 ± 3.0[1]	- 8.5 ± 5.2
Rumen fluid potassium mEq/l	22.3^{a} ± 1.8	14.4^{b} ± 1.6
Rumen fluid sodium mEq/l	89.8 ± 8.2	69.9 ± 10.4
Plasma potassium mEq/l	4.3 ± 0.2	4.1 ± 0.1
Plasma sodium mEq/l	152.8 ± 6.3	148.3 ± 7.4
Total VFA's um/ml	37.4 ± 2.2	27.9 ± 4.5
Acetate molar %	64.9 ± 0.8	68.4 ± 2.5
Propionate "	28.0 ± 0.8	23.4 ± 2.7
Isobutyrate "	1.6 ± 0.2	1.0 ± 0.3
Butyrate "	3.7 ± 0.3	4.6 ± 0.3
Isovalerate "	0.9 ± 0.2	1.4 ± 0.2
Valerate "	0.8^{a} ± 0.2	1.4^{b} ± 0.2

[a,b] Treatment means within an item not showing the same superscript letter are significantly ($P < 0.05$) different

[1] Standard error

when both groups received a ration containing 0.6% K the average daily feed consumption per lamb was 1.1 kg (Figure 5). On the second day feed consumption decreased to 0.73 kg and decreased further to 0.23 kg per day at 28 days. Throughout the experiment lambs on the low potassium treatment were very slow in eating the feed offered, while the lambs on the high potassium treatment ate all their feed within ten minutes after feeding.

Although feed intake was the same, lambs receiving 0.6% K gained an average 3.17 kg while those receiving 0.3% K lost 8.5 kg (Table 9). This difference was not statistically significant because individuals varied considerably within groups. The level of potassium in rumen fluid was significantly ($P < 0.05$) higher among lambs in the high potassium than among lambs in the low potassium group. The rumen fluid of lambs fed 0.6% K contained 22.3 mEq/l K as compared to 14.4 mEq/l for lambs fed 0.3% K. There was no significant difference between treatments in rumen fluid sodium, plasma sodium or potassium levels, although the level of each of these items was slightly higher for the high potassium group (Table 9).

The concentration of total VFAs in rumen fluid of lambs receiving 0.6% K was 37.4 um/ml and 27.9 um/ml for lambs receiving 0.3% K in the ration. The difference was not significant. Proportions of acetate, propionate, isobutyrate, butyrate and isovalerate were not significantly different. The level of valerate was significantly ($P < 0.05$) higher for the

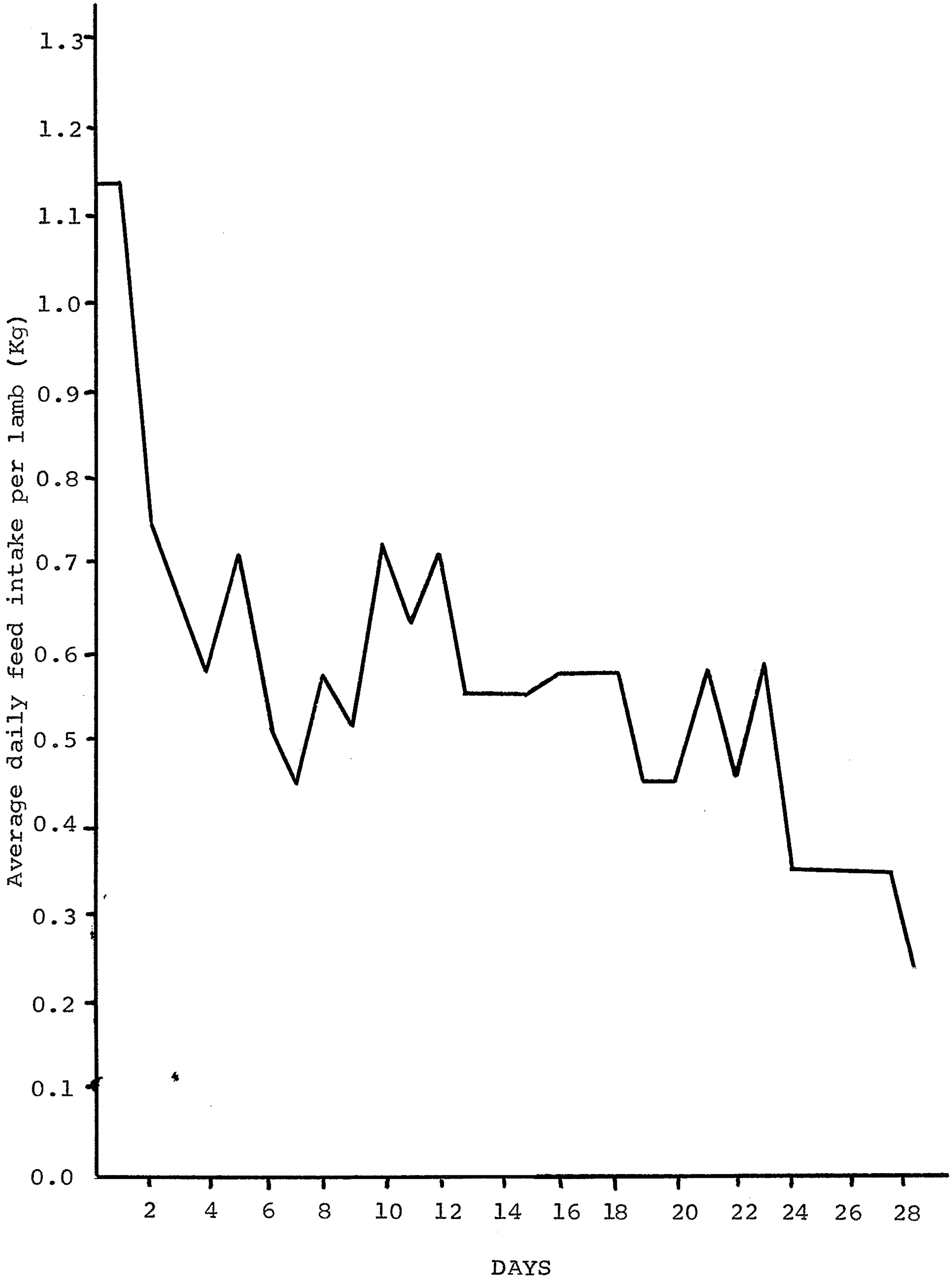


Figure 5. Average daily feed consumption of lambs receiving 0.3% K ad libitum and lambs receiving an equal amount of a ration containing 0.6% K.

low potassium treatment than for the high potassium.

Experiment 2b

The results of this experiment are presented in Table 10. Due to severe muscle stiffness and inability to walk it was necessary to remove 4, 1, 2 and 1 lambs from Treatments A, B, C and D, respectively. These lambs were killed by electrocution. Autopsies revealed hypertrophied kidneys and large amounts of wool in the rumen of six of the lambs. The average weight change per lamb during the 28-day period for Treatments A, B, C and D was -2.8, 4.7, 12.7 and 12.3 kg, respectively. The differences were not significant. Large variation within groups was observed. In Treatment A two animals gained 15.0 and 1.0 kg while the other two lost 11.0 and 16.0 kg, respectively. Similarly, weight changes among lambs in Treatment B ranged from -1.0 to +10.0 kg; in Treatment C from -6.0 to +28.0 kg and in Treatment D from -4.0 to +35.0 kg.

Average daily feed consumption was 0.70, 1.02, 1.23 and 1.12 kg for Treatments A, B, C and D, respectively. Relatively poor appetite was apparent among lambs in Treatment A, which was the low potassium treatment.

Average daily tap water consumption of lambs receiving the basal ration (Treatment A) was 2.02 l while that of lambs receiving intraruminal injections of KCl (Treatment B) was

TABLE 10

EFFECT OF VARIOUS FORMS OF POTASSIUM ADMINISTRATION ON APPETITE BEHAVIOR OF LAMBS OVER 28 DAYS

	Treatment[a,b]			
	A	B	C	D
No of lambs	8	8	8	8
No of lambs removed from experiment	4	1	2	1
Av weight change kg/lamb	-2.75 $\pm$1.9	4.71 $\pm$1.72	12.17 $\pm$ 5.04	12.33 $\pm$ 5.30
Av daily feed consumed, kg	0.70	1.02	1.23	1.12
Av daily K water consumed, l	-	-	2.64	1.82
Av daily tap water consumed, l	2.02	2.37	-	1.11

[a]All lambs received the same low potassium diet (0.3% K) *ad libitum*

[b]A - tap water; B - tap water plus intraruminal injection of 10 g K as KCl every 2 days; C - 5 g K as KCl supplied in the drinking water; D - tap water plus Treatment C

2.37 l. It was observed that water consumption of lambs in Treatment B was always higher on the day of the intraruminal injection of KCl than on the alternate day. Average water consumption was 2.60 l on injection days and 2.14 l on non-injection days. Lambs receiving 5.0 g K as KCl in the drinking water (Treatment C) consumed 2.64 l of potassium supplemented water while lambs allowed a choice between tap water and potassium supplemented water (Treatment D) drank 1.14 l tap water and 1.82 l potassium supplemented water. Since lambs on Treatments C and D consumed the same quantity of potassium in the water, the lambs in Treatment D drank a more concentrated salt solution than lambs on Treatment C.

DISCUSSION

Lamb Feedlot Performance

The first symptom of potassium deficiency was loss of appetite. Lambs receiving 0.1% K sharply reduced feed intake within 24-36 hours. Similarly Campbell and Roberts (13) observed this effect within 2 days and Telle *et al* (68) within 10 days when 0.1% K was fed to growing lambs. Jensen et al (38) observed a reduction in feed intake within 5 to 6 days in pigs fed a potassium deficient diet. When potassium deficient lambs were placed on a ration containing 0.5% K as KCl, appetite increased sharply within 24 hours. Telle *et al* (68) made similar observations. These workers observed an increased feed intake within 2 days when lambs were switched from a ration containing 0.1% K to one containing 0.62% K. Providing sodium or calcium as carbonate salts did not alleviate the appetite depression caused by potassium deficiency. In addition it can be said that supplying the ration with a metabolizable anion did not alleviate to any extent the potassium deficiency symptoms.

The effect of potassium on appetite may be due to several factors. It was observed that the plasma potassium level of lambs receiving 0.1% K was lower than that of lambs fed 0.6% K, at seven days after the feeding trial began. It is conceivable therefore that the appetite depression was concomitant with a decrease in plasma potassium. In this case it would have been desirable to measure plasma potassium levels precisely on the day that the appetite effect was first observed. A second explanation of the appetite effect of potassium might be that of an increase in "potassium capacity." According to the concept of "potassium capacity" (76) a high dietary protein level raises the "potassium capacity" which results in an increase in dietary potassium requirement. The lambs in this experiment received a diet containing 21.5% crude protein, which is much higher than that required for lambs (NRC recommends 10.6% crude protein). Therefore the high protein intake could have increased the "potassium capacity", thereby increasing the demand on extra-cellular potassium, which in turn could affect appetite.

The peculiar pica of wool biting by potassium deficient sheep was also observed by Campbell and Roberts (13). In the present study, some of the potassium deficient lambs that were autopsied had large quantities of wool in the rumen. Skin wipe data (68) and analysis of non-scoured wool (12, 13, 68) has indicated that the skin may be a major excretory route for potassium in lambs and that this excretion appears to increase with increasing dietary potassium. Non-scoured wool is fairly high in potassium. Campbell and Roberts (13) observed that non-scoured wool of lambs fed a 0.1% K diet contained 34.0 mg K per gram of wool. It appears then that the wool eating by potassium deficient lambs is an attempt to meet dietary requirements for potassium.

Weight gain and feed consumption data showed that when a large proportion of dietary potassium is supplied as supplemental salts, K_2CO_3 is superior to KCl for promoting growth. During the first adjustment period, when 0.5% potassium was added as KCl, lambs scoured severely and some deaths occurred. When the source of potassium was changed to K_2CO_3, the scouring ceased and the lambs consumed more feed. Similarly, during the experiment the lambs receiving K_2CO_3 consumed more feed and gained more rapidly in body weight than those lambs which received KCl. Two explanations of this observation are possible. First, it could be assumed that the administration of the chloride salt results in a change in optimum conditions of rumen environment, such as a decrease in rumen pH, thereby upsetting normal rumen metabolism. Second, it may be that the feeding of KCl in the all concentrate semi-purified ration resulted in a physiological anion-cation imbalance. Thacker (69) working with rabbits and Leach et al (41) working with chicks indicated that they had created a physiological anion-cation imbalance. They induced a sodium or potassium deficiency through dietary acidity by supplying high levels of chloride or sulfate which were not balanced by equimolar amounts of sodium or potassium. Since excess chloride is primarily excreted as an ammonium salt or neutral salt such as sodium or potassium chloride the animal is forced to draw on its body stores of certain cations to excrete the physiological excess of anions. Thus for the lambs the addition of KCl could have resulted in a physiological excess of anions (SO_4, Cl) which require a cation for excretion. Since potassium can perform this function, a partial potassium deficiency could have resulted in the lambs. When potassium was administered as K_2CO_3, the anion ($CO_3^=$) was metabolized to carbon dioxide and water, leaving the cation available for its metabolic functions.

Feeding a high level of potassion (1.0% added K) did not affect feedlot performance of lambs when compared to lambs fed 0.5% added K. Similarly, Campbell and Roberts (13) observed that lambs receiving 0.7% K performed comparably to lambs receiving 0.5% K: both levels of performance were superior to that in lambs receiving 0.3% K in the ration. However, Telle _et al_ (68) reported near optimum growth of lambs consuming a 0.3% potassium ration. Pickering (57) suggested that in cows the kidney is able to promote high rates of excretion of potassium to maintain satisfactory balance when potassium intake is high. Thus, in the present study the lambs were able to get rid of the excess potassium without adversely affecting growth.

It must be noted at this point that under practical conditions, the potassium intake can be considerably higher than 1.0%. Lambs receiving an all hay ration can consume a potassium level of approximately 2.0% without adverse effects (50). The observations made by Kunkel _et al_ (40) indicate that potassium toxicity can occur. These workers observed decreased weight gain and poor appetite in lambs fed a basal ration of cottonseed hulls, ground milo grain and soybean oil meal plus 5% K supplied as $KHCO_3$. Therefore, the high potassium level (1.1%) in the present study is well within the range of excess dietary potassium that can be tolerated by lambs.

Adding 0.5% Na to the potassium deficient ration resulted in less weight loss and higher plasma sodium levels compared with the potassium deficient ration. Similarly Burns et al (10) reported a sparing action of sodium on potassium in chicks fed a potassium deficient ration. Welt et al (76) reported that during potassium deficiency approximately two-thirds of the cellular potassium lost is replaced by sodium. The elevated plasma sodium levels encountered in the lambs may be an attempt by the animal to effect this replacement.

High levels of dietary sodium (0.5 and 1.0% Na added) with adequate potassium (0.6%) adversely affected lamb growth. These results are not in agreement with the observations made by Meyer and Weir (47) and Meyer et al (48) who showed that up to 13.0% added NaCl to rations of fattening cattle and lambs did not adversely affect feed consumption or weight gains. It has also been observed that increasing sodium chloride in the ration results in increased water consumption by both lambs and cattle (47, 48). Horrocks (34) reported that steers fed a high sodium diet were in strong negative potassium balance while 6 out of 8 steers on a low sodium diet were in apparent positive potassium balance. He suggested that potassium balance is influenced by levels of sodium intake. On the other hand, Devlin and Roberts (20) showed that cumulative potassium balance of wether lambs increases with increasing dietary sodium. Furthermore, Meyer et al (46) reported that potassium retention in pigs did not appear to be affected by the amount of sodium in the ration. Elam and Autry (21) observed that various levels of sodium chloride (1, 2, 4 and 8%) added to the drinking water of steers did not significantly affect potassium retention. The difference in results reported above may be due to differences in ration protein levels rather than a sodium effect since a relationship between potassium and protein metabolism has been demonstrated (14).

There was no significant difference in plasma sodium levels between lambs fed a potassium deficient diet and a potassium adequate diet, both containing 0.2% Na. This observation is in agreement with other reports (13, 64, 68). Also Kunkel et al (40) and Fontenot et al (26) observed that serum sodium levels of sheep were not affected by the addition of 5.0% K to the ration. It appears therefore that plasma sodium levels are not affected by dietary levels of potassium provided that sodium is not fed in excess.

The decrease of plasma and whole blood potassium levels of lambs on the potassium deficient rations was expected since there is a gross relationship between body deficit and plasma potassium levels. Decrease in serum potassium as a result of feeding low potassium rations has been reported by other workers (7, 13, 62, 64, 76). Telle et al (68) reported a pattern of plasma and whole blood potassium levels similar to those in the present study, except that Telle's values were lower. They suggested that a blood plasma potassium level below 12 mg % (3.0 mEq K/l) may be an indication of inadequate potassium intake. However, plasma values from the present experiment were 4.2, 3.8 and 3.8 for lambs in Treatment 1, 4 and 5, respectively, and these lambs exhibited signs of potassium deficiency. This discrepancy may be due to wide variation in plasma potassium levels found both among and within breeds of sheep (15).

Level of potassium in the diet did not significantly ($P > 0.05$) affect plasma levels of calcium, magnesium and inorganic phosphorus, but high levels of ration potassium resulted in a significant decrease in plasma chloride. Various reports on the effect of potassium on plasma electrolytes have been published. St. Omer and Roberts (65) and St. Omer (64) observed that potassium depletion in heifers and steers resulted in non significantly higher serum calcium and magnesium levels but serum phosphorus was significantly increased. Campbell and Roberts (13) and Telle et al (68) reported that level of potassium in the ration did not significantly affect serum levels of calcium, chloride, magnesium or sodium, but serum phosphorus levels were significantly lower in lambs fed the low potassium rations. Working with rats, Seta et al (62) and Forbes (27) reported an increase in plasma magnesium with a decrease in dietary potassium. Fontenot et al (26) and Kunkel et al (40) observed a decrease in plasma levels of magnesium and calcium in sheep when rations containing up to 5.0% potassium were fed.

Whole blood iron levels were highest for the lambs receiving a potassium deficient diet plus added sodium or calcium. Most of the iron in the blood is contained within the erythrocyte. The higher whole blood iron concentrations may be due to hemoconcentration which resulted from possible dehydration caused by the potassium deficiency. Lambs receiving 1.1% potassium had the lowest whole blood iron levels. The literature reviewed contains no data on the effect of ration potassium on whole blood or plasma iron concentration. Since 1.1% potassium is not an excessive potassium intake for lambs, it is difficult to explain the decrease in whole blood iron concentration when this level of potassium was fed as compared to feeding 0.6% potassium.

Experiment 1b and 2b

A great deal of credence cannot be placed on the results of these two experiments because the lambs had been on the potassium deficient treatments of the previous experiment. Despite a long adjustment period (30 days) in which adequate potassium was fed, several lambs although receiving adequate potassium displayed potassium deficiency symptoms and died. Their kidneys were pale in color and hypertrophied. Since it has been suggested that non-reversible structural changes result within the kidney during potassium depletion (76) it might be assumed that all the lambs in these experiments (1b and 2b) suffered from some degree of renal impairment. This may explain the large variation among lambs within treatments of these two experiments.

Although the total VFA concentration between potassium treatments was not significantly different lambs fed 0.6% K had 34% higher total VFA concentrations than those fed 0.3% K. These results are in agreement with the observations of McKay (42) that the addition of Na + K phosphates to the drinking water of lactating cows resulted in an increase of total VFA. In the present study, the relative level of propionate was slightly higher for the lambs receiving 0.6% K. Similarly Van Campen and Matrone (71) observed an increase in propionate in the rumen fluid of sheep receiving a basal diet plus added sodium and potassium.

In the present study, rumen fluid potassium was significantly higher for lambs fed 0.6% K than for lambs fed 0.3% K. There was no difference between treatments in rumen fluid sodium. Campbell and Roberts (13) reported no significant difference in the potassium levels of rumen fluid of lambs fed 0.3 and 0.7% K in an equalized feeding experiment. However when lambs were fed *ad libitum*, Campbell and Roberts

(13) and Telle *et al* (68) observed that rumen fluid potassium increased as ration potassium increased. St. Omer (64) reported that rumen fluid sodium and potassium in steers did not increase with ration potassium.

The increase in rumen fluid potassium concentration and total rumen fluid VFA might be explained on some basis other than a direct potassium effect. Rumen contents were obtained 3 hours after the two treatment groups were offered the same quantity of feed. It was observed that within 3 hours the lambs receiving 0.6% K had consumed all their feed, while the lambs receiving 0.3% K had consumed approximately one quarter of the feed offered. Thus since a greater amount of feed was consumed by the lambs on the 0.6% K treatment, these lambs would be expected to have higher rumen fluid potassium and VFA levels at the time of sampling. The increase in rumen fluid potassium level for the higher potassium treatment is therefore in agreement with the data observed by Campbell and Roberts (13) and Telle *et al* (68) under conditions of *ad libitum* feeding.

Although feed intake was the same for both treatments, lambs fed the 0.3% potassium ration lost 8.5 kg while lambs consuming the 0.6% potassium ration gained an average of 3.2 kg each: these values were not significantly different. Similarly Campbell and Roberts (13) observed superior weight gains in lambs consuming 0.7% K over those consuming 0.3% K when feed intake was the same for both groups. These results indicate that potassium intake has a direct effect upon growth which is not necessarily mediated through appetite. Campbell and Roberts (13) suggested that this might be due to adverse effects of low potassium intake upon protein metabolism since in metabolism trials they observed lowered nitrogen retention by lambs fed a low potassium ration.

Appetite Behavior of Lambs as Affected by Potassium Supplementation

In this experiment, lambs receiving inadequate potassium (Treatment A) lost weight and consumed less feed than the lambs receiving adequate potassium; an observation confirming the results of Experiment 1. Supplementing potassium by intraruminal injections of KCl resulted in improved appetite, superior weight gains and increased water consumption. Campbell (12) attempted to determine the effect of intraruminal injection of K_2CO_3 on appetite of lambs receiving a ration containing 0.1% K. He observed that the intraruminally injected group consumed less food than the control group. Subsequent work (59) showed that injection of the K_2CO_3 solution caused erosion of the rumen epithelium thereby causing poor appetite. In the present study no attempt was made to determine the effect of KCl injection on the rumen epithelium. St. Omer (64) observed superior appetite and weight gains of steers receiving intraruminal injections of K_2CO_3 in conjunction with a low potassium diet. It is apparent therefore that the appetite effect of a low potassium ration is not mediated solely via the oral cavity.

It was observed that lambs receiving 5 grams of potassium in the drinking water gained 2.5 times more weight than lambs receiving the same level of potassium by intraruminal injection, even though feed consumption of the latter was only slightly less than that of the former. Ward (72) observed that when half the daily potassium intake of a cow was administered at one time by stomach tube as KCl the animal died within 10 minutes. Potassium is readily absorbed from the rumen as a function of its concentration gradient (55); the potassium plasma concentration of the cow was found to be 15.2 mEq/l immediately post mortem. In the present experiment, the sudden potassium loading of lambs by intraruminal injection could have resulted in a sudden excess of plasma potassium which was quite rapidly excreted by the kidney. Ruminants have an enhanced excretory capacity for potassium rather than tolerance of high potassium levels in the plasma, (57). This situation could probably satisfy the requirement of potassium for appetite in lambs, but not for protein anabolism. On the other hand, when potassium was supplied in the drinking water, the potassium intake was spread over a longer time thereby allowing the animal to make more efficient use of the potassium.

There is a paucity of information on potassium and water intake relationships. Ward (73) in his recent review of potassium metabolism of ruminants stressed the need for investigations on the relationship of potassium intake to water requirements and water turnover rate. In the present study, lambs on Treatment D consumed 1.82 l of potassium supplemented water while lambs on Treatment C consumed 2.64 l. Also lambs on Treatment D drank an additional 1.1 l tap water, with the result that the total water intake of this group was the highest for all treatments. Roberts and Campbell (59) observed that lambs given a choice consumed more potassium supplemented than tap water. St. Omer (64) observed that heifers receiving 1086.5 mEq K per day drank significantly more water than heifers receiving 439.4 mEq or 156.6 mEq K per day. However, daily water retention was the same for all three treatments since the high potassium group excreted a significantly greater volume of urine.

Investigations carried out by Weeth _et al_ (74) and Weeth and Haverland (75) have shown that the addition of 1.2% NaCl to the drinking water of heifers was deleterious in that feed consumption and weight gains were decreased. On the other hand, Meyer _et al_ (48) reported that steers can tolerate 9.33% NaCl in the ration without loss in weight and appetite when water was offered ad libitum. Restricted as compared to unrestricted water intake has been shown (40) to depress weight gains and feed consumption in ewes on high potassium diets diets (5.0% K added). It appears then that the ability of ruminants to tolerate high levels of dietary electrolytes is closely related to water intake and turnover rate.

SUMMARY

A 56-day feeding trial was conducted, utilizing 128 western range wether lambs, to study some of the effects of adding cations (K, Na, Ca) to a potassium deficient ration upon growth and various plasma electrolytes. In addition, a 28-day equalized group feeding trial and an appetite trial were conducted to study the effect of potassium on growth and appetite behavior of lambs.

Data collected indicate the following:

(1) When a large proportion of dietary potassium was provided as supplemental salts, K_2CO_3 was superior to KCl in promoting growth of fattening lambs.

(2) Potassium level in the diet had a marked effect on appetite. Average daily feed consumption decreased within 24 hours when lambs were switched from a ration containing 0.6% K to a ration containing 0.1% K. Feed intake was markedly increased within 24 hours after lambs on a potassium deficient diet were given an adequate potassium diet.

(3) Supplemental sodium or calcium supplied as carbonate salts did not alleviate the marked depression in appetite associated with potassium deficiency. This also indicates that supplying the ration with a metabolizable anion ($CO_3^=$) will not alleviate to any extent the potassium deficiency symptoms.

(4) The decrease in appetite of lambs receiving a potassium deficient diet was associated with a decrease

in plasma potassium levels. It was suggested that further study is required on the relationship of appetite in lambs to plasma potassium concentrations.

(5) Dietary level of potassium higher than 0.6% of the ration did not adversely affect lamb growth when 0.21% sodium was fed.

(6) A high level of dietary sodium with adequate potassium adversely affected lamb growth.

(7) Potassium deficiency in lambs resulted in a peculiar pica of wool biting. It is suggested that the lambs were attempting to meet their dietary potassium requirement by this wool biting.

(8) Potassium levels in the ration did not significantly affect plasma concentrations of sodium, calcium, magnesium and phosphorus. Plasma chloride level was significantly ($P < 0.01$) decreased by high dietary potassium. Low potassium, high sodium in the ration resulted in a significant ($P < 0.01$) increase in plasma sodium concentration.

(9) When feed intake was equalized potassium had a non significant effect on growth and volatile fatty acid production.

(10) The effect of potassium does not seem to be mediated solely via the oral cavity. Lambs receiving a potassium deficient ration in conjunction with intraruminal injections of potassium displayed superior appetite and gained more body weight (not significant) than lambs receiving the inadequate potassium ration only. However, the lambs receiving potassium in the drinking water, drank more

water and gained more weight than the lambs receiving intraruminal injections of KCl.

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APPENDIX

TABLE 11

MEAN SQUARES FOR WEIGHT GAINS, PLASMA AND WHOLE BLOOD COMPONENTS AT 35 DAYS OF EXPERIMENT 1

Item	Degrees of Freedom	Mean Squares	
		Treatment	Error
Weight gains	124	752.5*	10.4
Plasma potassium	44	3.3*	0.2
" phosphorus	44	15.0*	2.7
" calcium	44	6.2*	1.0
" magnesium	44	0.24*	0.06
" chloride	44	90.4*	7.8
" sodium	44	351.7*	48.6
Whole blood potassium	43	7.7*	0.6
" " sodium	43	73.7	35.6
" " iron	43	527.7*	113.3

* ($P < 0.01$)

TABLE 12

MEAN SQUARES FOR WEIGHT GAINS, PLASMA AND WHOLE BLOOD COMPONENTS AT 56 DAYS OF EXPERIMENT 1

Item	Degrees of Freedom	Mean Squares	
		Treatment	Error
Weight gains[1]	76	70.8**	14.8
Plasma potassium	44	0.9**	0.3
" phosphorus	44	7.6**	1.4
" calcium	44	3.0	2.2
" magnesium	44	0.21*	0.09
" chloride	44	223.1**	20.3
" sodium	44	23.2*	8.9
Whole blood potassium	42	2.1	2.3
" " sodium	42	31.0	29.2
" " iron	42	110.3*	49.1

[1]Weight gains for treatments 2, 3, 6, 7, 8 over 56 days

*(P< 0.01)

**(P< 0.05)

TABLE 13

MEAN SQUARES FOR WEIGHT GAINS, PLASMA AND RUMEN FLUID COMPONENTS OF EXPERIMENT 1b

Source of variation	Treatment	Error
Degrees of freedom	1	8
	(Mean Squares)	
Weight gains	326.9	75.0
Plasma sodium	48.0	236.6
Plasma potassium	0.1	0.3
Rumen fluid sodium	1045.3	412.8
Rumen fluid potassium	149.4*	16.4
Total VFA	214.8	48.0
acetate	29.7	11.4
propionate	52.1	13.3
isobutyrate	0.7	0.3
butyrate	1.9	0.5
isovalerate	0.6	0.2
valerate	1.0*	0.1

* ($P < 0.05$)