Effect of Dietary Aluminum and Phosphorus on Performance, Phosphorus Utilization and Tissue Mineral Composition in Sheep

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EFFECT OF DIETARY ALUMINUM AND PHOSPHORUS ON PERFORMANCE, PHOSPHORUS UTILIZATION AND TISSUE MINERAL COMPOSITION IN SHEEP[1,2]

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Summary

An experiment was conducted to determine the effects of dietary Al and P on P utilization and tissue mineral composition in sheep. Twenty Florida native wether lambs, averaging 36.7 kg, were assigned to four groups in a 2 × 2 factorial arrangement of treatments, with two levels of dietary P as NaH_2PO_4 (.15 and .29%) and two levels of supplemental Al as $Al_2Cl_3 \cdot 6H_2O$ (0 and 2,000 ppm). Lambs were used in the same design in three experiments; a feeding trial, a P balance study, and a tissue mineral study. During the 56-d feeding trial, average daily gains by lambs in the four treatments (low P-low Al, high P-low Al, low P-high Al and high P-high Al) were 109, 116, −38 and 15 g, and average daily dry matter intakes were 1,280, 1,320, 780 and 1,080 g, respectively. Both dietary Al and P influenced (P<.05) these values. At the end of the feeding trial, plasma P was lower (P<.05) for sheep given high Al diets and higher (P<.01) for sheep given high P diets. Plasma Ca was decreased (P<.05) by high P and Mg was depressed (P<.01) by high Al. Three lambs in each group were injected iv with .2 mCi of ^{32}P for 10 consecutive d before the P balance study. True P absorption coefficients were 28.7, 32.8, −9.2 and 8.5%, and net P retention −48, −4, −404 and −325 mg/animal daily for the four treatment groups, respectively. Al depressed (P<.05) P absorption and retention. Metabolic fecal P averaged 483, 820, 206 and 460 mg/animal daily, respectively, and was influenced (P<.05) by P and Al in the diet. Apparent Ca absorption was reduced (P<.05) by dietary Al. Dry matter and organic matter digestibilities and apparent Mg absorptions were not affected by dietary P or Al. Liver Al levels increased (P<.01) with the high Al diet, and Al also tended to increase in kidney and longissimus muscle. Brain Al was not related to dietary Al. Fe (P<.05) in liver and kidney and Cu (P<.01) in kidney increased and Mg decreased (P<.01) as a result of high dietary Al. Zn in kidney (P<.01) and Mn in muscle (P<.05) decreased with high P diets. For all minerals studied, brain seemed to be the least affected by dietary mineral levels.

(Key Words: Aluminum, Phosphorus, Tissue Minerals, Phosphorus Balance, Sheep.)

Introduction

Under grazing conditions, sheep and cattle can ingest large amounts of Al of nonplant origin when soil is involuntarily ingested with forages (Healy, 1967, 1968; Mayland et al., 1975). Exchangeable Al concentrations of 6,000 and 18,000 ppm have been reported for samples of temperate and tropical soils, respectively (Velez and Blue, 1971). Al has been shown to interfere with P availability in nonruminants by forming insoluble phosphates (Jones, 1938; Street, 1942; Storer and Nelson, 1968). Valdivia et al. (1978), however, reported no differences in serum or tissue P levels when 1,200 ppm Al was fed to steers. Dietary Al levels above 1,200 ppm apparently have not been studied in ruminants. Thompson et al.

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(1959) suggested that differences exist between ruminants and nonruminants with regard to dietary Al effects, on the basis of more complex digestive processes in the former. Organic acids produced in the rumen may bind Al to some extent, preventing P precipitation at normal rumen pH levels.

The present study was conducted to evaluate the effect of high levels of Al and increasing levels of P in the diet on performance, P balance and tissue mineral composition in growing lambs.

Experimental Procedure

Twenty Florida native wether lambs approximately 10 mo old, averaging 36.7 kg, were randomly assigned to four treatments in a 2 × 2 factorial arrangement, with two levels of added Al ($Al_2Cl_3 \cdot 6H_2O$) designed to provide 0 or 2,000 ppm supplemental dietary Al, and two levels of P. Monosodium phosphate (NaH_2PO_4) was added to provide .15 and .29% dietary P on an as-fed basis (.17 and .32% dry basis). Calcium carbonate ($CaCO_3$) was also added to keep the Ca:P ratio constant (1.4:1) in all treatments. Minerals were added to the basal diet (table 1) at the expense of cornstarch.

The experiment consisted of three consecutive phases; (1) a feeding trial, (2) a P balance study and (3) a mineral composition study of selected tissues. A short preliminary trial was conducted with eight additional lambs fed 0 to 6,000 ppm Al to determine the maximum amounts of Al that could be added to the basal diet, before rejection of feed occurred.

Phase 1. In the feeding trial lambs were fed individually in elevated wire floor pens for 56 d. Lambs were drenched with levamisole HCl[5] for control of internal parasites and allowed to adjust to the basal diet. Weights were taken on 2 consecutive d and jugular blood samples were taken at the beginning of the experiment. Thereafter, weights were recorded and blood samples collected every 14 d.

Phase 2. A 7-d P balance study was preceded by a preliminary 14-d adjustment to metabolism crates. Feed allowance per lamb was limited to 900 g, and tap water (13 ppm P and <.1 ppm Al) was provided ad libitum. Rejected feed, feces and urine were collected daily for 7 d.

[5] American Cyanamid Co., Princeton, NJ.

TABLE 1. COMPOSITION OF BASAL DIET

Item	%
Ingredient composition[a]	
Corn, grnd (IFN 4-02-992)	44.0
Soybean, seeds (IFN 5-04-604)	2.0
Cotton, seed hulls (IFN 1-01-599)	26.0
Alfalfa, mn 17% protein (IFN 1-00-023)	2.0
Sugarcane, molasses (IFN 4-04-696)	3.0
Cornstarch (IFN 4-02-889)	20.2
Salt, trace mineralized[b]	1.0
Urea	1.5
Calcium carbonate, mn 38% Ca (IFN 6-01-069)	.3
Vitamins A and D[c]	+
Total	100.0
Chemical composition[d]	
Crude protein, %	11.92
P, %	.17
Ca, %	.23
Al, ppm	168

[a] As-fed basis.

[b] Analysis (%) listed as: NaCl, 98.15; Fe, .30; Mn, .26; S, .10; Cu, .08; Co, .01; I, .01; Zn, 1.00.

[c] Vitamins added per kilogram of diet: 2,200 IU vitamin A palmitate, 440 IU vitamin D_3.

[d] Dry matter basis.

Daily 10% aliquots of feces and urine were composited for analysis. Urine samples were collected into 100 ml of 25% 12 N HCl and stored at 3 C and fecal samples were frozen. For an assessment of metabolic fecal P excretion, three animals from each group were selected randomly and injected iv with .2 mCi of ^{32}P for 10 consecutive d to attain isotope equilibrium within the body compartments (Kleiber et al., 1951). The 7 d following the last isotope injection constituted the P balance period, during which daily samples of blood, feces and urine were collected from individual animals for an evaluation of P specific activity.

Phase 3. At the end of the balance period, all animals were slaughtered, and liver, kidney, brain, metacarpal bones and a portion of the longissimus muscle were removed, weighed and frozen for laboratory analyses.

Dry matter and ash determinations were made on duplicate samples of feed, orts and feces by AOAC (1975) methods. Concentrations of Al, Ca, Mg, Fe, Cu, Zn and Mn were determined by atomic absorption spectrometry according to methods recommended by the manufacturer (Perkin-Elmer, 1973). P was determined by a modified colorimetric method (Fiske and Subbarow, 1925). Feed and fecal samples were dry ashed and the ash put into a HCl solution, from which mineral determinations were made. Minerals in plasma samples were determined after plasma deproteinization with 10% trichloroacetic acid. Tissue samples of approximately 10 g were taken, weighed, placed in 50% 16 N nitric acid solution for protection from contamination and boiled in covered glass containers until the solutions turned clear.

Bones were cleaned of adherent tissue manually, defatted by solvent extraction, dried and ashed. Bone minerals were determined from the nitric acid solution of bone ash. Hemoglobin was determined by the acid hematin method (Cohen and Smith, 1919), and hematocrit by the microhematocrit method.

Isotope activity was determined by liquid scintillation in undiluted plasma and urine samples and in fecal samples previously ashed and treated with HCl. Stable P was determined in all radioactive samples as described previously. Specific activity was calulated for each sample and corrected for isotope decay.

Analyses of variance (Barr et al., 1976) of weight gains, feed intake, plasma minerals, hemoglobin and hematocrit were performed with dietary levels of P and Al as main treatments, animals nested within treatments and time (measurements every 14 d) as a subtreatment. Characteristics in the P balance study and mineral concentrations in tissues were evaluated considering treatments as main effects and animals nested within treatments.

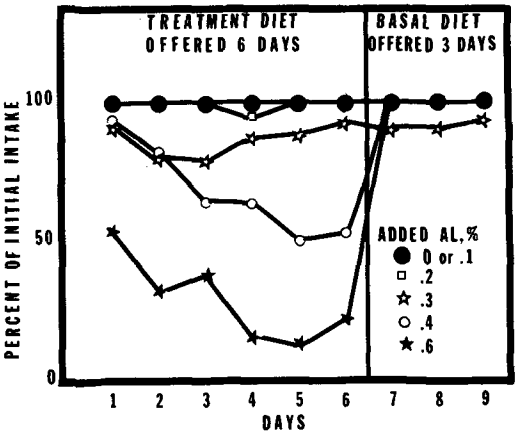

Figure 1. Effect of added Al on percentage of initial feed intake of sheep. Inappetance and recovery measured following an adjustment period (not shown) to the basal diet. Two sheep used per treatment and offered 1200 g feed/sheep daily.

Results

Animal Performance. Addition of Al at levels above 2,000 ppm (.2%) caused feed rejection (figure 1); consequently, that level was chosen for this experiment. Increasing dietary Al reduced average daily feed intake from 1.30 to .93 kg ($P<.01$) and reduced average daily gain from 113 to −12 g ($P<.01$; table 2). Additional P tended to increase feed intake from 1.03 to 1.20 kg and increased gain from 36 to 66 g ($P<.05$). Feed conversion ratios were increased by additional dietary Al and decreased by additional P. There was a larger increase in feed intake due to additional P in the presence of 2,000 ppm Al. Animals within treatment, time and treatment × time interaction were significant sources of variation ($P<.01$) in body weight gain and average daily intake. The treatment × time interactions are indicative of the effect of dietary P increasing and dietary Al reducing feed intake and weight gain with time.

Blood Traits. Hemoglobin and hematocrit averaged 17.6 g/100 ml and 46.3%, respectively, for all sheep and values were not affected by

addition of Al or P. Plasma P levels at the end of the experiment were higher (P<.01) in sheep fed the diet containing the higher level of P, and lower (P<.05) with high Al diets (table 3). The interaction of P × Al was significant (P<.01); Al depressed plasma P in the presence of high dietary P.

Increases in dietary P reduced (P<.05) plasma Ca (10.75 vs 9.63 mg/100 ml). Al addition did not change plasma Ca. Time had an effect (P<.01) on plasma Ca, which changed in a curvilinear (quadratic) fashion. Animals within treatment (P<.01), P × time and Al × time (P<.05) also were significant.

Lower plasma Mg concentrations (1.79 mg/100 ml) were observed (P<.01) in animals fed high levels of dietary Al than in those fed low Al (2.42 mg/100 ml). Dietary P level had no apparent effect on plasma Mg; however, animals within treatment were influenced (P<.01), and there was an Al × time interaction (P<.01).

Nutrient Utilization. Dry matter and organic matter digestibilities for all diets averaged 68.3 and 69.7%, respectively, and were not affected by treatment. Dry matter intake was decreased (P<.01) by additional dietary Al (758 vs 561 g; table 4). Apparent P absorption was negative in all treatment groups, except the group given high P and low Al. Metabolic fecal P amounted to .640 g/d and was approximately two times higher (P<.05) in lambs fed high dietary P than in those fed the low level of P. Lambs consuming high Al diets excreted .333 g metabolic fecal P/d, less (P<.05) than that excreted by lambs fed low Al diets (.652 g/d). The gross correlation between P intake and metabolic fecal P was significant (r = .77, P<.01).

The higher level of P in the diet increased (P<.05) the amount of P excreted in the urine. In general, the amount of P excreted in feces and urine closely corresponded with the amount of P ingested. Metabolic fecal P as a percentage of total fecal P averaged 18% in lambs fed high

TABLE 2. EFFECTS OF DIETARY LEVELS OF PHOSPHORUS AND ALUMINUM ON PERFORMANCE OF LAMBS[a]

Dietary P, %	Added Al, ppm	Avg daily feed intake, kg	Avg daily gain, g	Feed/unit gain
			Subtreatment effect	
.15	0	1.28	109	11.8
.29	0	1.32	116	11.3
.15	2,000	.78	−38	
.29	2,000	1.08	15	72.1
SD[b]		.084	24	
			Main treatment effect	
.15	–	1.03	36	–
.29	–	1.20	66	41.7
–	0	1.30	113	11.6
–	2,000	.93	−12	–
			Statistical significance[c]	
P		NS	P<.05	
Al		P<.01	P<.01	
P × Al		NS	P<.05	
Animals (P, Al)		P<.01	NS	
Time (T)		P<.01		
P × T		P<.01		
Al × T		P<.01		
P × Al × T		NS		

[a]Each value represents the mean for five lambs, in subtreatment groups and for 10 lambs, in main treatment groups. Feed on dry matter basis.

[b]Standard deviation calculated from the residual mean square.

[c]NS denotes (P>.05).

Al and 37% in those not fed additional Al. This suggests that a larger amount of fecal P was of dietary origin in those lambs fed the high level of Al. This can be interpreted as a reduction in P absorption induced by the inclusion of Al in the diet.

Lambs fed 2,000 ppm Al had lower (P<.01) coefficients for true absorption (−.35%) than those fed low levels of dietary Al. Overall true P absorption values were higher than apparent P absorption values, but were closely correlated (r = .91, P<.01). P retained in the body was −.365 g/d with high Al diets compared with −.026 g/d with low Al diets. P retained was positively correlated with apparent P absorption (r = .91, P<.01) and true absorption (r = .76, P<.01). The apparent absorption of dietary Ca was lower (P<.05) with the high Al diet. Mg absorption was not affected by dietary Al, but tended to be higher with low levels of dietary P.

Tissue Minerals. The high Al diet resulted in higher levels of Al (P<.01) and Fe (P<.05) in the liver, and lower levels of Mn (P<.05) than did the low Al diet (table 5). Kidney Fe (P <.05) and Cu (P<.01) were higher and kidney Mg lower (P<.01) when the high Al diet was fed than when the low Al diet was offered. Zn levels in the kidney were lower (P<.01) with high dietary P than with low P.

Mn in longissimus muscle was reduced (P<.05) by high levels of dietary P. Dietary Al increased (P<.01) Cu concentration in muscle. Concentrations of minerals in brain tissue seemed to be less affected by the dietary treatments but a P × Al interaction (P<.01) was observed for P and Mg concentrations in the brain. For both minerals, dietary Al overcame the depressing affect of dietary P. Bone ash (P<.05) and Mn levels (P<.05) were higher in those lambs fed the high level of Al (table

TABLE 3. EFFECTS OF DIETARY LEVELS OF PHOSPHORUS AND ALUMINUM ON PLASMA CONCENTRATION OF MINERALS IN LAMBS[a]

Dietary P, %	Added Al, ppm	P		Ca		Mg	
		Final	Change	Final	Change	Final	Change
		mg/100 ml					
		Subtreatment effect					
.15	0	6.90	.96	10.55	−.76	2.60	.16
.29	0	7.82	2.11	9.08	−2.36	2.23	−.12
.15	2,000	3.62	−2.88	10.95	.24	1.75	−.72
.29	2,000	7.73	1.56	10.18	−1.03	1.83	−.63
SD[b]		1.79		.60		.16	
		Main treatment effect					
.15	–	5.26	−.96	10.75	−.26	2.18	−.28
.29	–	7.78	1.84	9.63	−1.70	2.03	−.38
–	0	7.36	1.54	9.82	−1.56	2.42	.02
–	2,000	5.68	−.66	10.57	−.40	1.79	−.68
		Statistical significance[c]					
P		P<.01		P<.05		NS	
Al		P<.05		NS		P<.01	
P × Al		P<.01		NS		NS	
Animal (P, Al)		NS		P<.01		P<.01	
Time (T)		P<.01		P<.01		P<.01	
P × T		NS		P<.01		NS	
Al × T		NS		P<.05		P<.01	
P × Al × T		NS		NS		NS	

[a]Each subtreatment value represents the mean for five lambs, and each main treatment value is the mean for 10 lambs

[b]Standard deviation calculated from the residual mean square.

[c]NS denotes (P>.05).

TABLE 4. EFFECTS OF DIETARY LEVELS OF PHOSPHORUS AND ALUMINUM ON PHOSPHORUS UTILIZATION AND CALCIUM AND MAGNESIUM ABSORPTION[a]

Item	Dietary P, %: / Added Al, ppm:	.15 / 0	.29 / 0	.15 / 2,000	.29 / 2,000	SD[c]	Statistical significance[d] P	Al	P X Al
		g/d							
Dry matter intake		745	771	529	592	149	NS	P<.01	NS
Phosphorus									
Intake[a]		1.196	2.476	.969	1.949	.258	P<.01	P<.01	NS
Fecal[a]		1.229	2.408	1.366	2.173	.506	P<.01	NS	NS
Apparent absorption[a]		−.033	.068	−.397	−.224	–	NS	P<.01	NS
Endogenous fecal[b]		.483	.820	.206	.460	.197	P<.05	P<.05	NS
True absorption[b]		.450	.888	−.191	.236	–	NS	P<.01	NS
Urinary[a]		.015	.073	.007	.101	–	P<.01	NS	NS
Net retention[a]		−.048	−.004	−.404	−.325	.313	NS	P<.05	NS
		%							
Apparent absorption[a]		−2.6	2.7	−35.9	−10.7	2.6	NS	P<.01	NS
True absorption[b]		28.7	32.8	−9.2	8.5	.3	NS	P<.01	NS
Apparent Ca absorption[b]		21.9	17.6	−5.9	−1.7	11.4	NS	P<.05	NS
Apparent Mg absorption[b]		44.6	38.7	39.5	30.6	4.9	NS	NS	NS

[a]Mean based on five lambs/treatment.

[b]Mean based on three lambs/treatment.

[c]Standard deviation calculated from the residual mean square.

[d]NS denotes (P>.05).

6). A P × Al interaction (P<.05) was observed for bone Fe concentrations. Al again overcame the depression brought about by dietary P.

Discussion

Increasing dietary Al levels by 2,000 ppm decreased feed intake and average daily gain of lambs. Valdivia et al. (1978) fed steers 1,200 ppm Al as $AlCl_3 \cdot 6H_2O$ and Thompson et al. (1959) fed lambs 810 ppm Al as aluminum sulfate and found no depression on animal performance. In a study with chicks (Storer and Nelson, 1968), 325 ppm Al as $Al(SO_4)_3 \cdot 18H_2O$ produced 5% mortality, and 447 ppm Al as $AlCl_3 \cdot 6H_2O$ caused 25% mortality. Ruminants appear to be less susceptible to the toxic effects of Al.

Changes in weight gain and plasma minerals induced by a high level of dietary Al in this experiment were similar to those observed in rats fed .24% P and aluminum sulfate in amounts designed to provide an Al:P ratio of 1:1 (Street, 1942). Alsmeyer et al. (1963) found that

TABLE 5. EFFECTS OF PHOSPHORUS AND ALUMINUM LEVELS IN THE DIET ON TISSUE MINERAL COMPOSITION[a]

Dietary P, %	Added Al, ppm	Tissue minerals, ppm fresh tissue							
		Al	Fe	Zn	Cu	Mn	P	Ca	Mg
					Liver[bh]				
.15	0	2.64	45.56[d]	19.69	117.7	3.42[d]	1,972	40.44	129.7
.29	0	2.94	71.04	18.17	175.0	3.06	1,900	38.22	118.8
.15	2,000	6.70	102.82	22.68	176.9	2.68	1,677	38.68	112.4
.29	2,000	6.34	69.74	15.30	149.7	2.45	1,698	35.56	108.6
SD		2.30	34.52	10.25	70.14	.54	287	3.07	16.8
					Kidney[bh]				
.15	0	2.37	36.6[d]	27.56[e]	3.17[c]	.82	1,731	97.8	188.8[c]
.29	0	3.35	42.68	22.14	3.18	.83	1,747	112.0	183.2
.15	2,000	4.66	63.56	32.46	4.59	.73	1,743	97.1	157.4
.29	2,000	5.17	45.80	23.58	3.73	.71	1,729	137.1	167.4
SD		2.35	13.55	5.47	.57	.22	100	67.3	8.9
					Muscle[bh]				
.15	0	2.33	24.59	23.44	.98[c]	.09[f]	1,452	22.22	232.0
.29	0	2.81	22.02	23.44	.98	.04	1,399	21.84	235.1
.15	2,000	4.08	26.14	22.68	1.14	.08	1,428	24.24	230.8
.29	2,000	3.89	22.97	23.02	1.14	.05	1,412	24.50	218.1
SD		1.71	3.23	3.20	.12	.03	184	4.43	32.0
					Brain[bh]				
.15	0	3.71	17.13	11.40	3.70	.24	2,106[g]	53.5	132.0[g]
.29	0	5.37	17.19	11.22	3.56	.26	1,987	63.5	123.0
.15	2,000	4.04	17.47	11.84	3.35	.22	1,982	45.1	126.0
.29	2,000	5.04	17.20	12.54	3.74	.25	2,236	100.4	140.2
SD		1.84	1.78	1.11	.64	.07	118	43.1	8.76

[a]Means represent five lambs.

[b]SD is standard deviation calculated from the residual mean square.

[c]Main effect (P<.01) of Al.

[d]Main effect (P<.05) of Al.

[e]Main effect (P<.01) of P.

[f]Main effect (P<.05) of P.

[g]P × Al (P<.01).

[h]Dry matter contents of tissues (%) were: liver, 30.77 ± 1.88; kidney, 22.46 ± .70; muscle, 28.01 ± 1.36; brain, 23.25 ± 1.14.

rats fed 3,700 and 7,400 ppm Al (aluminum sulfate) gained 20 and 60% less weight than a control group fed no Al and had reduced plasma P concentrations. Cox et al. (1931), using guinea pigs and rabbits, found that diets containing Al (1,400 ppm) that was chemically in excess of the total P produced a 15% decrease in blood P. Low plasma P levels induced by the feeding of Al also have been observed in chicks (Deobald and Elvehjem, 1935; Williams and Rodbard, 1957; Storer and Nelson, 1968). The reduction in serum Mg resulting from Al addition has also been reported by Allen et al. (1980).

Marked decreases in P absorption and net P retention were observed when lambs were fed 2,000 ppm Al in the diet. This suggests that Al in the diet reduced P absorption. Increases in dietary P tended to overcome this adverse effect. Similar results were reported by Street (1942) for rats.

The borderline P equilibrium in those lambs fed the low Al diet may have been due partially to limited P intake during the balance trial, suggesting that P intakes were slightly below minimum requirements for maintenance. This situation would have been aggravated by the high Al concentration in the diet. A potential or a borderline P deficiency would obviously make animals more susceptible to the negative effect of Al. We estimated that approximately 72% of the dietary P could have reacted with Al leaving 28% P for absorption. This is equivalent to .09% of available P in the diet, an insufficient amount for maintenance requirements. The observed reductions in animal performance, plasma P and P retention are consistent with this speculation.

Tissue mineral composition in the present study varied with levels of P and Al in the diet, and also with the tissue. The Al deposited in liver, kidney and longissimus muscle reflected the level of dietary Al. These results are in accord with those reported by Vozar (1959) and Berlyne et al. (1972) in studies with rats fed aluminum chloride and aluminum sulfate, respectively. Contrary to findings of the cited investigators, brain tissue in this experiment seemed to be less affected than other tissues by Al levels in the diet. Valdivia et al. (1978) reported no change in brain mineral composition when 1,200 ppm Al was fed to steers. Higher concentrations of Fe in liver and kidney were observed with high Al diets. In liver, the high levels of Fe accompanied low levels of P. A metabolic antagonism of Fe and P has been demonstrated by Harmon et al. (1968) and Standish and Ammerman (1971). Low levels of Zn in the kidney were observed when the high P diet was fed, and also, a similar, although not significant, trend was observed in liver. A similar effect of P was reported by Standish and Ammerman (1971) with low Fe diets.

Cu levels in the kidney were lowered by high Al levels in the diet, and a similar effect was observed in muscle. High Al diets induced low Mn levels in the liver, but in muscle, Mn levels were negatively influenced by higher levels of dietary P.

Higher concentrations of Fe and Cu with

TABLE 6. EFFECTS OF PHOSPHORUS AND ALUMINUM LEVELS IN THE DIET ON BONE MINERAL COMPOSITION[a]

Dietary P, %	Added Al, ppm	Ash[b]	Minerals (bone-ash basis)					
			Ca	P	Mg	Cu	Fe	Mn
			%			ppm		
.15	0	63.94[d]	35.29	14.75	.54	5.39	29.03[e]	6.37[d]
.29	0	65.81	35.68	14.75	.52	5.06	22.42	6.14
.15	2,000	64.39	35.24	14.28	.41	5.27	23.50	6.48
.29	2,000	65.82	35.81	14.86	.47	5.25	27.76	6.50
SD[c]		1.83	1.10	.40	.05	.61	5.73	.19

[a]Means represent five lambs.

[b]Fat-free, dry bone basis.

[c]Standard deviation calculated from the residual mean square.

[d]Main effect (P<.05) of Al.

[e]P × Al (P<.05).

high Al diets were observed in the kidney, and higher levels of Fe were found in the liver. Usually, an antagonistic effect of Cu on Fe storage has been observed (Cook et al., 1966). In the present study, high Al diets decreased bone ash and increased Mn content in bone. A similar reduction in bone ash resulting from the feeding of Al was found by Deobald and Elvehjem (1935) and Storer and Nelson (1968).

The changes in tissue mineral concentrations caused by the various levels of Al in the diet are difficult to explain, because the interaction of Al with other minerals has not been fully elucidated. It is possible that the changes observed are the result of an indirect effect of Al on other minerals.

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