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Akmed S. Hussein
University of Kentucky

Austin H. Cantor
University of Kentucky, acantor@uky.edu

Thomas H. Johnson
University of Kentucky

Robert A. Yokel
University of Kentucky, ryokel@email.uky.edu

Effect of Dietary Aluminum Sulfate on Calcium and Phosphorus Metabolism of Broiler Chicks[1]

AHMED S. HUSSEIN,[2,3] AUSTIN H. CANTOR,[2,4] THOMAS H. JOHNSON,[2] and ROBERT A. YOKEL[5]

Department of Animal Sciences and Division of Pharmacology and Toxicology, University of Kentucky, Lexington, Kentucky 40546-0215

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ABSTRACT The effect of dietary aluminum sulfate on Ca and P metabolism was studied using 1-day-old male broiler chicks. In Experiment 1, practical diets providing .90% Ca plus .45% available P (P_{av}), .90% Ca plus .78% P_{av}, 1.80% Ca plus .45% P_{av}, or 1.80% Ca plus .90% P_{av} were fed with 0 or .392% Al as aluminum sulfate for 21 days. The control diet (.90% Ca plus .45% P_{av}) without added Al was fed to all chicks during Days 22 to 49. In general, Al significantly ($P<.05$) decreased BW gain, feed intake, gain:feed ratio, plasma inorganic P (Pi), tibia breaking strength, tibia weight, percentage of tibia ash, and plasma Zn, measured at Day 21. Elevating P_{av} increased BW gain, feed intake, gain:feed ratio, tibia weight and plasma Zn, and decreased plasma total Ca in the presence of .392% Al plus 1.80% Ca. Plasma P_i, tibia breaking strength, and percentage of tibia ash were increased by raising dietary Pav in the presence of .392% Al with either level of Ca. Negative effects of dietary Al on feed intake and BW persisted through Day 49.

In Experiment 2, a control diet (.90% Ca, .45% P_{av}) was fed for *ad libitum* access either alone or supplemented with .2% Al as aluminum sulfate or with an equivalent amount of sulfate provided by potassium sulfate. The control diet was also pair-fed to chicks given .2% Al. Dietary Al significantly depressed weight gain, feed intake, gain:feed ratio, and plasma P_i. No effects were noted due to adding potassium sulfate to the diet. Pair-feeding the control diet decreased weight gain, feed intake, and tibia weight, but not plasma P_i. These results indicate that the toxic effect of aluminum sulfate is due to the aluminum and not the sulfate ions. The influence of aluminum on growth is mainly due to depressed feed intake, while the altered Ca and P metabolism results from a direct effect of Al *per se*.

(*Key words*: aluminum, sulfate, calcium, phosphorus, broiler chicks)

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INTRODUCTION

Previous work in the authors' laboratory showed that high levels of dietary aluminum sulfate induced pauses in egg production, decreased feed intake, and decreased plasma inorganic phosphorus (P_i) in Japanese quail hens (Hussein *et al.*, 1988) and in Single Comb White Leghorn (SCWL) laying hens (Hussein *et al.*, 1989a,b). In other studies, plasma P_i of broiler chicks was significantly decreased by dietary Al and increased by dietary available P (P_{av}), while weight gain, feed intake, and feed efficiency were significantly decreased by Al (Hussein *et al.*, 1989c). Storer and Nelson (1968) observed that dietary aluminum sulfate caused growth, bone ash, and the efficiency of feed utilization to be decreased in SCWL chicks. Substantial decreases in plasma P_i (58 to 75%) and smaller decreases in BW gain (24 to 30%) were observed in White Rock male chicks fed *ca.* 1 to 1.3% Al provided by alum-flocculated algae (Lipstein and Hurwitz, 1981). When *ca.* .48% Al supplied by algae was fed, BW gain and feed intake were decreased by only 7 and 2%, respectively.

Experiment 1 was conducted to determine the interactive effects of dietary Al, Ca, and P on Ca and P metabolism and growth performance of broiler chicks during a treatment period (21 days) and during a posttreatment period (28 days) after withdrawing Al from the diet. The objectives of Experiment 2 were to determine if the negative effect of aluminum sulfate was due to simply a reduction in feed intake or to a direct effect of aluminum sulfate *per se* and to determine if the effect was due to the Al ions or to the sulfate ions.

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[2]Department of Animal Sciences.

Present address: Nutrition Laboratory, Department of Human Ecology, University of Maryland Eastern Shore, Princess Anne, MD 21853.

[4]Corresponding author.

[5]Division of Pharmacology and Toxicology.

MATERIALS AND METHODS

Experiment 1

Three groups of 11 male chicks, 1 day of age, were randomly assigned to each of eight treatments. The chicks were housed in pullet cages (61 cm long by 51 cm wide by 36 cm high) for 49 days. Infrared lamps were used for supplemental heat during the brooding period. All 11 chicks in each replicate were started in 1 cage and divided between 2 cages after 3 wk. Feed and water were provided for *ad libitum* access.

Practical diets providing .90% Ca plus .45% P_{av}, .90% Ca plus .78% P_{av}, 1.80% Ca plus .45% P_{av}, or 1.80% Ca plus .90% P_{av} were fed during Days 1 to 21 with 0 or .392% Al as $Al_2(SO_4)3 \cdot 14\ H_2O$ (U.S.P. grade). The control diet (.90% Ca plus .45% P_{av}) without added Al was fed to all chicks during Days 22 to 49. On a molar basis, the highest level of Al (.392%) was equivalent to the lowest calculated level of P_{av} (.45%). The composition and calculated nutrient content of the diets, based on ingredient composition tables (Scott *et al.*, 1982), are shown in Table 1. Each of the four diets shown in Table 1 was fed with or without supplemental Al. During Days 22 to 49, all chicks were fed the control diet (.90% Ca plus .45% P_{av}, Table 1) without added Al. Blood samples were obtained weekly (except for Day 42), and tibia samples were taken on Day 21.

Experiment 2

Three replicate groups of 11 to 15 male chicks, 1 day of age, were randomly assigned to each of four treatments. Early mortality unrelated to treatments reduced the number of chicks in some groups. The chicks were housed and managed as in Experiment 1. The first three dietary treatments consisted of an *ad libitum* control diet (.90% Ca plus .45% P_{av}) fed alone (Table 1), supplemented with .2% Al as aluminum sulfate, or 1.067% sulfate as potassium sulfate. The latter treatment provided the same level of sulfate as did the .2% Al as aluminum sulfate. Starting at Day 4, birds in the fourth treatment were pair-fed the control diet at the level of intake of birds fed the diet supplemented with aluminum sulfate. The daily feed intake was measured for groups receiving dietary aluminum sulfate and that amount of the control diet was fed on the next day to pair-fed groups based on the average daily feed intake per chick. Water was provided for *ad libitum* access for all treatment groups.

Tissue Samples and Analyses

Blood samples were taken by cardiac puncture from two randomly selected birds per replicate group using 150 units of heparin per 5 mL blood. Plasma was separated following centrifugation for 10 min at 1000 times *g*, pooled within replicate groups, and stored at <0 C until the analyses were performed. Plasma P_i, total Ca (Ca_t), Zn, Mg and Al were determined using methods described by Hussein *et al.* (1990). Bone samples were obtained from two chicks per replicate group following cervical dislocation. They were prepared and assayed for dried and defatted weight, breaking strength, and ash content using methods described by Cantor *et al.* (1980). In the present study, bones were supported by fulcra placed 3.5 cm apart when measuring breaking strength.

Statistical Analyses

Data were subjected to one-way ANOVA using the General Linear Models program of the Statistical Analysis System (SAS Institute, 1982). The test of least significant difference was used to separate means only when a significant value of F was obtained in the ANOVA (Snedecor and Cochran, 1980). A probability level of <.05 was required for significance in all statistical analyses.

RESULTS

Experiment 1

Dietary Al, added to any of the four combinations of Ca plus P_{av}, significantly reduced weight gain and feed intake during Days 1 to 21 (Table 2). A reduction in the gain:feed ratio due to Al was also observed with all combinations of Ca plus P_{av}, except 1.80% Ca plus .90% P_{av}. Increasing P_{av} in the presence of Al plus 1.80% Ca corrected the gain:feed ratio and improved, but did not completely correct, gain and feed intake.

Dietary Al fed during Days 1 to 21 significantly reduced subsequent feed intake during Days 22 to 49 (Table 2). Gain:feed was increased when Al was added to diets containing .45% P_{av} with either .90 or 1.80% Ca. Final BW

TABLE 1. *Composition of diets (Experiments 1 and 2)*

Ingredient	.90% Ca, .45% P_{av}[1]	.90% Ca, .78% P_{av}	1.80% Ca, .45% P_{av}	1.80% Ca, .90% P_{av}
	(%)			
Ground yellow corn	55.30	53.80	50.12	48.49
Soybean meal (48% protein)	34.77	35.04	35.71	35.65
Blended animal-vegetable fat	5.45	5.99	7.31	8.00
Sodium chloride	.52	.52	.52	.52
Ground limestone	1.06	.00	3.42	1.90
Dicalcium phosphate (22% Ca, 18.5% P)	1.69	3.44	1.71	4.22
Vitamin-mineral premix[2]	1.00	1.00	1.00	1.00
DL-methionine, 99%	.21	.21	.21	.22
Calculated analysis:				
ME, Mcal per kg	3.15	3.15	3.15	3.15
Protein, %	21.50	21.50	21.50	21.50
Methionine, %	.55	.55	.55	.56
Methionine plus cystine, %	.91	.91	.91	.91
Lysine, %	1.19	1.19	1.19	1.20

[1]Available phosphorus.

[2]Provided the following per kilogram of diet: vitamin A, 6,000 IU; vitamin D_3, 1,000 ICU; vitamin E, 15 IU; menadione dimethylpyrimidinol bisulfite, 2.0 mg; thiamin, 5.94 mg; riboflavin, 5.4 mg; pantothenic acid, 15 mg; niacin, 41 mg; pyridoxine, 4.5 mg; biotin, .23 mg; choline, 1,450 mg; folacin, .83 mg; vitamin B_{12}, .014 mg; ethoxyquin, 125 mg; Se, .2 mg; Cu, 6 mg; I, .53 mg; Fe, 120 mg; Mn, 83 mg; Zn, 60 mg; and Co, 5 mg.

was reduced by Al when added to any of the four dietary combinations of Ca plus P_{av}. Increasing P_{av} in diets containing .392% Al plus 1.80% Ca increased final BW and feed intake during Days 22 to 49.

Tibia weight was significantly reduced by dietary Al with all combinations of Ca plus P_{av} (Table 3). Increasing P_{av} to .90% in the presence of .392% Al plus 1.80% Ca significantly improved this parameter. Feeding Al also reduced tibia breaking strength in comparison with the control treatment. Tibia ash was reduced by Al except when it was added to the diet containing 1.80% Ca plus .90% P_{av}. Tibia breaking strength and ash were significantly increased by raising dietary Pav in the presence of all combinations of Al plus Ca except for the combination of 0% Al plus .90% Ca. The

TABLE 2. *Effect of dietary aluminum, calcium, and available phosphorus (P_{av}) on growth performance of broiler chicks (Experiment 1)*[1]

Dietary treatment			Days 1 to 21			Days 22 to 49			Day 49
Al	Ca	P_{av}	BW gain	Feed intake	Gain: feed	BW gain	Feed intake	Gain: feed	BW
(%)			(g)		(g/g)	(g)		(g/g)	(g)
0	.9	.45	622[a]	865[a]	.720[ab]	1,583	3,156[ab]	.501[c]	2,243[a]
0	.9	.78	627[a]	900[a]	.697[b]	1,580	3,060[ab]	.518[bc]	2,246[a]
0	1.8	.45	608[a]	799[b]	.762[a]	1,505	3,090[ab]	.487[c]	2,152[a]
0	1.8	.90	616[a]	871[a]	.707[ab]	1,619	3,298[a]	.491[c]	2,273[a]
.392	.9	.45	157[c]	285[d]	.551[c]	1,292	2,213[d]	.585[a]	1,488[c]
.392	.9	.78	184[c]	316[d]	.582[c]	1,406	2,457[cd]	.573[ab]	1,628[bc]
.392	1.8	.45	175[c]	309[d]	.566[c]	1,328	2,337[d]	.572[ab]	1,542[c]
.392	1.8	.90	288[b]	472[c]	.665[b]	1,541	2,834[bc]	.544[abc]	1,866[b]
Pooled SEM			16	20	.019	79	136	.019	84

[a–d]Means within a column with no common superscript differ significantly (P<.05).

[1]Each diet was fed to three groups of 11 chicks during the treatment period (Days 1 to 21). All chicks were fed the control diet (0% Al plus .90% Ca plus .45% P_{av}) during the posttreatment period (Days 22 to 49).

TABLE 3. *Effect of dietary aluminum, calcium, and available phosphorus (P_{av}) on tibia weight, breaking strength, and ash and plasma zinc, magnesium, and aluminum of broiler chicks at Day 21 (Experiment 1)*

Dietary treatment			Tibia			Plasma		
Al	Ca	P_{av}	Weight	Breaking strength	Ash	Zn	Mg	Al
(%)			(g)	(kg)	(%)	(μg per dL)	(mg per dL)	(μg per dL)
0	.90	.45	1.68^{a}	10.23^{b}	44.7^{bc}	99.2^{a}	2.82	9.5
0	.90	.78	1.78^{a}	8.53^{bc}	47.5^{ab}	87.1^{a}	2.72	8.2
0	1.80	.45	1.86^{a}	9.98^{b}	42.1^{cd}	102.2^{a}	2.80	7.9
0	1.80	.90	1.90^{a}	14.23^{a}	48.9^{a}	NA[2]	2.74	11.9
.392	.90	.45	.50^{c}	2.75^{f}	27.1^{e}	67.9^{cd}	2.38	6.5
.392	.90	.78	.57^{c}	4.97^{de}	39.7^{d}	58.5^{d}	2.69	6.9
.392	1.80	.45	.52^{c}	3.33^{ef}	27.7^{e}	72.9^{c}	2.82	14.5
.392	1.80	.90	1.00^{b}	6.65^{cd}	46.6^{ab}	97.3^{a}	2.75	10.7
Pooled SEM			.10	.67	1.0	3.3	.12	3.9

a–fMeans within a column with no common superscript differ significantly (P<.05).

1Each diet was fed to three groups of 11 chicks each during Days 1 to 21. Tibia and blood samples were obtained from two chicks per replicate group.

2NA = Not analyzed.

highest mean values for tibia weight, breaking strength, and ash were obtained by feeding 1.80% Ca plus .90% P_{av} in the absence of added Al. Several cases of rickets were observed in groups fed .392% Al within the firstweek of the experiment. These birds died shortly thereafter. Therefore, this occurrence probably had little influence upon performance during the remainder of the experiment.

Dietary Al significantly reduced plasma Zn at Day 21, except when it was added to the diet containing 1.8% Ca plus .9% P_{av} (Table 3). Dietary treatments failed to affect plasma Mg and plasma Al at Day 21. Plasma Zn and Mg at Day 14 and plasma Al at Day 7 were also unaffected by dietary treatments.

Plasma P_i at Days 7, 14, and 21 was, on the average, significantly depressed by adding Al to the diets or by increasing the dietary Ca to 1.80% (Table 4). However, the depression in plasma P_i was alleviated by increasing dietary P_{av}. Feeding the higher levels of P_{av} at either level of dietary Ca without added Al significantly elevated plasma Pi at Days 7, 14, and 21. The

TABLE 4. *Effect of dietary aluminum, calcium, and available phosphorus (P_{av}) on plasma inorganic phosphorus (P_i) of broiler chicks (Experiment 1)*[1]

Dietary treatment			Plasma P_i					
Al	Ca	P_{av}	Day 7	Day 14	Day 21	Day 28	Day 35	Day 49
(%)			(mg per dL)					
0	.90	.45	6.8^{d}	7.0^{bc}	8.3^{a}	8.9^{ab}	8.3	8.5
0	.90	.78	10.3^{a}	10.2^{a}	6.5^{b}	8.1^{b}	7.1	7.2
0	1.80	.45	4.6^{e}	3.5^{d}	3.4^{c}	9.4^{a}	7.4	7.8
0	1.80	.90	9.6^{b}	9.7^{a}	7.8^{ab}	9.1^{a}	8.3	7.3
.392	.90	.45	3.0^{f}	2.1^{de}	2.6^{cd}	6.4^{c}	6.8	8.7
.392	.90	.78	7.2^{d}	8.5^{ab}	7.8^{ab}	7.2^{c}	7.6	8.1
.392	1.80	.45	2.6^{f}	1.4^{e}	1.8^{d}	6.3^{d}	7.7	8.7
.392	1.80	.90	8.1^{c}	5.5^{c}	8.4^{a}	8.6^{ab}	8.4	8.4
Pooled SEM			.2	.6	.5	.3	.6	.5

a–fMeans within a column with no common superscript differ significantly (P<.05).

1Each diet was fed to three groups of 11 chicks each during the treatment period (Days 1 to 21). All chicks were fed the control diet (0% Al plus .90% Ca plus .45% P_{av}) during the posttreatment period (Days 22 to 49). Plasma samples were obtained from two chicks per replicate group at each sampling time.

TABLE 5. *Effect of dietary aluminum, calcium, and available phosphorus (P_{av}) on plasma total calcium (Ca_t) of broiler chicks (Experiment 1)*[1]

Dietary treatment			Plasma Ca_t					
Al	Ca	P_{av}	Day 7	Day 14	Day 21	Day 28	Day 35	Day 49
(%)			(mg per dL)					
0	.90	.45	10.3^{c}	9.1^{cd}	7.7^{c}	10.8	10.8	10.7
0	.90	.78	9.1^{d}	9.1^{cd}	8.9^{bc}	10.5	11.0	10.6
0	1.80	.45	12.5^{b}	11.8^{b}	11.1^{a}	11.0	10.1	10.3
0	1.80	.90	9.6^{cd}	9.9^{c}	8.9^{bc}	10.9	10.4	9.8
.392	.90	.45	9.4^{d}	11.1^{b}	8.6^{c}	12.1	11.7	10.9
.392	.90	.78	7.9^{e}	8.5^{d}	8.1^{c}	11.1	10.5	10.4
.392	1.80	.45	13.4^{a}	13.3^{a}	10.2^{ab}	12.0	10.4	10.8
.392	1.80	.90	8.9^{d}	9.0^{cd}	8.0^{c}	11.6	10.6	10.9
Pooled SEM			.3	.3	.5	.5	.4	.4

[a–e]Means within a column with no common superscripts differ significantly ($P<.05$).

[1]Each diet was fed to three groups of 11 chicks each during the treatment period (Days 1 to 21). All chicks were fed the control diet (0% Al plus .90% Ca plus .45% P_{av}) during the posttreatment period (Days 22 to 49). Plasma samples were obtained from 2 chicks per replicate group at each sampling time.

lowest value of plasma P_i was obtained with the high level of Ca in the presence of dietary Al. The depression in plasma P_i due to dietary Al persisted until Day 28, i.e., 7 days after feeding the control diet to all treatment groups. Thereafter, no differences among treatments were noted for plasma P_i.

In most cases, plasma Ca_t was significantly elevated by increasing dietary Ca with or without added Al and was decreased by using higher levels of P_{av} at Days 7, 14, and 21 (Table 5). The highest values for plasma Ca_t were observed at Days 7 and 14 in chicks fed the diet containing .392% Al plus 1.80% Ca plus .45% P_{av}. No differences in plasma Ca_t among treatments were noted during the posttreatment period.

Experiment 2

Supplemental potassium sulfate failed to affect growth performance and bone parameters compared with the control treatment (Table 6). Potassium sulfate elevated plasma P_i at Day 14, but not at Days 7 and 21, and did not significantly influence plasma Cat. The pair-feeding treatment significantly decreased BW gain without affecting the gain:feed ratio compared with the control treatment. Pair-feeding also lowered tibia weight and plasma P_i at Day 7 but not at other times. Feeding aluminum sulfate decreased BW gain to a greater degree than did pair-feeding of the control diet. In addition, dietary Al decreased the gain:feed ratio, increased plasma Ca_t, at Day 14, and substantially reduced plasma P_i at all three sampling times.

DISCUSSION

The results of feeding broiler chicks high levels of dietary Al, P, and Ca in the first 3 wk upon growth performance and Ca and P metabolism (Tables 2 to 5) are similar to those obtained by Hussein *et al.* (1990) in which similar experimental conditions were used. In general, increasing dietary P_{av} corrected the negative effect of Al on plasma Pi, but failed to completely correct the negative effect on growth performance in Experiment 1. Berlyne *et al.* (1972) and Lipstein and Hurwitz (1982) reported that Al primarily depletes plasma P_i while indirectly affecting feed intake.

Dietary Al decreased percentage bone ash by almost 40% in Experiment 1 (Table 3). Substantial reductions in bone ash content were also observed by Storer and Nelson (1968). In the present study, several cases of rickets were observed in chicks within 1 wk of feeding .392% added Al. Deobald and Elvehjem (1935) found that diets containing .22 to .44% Al fed to day-old SCWL chicks produced rickets within 2 wk. Increasing dietary P_{av} and Ca improved tibia weight, breaking strength, and percentage ash at 3 wk of age (Table 3); this is in agreement with previous findings (Hussein *et al.*, 1990). The highest values for these parameters were obtained by feeding 1.80% Ca plus .90% P_{av}. Hulan *et al.* (1985) reported that tibia weight, breaking

TABLE 6. *Effect of dietary aluminum sulfate, potassium sulfate, and pair-feeding on growth performance, bone parameters, plasma inorganic phosphorus (P_i), and plasma total calcium (Ca_t) of broiler chicks (Experiment 2)*[1]

	Dietary treatment				
Measurement	Control	Pair-fed	Potassium sulfate[2]	Aluminum sulfate[3]	SEM
BW gain, g	662^a	434^b	622^a	360^c	18
Feed intake, g	895^a	544^b	854^a	572^b	23
Gain:feed	$.740^a$	$.801^a$	$.728^{ab}$	$.630^b$	.03
Tibia weight,[4] g	1.86^a	1.07^b	1.36^{ab}	1.19^{ab}	.23
Tibia breaking strength,[4] kg	7.85	6.25	7.92	6.80	1.31
Tibia ash,[4] %	47.7	45.5	44.0	42.5	1.7
Plasma P_i,[4] mg/dL					
Day 7	7.7^a	5.3^b	9.0^a	4.3^b	.7
Day 14	7.6^b	7.0^b	8.9^a	3.6^c	.3
Day 21	6.7^a	6.0^a	6.3^a	3.0^b	.3
Plasma Ca_t,[4] mg/dL					
Day 7	9.6	9.5	9.3	9.5	.2
Day 14	9.2^b	9.3^b	9.0^b	10.4^a	.2
Day 21	8.8	8.9	8.2	9.0	.3

[a–c]Means within a row with no common superscript differ significantly ($P<.05$).

[1]Each diet was fed to three groups of 11 to 15 chicks each for 21 days. Chicks in the pair-fed treatment were fed the control diet at the level of intake of the chicks fed aluminum sulfate. Chicks in other treatments were fed for *ad libitum* intake.

[2]Provided 1.067% sulfate.

[3]Provided .2% aluminum and 1.067% sulfate.

[4]Each value represents the mean of two samples from each of three replicate groups per treatment.

strength, and ash were maximized upon feeding broilers a diet containing 1.47% Ca and .67% P_{av}. The levels of dietary Ca and P_{av} used in the study by Hulan *et al.* (1985) and in the present experiment are considerably higher than the requirements established by the National Research Council (1984).

During the posttreatment period of Experiment 1, birds in the different treatment groups were growing at similar rates. However, birds previously fed Al had decreased final BW (Day 49) and reduced feed intake during the posttreatment period (Table 2). Much of this effect was the result of reduced BW at the start of the posttreatment period. Birds previously fed .392% Al plus .45% P_{av} had a higher gain: feed ratio, compared with birds previously fed the control diet. This effect may have been due to the greater maintenance requirement of birds fed the control diet as a result of their greater BW at Day 21.

Plasma Al was not affected by dietary treatments. Similar results were obtained in a previous study (Hussein *et al.*, 1990). A number of reports (McCollum *et al.*, 1928; Myers and Morrison, 1928; Mackenzie, 1930, 1931) have indicated that Al is poorly absorbed by animals. These observations explain why it is difficult to obtain differences in tissue aluminum levels due to Al supplementation. Dietary Al decreased plasma Zn at Day 21 but failed to affect plasma Zn at Day 14 and plasma Mg at Days 14 and 21. In a previous study, Hussein *et al.* (1990) observed that dietary Al significantly reduced both plasma Mg and Zn after 21 days of treatment.

One of the objectives of Experiment 2 was to determine if the toxicity of aluminum sulfate was due to the Al or the sulfate ions. Growth performance was adversely affected by aluminum sulfate but was not affected by potassium sulfate. Valdivia *et al.* (1982) using aluminum chloride; Allen and Fontenot (1984) using aluminum sulfate, chloride, and citrate; Miles and Rossi (1985) using aluminum acetate; and Hussein *et al.* (1988, 1989a,b; 1990) using aluminum sulfate all reported that dietary aluminum reduced feed intake in animals. The results of the present study confirm that the negative effect of dietary aluminum sulfate is caused by the aluminum and not the sulfate ions.

The results of Experiment 2, using a pair-feeding treatment, showed that approximately 75% of the growth depression due to Al resulted from reduced feed intake (Table 6).

Compared with the control treatment, pair-feeding the control diet and feeding the Al-supplemented diet, *ad libitum*, reduced BW gain by 228 and 302 g, respectively. BW gain and feed efficiency of chicks fed aluminum sulfate were significantly poorer than the respective values for the pair-fed group at 3 wk of age. Plasma P_i and gain:feed ratio of pair-fed chicks were unaffected compared with respective values of the control treatment.

In summary, the addition of dietary Al had a significant negative effect on growth performance and Ca and P metabolism in chicks. Increasing P_{av} in the presence of dietary Al increased plasma P_i, but did not completely correct growth parameters. These results show that the negative effects of aluminum sulfate are due to the Al and not the sulfate ions. They also indicate that the negative effect of Al on growth performance is mainly due to reduced feed intake while the altered metabolism of Ca and P results from a direct effect of Al *per se*.

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