

Mineral Nutrition, Calcium, Phosphorus, Magnesium, and Potassium Interrelationships^{1,2}

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Abstract

There are over 70 known mineral interrelationships in which an additional dietary quantity of one mineral element will influence absorption or utilization of another mineral element. As the animal ages, the readiness of availability of stored mineral elements in the bone decreases. Animals do adapt to reduced dietary intake of minerals as shown for Ca by reducing fecal excretion and increasing absorption. The adaptation, however, may occur simultaneously with a reduction in milk production. Borderline deficiency or insufficiency of mineral elements leads to decreased feed intake and milk production. Diagnosis is extremely difficult. A large proportion of commonly used feedstuffs are below the required concentration of at least one mineral element for high milk production. Since few dairymen know how much of each mineral element is in their cows' diet, milk production may unwittingly suffer from mineral deficiency, insufficiency, or toxicity. Excessive rather than too little dietary Ca during the dry period prior to calving is likely contributing to an increased incidence of milk fever. Basically, blood P must be maintained by absorption from the gut as there is no known specific mechanism for bone resorption. Therefore, it is important always to include adequate P in the diet. Too little Mg may be causing problems that are not well understood, or widely appreciated. Supplemental K is

probably indicated on some high concentrate feeding programs. All mineral elements should be considered in ration formulation for high performance and a reduction in mineral nutrition anomalies.

Introduction

The term interrelationships is the most pertinent word in the title. This is the area which least is known in the mineral nutrition of dairy cattle (57). It follows, then, that this is perhaps the area in which much progress in the mineral nutrition of dairy cattle can be made.

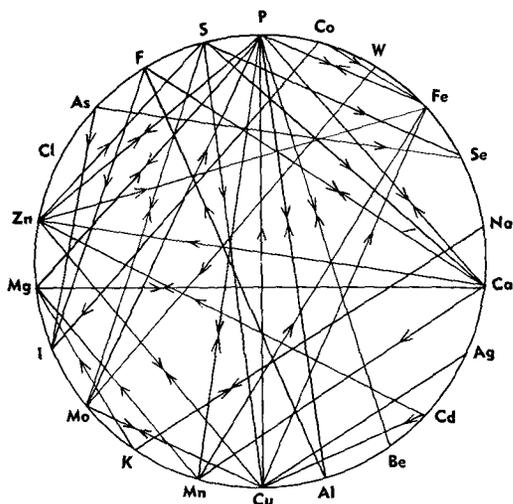


FIG. 1. Mineral interrelationships in animals.

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Based on the umbrella concept of Schutte (73), Figure 1 illustrates most of the reported dietary interrelationships. In this brief paper with such a broad title assigned, only a part of the literature could be cited in the review portion. The review serves as a background for the discussion of milk fever, mineral requirements, and the mineral supplementation of practical dairy rations. The latter portion is intended to assist in the application of the review.

While four elements have been selected for

this discussion, the importance of their interrelationships with other minerals and nutrients is recognized.

Review of Selected Literature

In considering the interrelationships of these mineral elements, it is of fundamental importance to recognize, first, that a very high percentage of the body calcium (Ca), phosphorus (P), and magnesium (Mg) is located in the bone and that most of these mineral elements located therein can be mobilized when needed for use in the metabolic events of body tissue. The bone, therefore, serves as a very large reservoir of these mineral elements (47). All four elements, Ca, P, Mg, and potassium (K) are closely related to many metabolic events in the body. Potassium, however, is not stored to any large extent in the bone; it exists in the body primarily as a cellular constituent. As the animal ages, the readiness of availability of stored mineral elements in the bone does decrease (25, 28). Not only can the animal draw on bone reserves, but there is considerable evidence that the animal tissue is able to adapt to varying dietary inorganic elements in such a way as to avoid clinical symptoms of deficiency or insufficiency. A deficiency of any of these elements leads to reduced voluntary feed consumption and reduced milk production. Borderline deficiencies in any one or any combination of these elements are extremely difficult to diagnose. Dairy farmers simply do not know a) how much of each mineral element is in their feedstuffs and b) how much of each mineral element should be added to the concentrate mixture fed. Consequently, milk production may unwittingly suffer from mineral deficiency, insufficiency, or toxicity.

Calcium metabolism has been studied by several workers in a number of species including cattle, (12, 13, 14, 21, 22, 26, 29, 30, 32, 33, 63, 66, 72). Animals adapt to low-calcium diets by a reduction in fecal excretion and increased absorption of calcium. Older animals take longer to adapt than younger ones. Calcium retention was 25% on a low-phosphorus diet but 96% on a high-phosphorus diet (33), suggesting that retention of calcium, even though it may be quite available in the diet, is dependent upon the concurrent availability of phosphorus. In sheep (78) adaptation to low intakes of calcium can be accomplished by increasing the efficiency of calcium absorption. This efficiency is reported to be due in part to the formation of a greater amount of

calcium-binding protein (CaBP) in the intestinal mucosa. Calcium-binding protein is a specific protein in the intestinal mucosa that binds and transports calcium. Vitamin D is required for its formation. The adaptation is quickly acquired and quickly lost and is partial rather than complete.

Much has been said about the proper dietary Ca to P ratio (94). Holstein steers gained faster on either a 4:1 or 1:1 Ca to P ratio diet with P held at National Research Council recommended amounts than those on a 8:1 ratio (66). For milk production, most authors prefer a Ca to P ratio between 1:1 and 2:1 (12, 79, 80).

In cows, urinary excretion of Ca is between 1 and 2 g daily, relatively constant, and independent of diet. A report involving many diets states that "it should be possible to keep lactating cows in Ca balance, not by high dietary Ca but by including appropriate feed in the diet" (61).

In 1923 (5) it was suggested that the nutritive failure of calves given whole milk for long periods was related to a deficiency of Mg. Duncan, Huffman, and Robinson (20) estimated that 30 to 40 mg/kg body weight (BW) or about 2,000 ppm Mg were necessary to maintain normal plasma Mg when supplement was given as magnesium salts. Only 12 to 15 mg Mg/kg BW from natural feedstuffs were sufficient. When feeding synthetic milk diets containing from .5 to 24 mg Mg/100 ml diet to calves 1 to 2 weeks old, Blaxter et al. (5) noted clinical signs of magnesium deficiency in calves after blood serum magnesium was reduced to below .7 mg per 100 ml. This occurred when the diet contained .5 to 1.6 mg/100 ml. One calf in tetany increased its serum Mg spontaneously, possibly from tissue release. If this is typical, blood samples from cows after tetany may not indicate pre-tetany levels. In these studies no calcification of tissues was observed; however, bone Mg was reduced to 1/3 normal. It is now recognized that calves on milk alone for long times may also be deficient in vitamins A, D, E, and iron, copper, and manganese (59). Bone depleted of Mg may or may not have an increased Ca content. Most researchers employing low-Mg diets have observed calcification of the soft tissues (19).

Magnesium deficiency has been discussed and reviewed on numerous occasions (19, 37, 53, 58, 59, 60, 69, 70, 75, 87, 90, 96). Hypomagnesemic tetany is quite distinct from hypo-

calceic tetany (39, 40, 41). The two distinctive symptoms of Mg deficiency across species are hyperirritability and metastatic calcification. Of particular interest have been the observations of the group at Missouri that on a low-magnesium diet exostosis, soft tissue calcification and stiffness in the hind limbs occur in guinea pigs (59). Tissue mineral concentration changes associated with Mg deficiency are numerous (24, 53). The requirement for Mg (in mg per 100 g of diet) is for rats 20, guinea pigs 80, and calves 200 (59). Why should guinea pigs and cattle have a much higher requirement for Mg than rats and other monogastric species? The cattle requirement for Mg is 10 to 15 mg per kilogram body weight (59). The Mg requirement is increased as dietary Ca alone or dietary calcium and environmental temperature are increased (90). Kidney calcification on low-Mg diets may result in an eleven-fold increase in kidney Ca while kidney Mg is unchanged (51). Keeping both Ca and P high, as opposed to either high, is more effective in accentuating Mg deficiency (60). There are a number of published papers on the P (93, 94), Ca or K requirements in ruminants (8, 17, 18, 22, 29, 31, 43, 64, 67, 68, 71, 77, 83, 84, 91, 92).

Many of the dietary interrelationships among these minerals occur at the absorption site (1, 23, 45). High dietary K impaired intestinal absorption of sodium whereas low K increased urinary sodium excretion (74). Normally, K has no specific effect on Mg requirement. However, very high K, of the order of 3 or 4% of the diet, does enhance Mg deficiency (58). Apparent absorption of Mg in rats was reduced by an increase in dietary Ca from .34 to .68 or of P from .39 to .79% and further reduced by increasing both. Also, increasing dietary Ca decreased percent P absorption (85). High Mg intake increased Ca loss from the body (59). High-P prevented the Ca loss, and high-K tended to prevent the Ca loss. Magnesium absorption is enhanced by neomycin (59). Vitamin D affects Mg absorption only slightly but Ca absorption quite markedly. Increased dietary P decreases absorption of Mg. When the diet is low in P, excess dietary Mg causes loss of Ca but not when P is adequate. Vitamin D and bile are required for Ca absorption (13) and perhaps also for P absorption (23).

Some of the interrelationships in blood minerals include the following: low Mg in the diet and blood did not affect blood Ca or P or bone content. In general, diets low in any of

these mineral elements will cause reductions in blood levels (42). Low K diets and the consequent low-feed and P intakes lead to reductions in serum P but little change in sodium, Ca, or Mg (8).

The Ca content of the red blood cells is near zero whereas the K content is high. In cattle, mean serum Ca is (mg/100 ml) 12.9, whereas the diffusable portion is 4.9; inorganic P is 4.9, but total blood P is perhaps 4 times and red-cell P approximately 10 times this figure. In man, whole blood magnesium is 4.6, red blood cell magnesium 6.6, plasma 2.7, serum 2.5, and diffusable serum 1.9 (46, 74).

In ruminants a high percentage of the Ca and P excreted is via the gut. More than half of the magnesium excreted is via the gut. On the other hand, urinary excretion accounts for 90% of the total K excreted and large quantities may be easily excreted via this route (74). Urinary Mg excretion was between 1 and 3 g per cow per day. There is an obligatory excretion of these elements which continues even when animals are fed diets completely devoid of each mineral element (74). Dietary K has little influence on Ca excretion; however, parathyroid hormone (PTH) increases Ca excretion. A high Mg intake decreases the percent of bone ash, and increases bone Mg content and decreases manganese retention. Acidosis, or an acid diet, leads to increased renal excretion of P, though the urine is not a major pathway of P excretion, usually of the order of 2 to 8% of the intake of sheep and cattle on roughage diets. Insulin causes a reduction in plasma inorganic P. Urinary excretion of calcium seems to be related to urine pH (74). Bone is the probable source of the Ca, as fecal excretion in these studies remained constant.

The endocrine regulation of Ca metabolism has been adequately reviewed by Copp (15, 16). Some of the more significant points include the following: the two hormones that regulate Ca are PTH and calcitonin (CT). The secretion rates of these two hormones may be mediated by changes in the Ca concentration of the perfusing blood without mediation by the pituitary or the central nervous system. Increased Ca increased CT secretion, and decreased Ca decreased CT secretion whereas increased Ca decreased PTH secretion and decreased Ca increased PTH secretion. If plasma Ca was kept constant, changes in P did not affect PTH. However, with constant Ca concentrations, lowered plasma Mg stimulated secretion of PTH and high Mg inhibited it.

This mechanism provides a highly efficient negative-feedback control. Both 3', 5' cyclic adenosine monophosphate (cAMP) and glucagon stimulate release of CT from pig thyroid (11). Administration of PTH to dogs and humans caused a rise in plasma Ca and a fall in plasma P which began within 30 to 60 min and continued from 12 to 24 hr. Calcitonin normally lowers both plasma Ca, and P. The target organ of calcitonin is bone. Parathyroid hormone stimulates whereas CT inhibits bone resorption.

Parathyroidectomy depressed Ca absorption from the gut in the rat whereas administration of parathyroid extract restored or enhanced Ca absorption. Calcitonin had no effect on absorption of Ca, Mg, or P from intestinal loops in dogs but did cause increased excretion of phosphate in the urine. Parathyroid extract increased urinary excretion of phosphate and seemed to enhance tubular re-absorption of Ca. Parathyroid hormone enhances uptake of Ca by monkey kidney cells by 3 to 30-fold. It has been proposed that PTH activates adenyl cyclase and that the resulting increase in cAMP increases the permeability of the cell membrane to Ca^{++} . Parathyroid hormone tended to increase total calcium absorption but net absorption was unchanged in ^{47}Ca studies (97). Calcitonin secretion or release is increased by a) glucagon, b) porcine pancreaticozym, c) dibutyryl cyclic AMP which is enhanced by theophylline, d) adrenaline in the presence of α -adrenergic blockade with phentolamine, e) increased Ca, f) to a lesser degree by increased Mg, and depressed by progesterone.

Calcitonin is low or undetected and PTH high in the blood of parturient cows (3, 10, 97), though there is normally a basal secretion rate. There are a number of discussions and reviews on milk fever (3, 6, 27, 34, 81, 82). Cows in advanced pregnancy are more hypocalcemic than either milk-fever-prone or normal lactating cows when subjected to experimental hypocalcemia (62). Cows with milk fever often have reduced blood serum Ca, inorganic P and increased blood serum Mg (34). Inorganic P decreases from about 6 to perhaps 1.5, Ca down from 10 to 11 to 5 and Mg up from 2 to possibly 3.5 mg %. Lactating cows are frequently in negative calcium and magnesium balance (50, 61). In attempts so far, parathyroid extract has not usually been effective in treating cows with early symptoms of milk fever (35, 54).

Magnesium has been particularly involved

in atherosclerosis. Increased dietary Mg decreases lipid deposition (sudanophilia) of the aorta of rats on atherogenic diets. High-Mg diets exert an "anti-sudanophilic" effect. The addition of thyroxine definitely reduced the sudanophilia (56). On low-Mg diets sudanophilia increased after 6 to 12 months, and several animals showed grossly visible aortic intimal plaques (56). Increased dietary K has reduced the mineralized aortic Ca and P in dogs (7). Rats and monkeys fed diets low in Mg developed high blood cholesterol and were more susceptible to atherosclerosis by cholesterol feeding. Additional reports discuss the relationship between Mg and atherosclerosis (4, 7, 44, 48, 52, 55, 76, 88, 89).

The project initiated sometime ago (38) was intended to consider the dietary interrelationships between Ca, P, Mg, and K. The first experiment was an attempt to study the effect of dietary Mg, but feed consumption was poor, and the experiment was terminated. However, some observations on milk fever, deformed calves, and abnormal blood values were obtained.

The second experiment was started in December, 1971 (Jersey heifers and cows assigned as they approached 60 days prior to expected date of calving). The design was a 2³ factorial design with two dietary amounts (low and high), of Ca, P, and Mg. In addition, a treatment with more desirable amounts of minerals was included. Corn silage served as the only roughage. Silage to grain ratio was held constant at 4.5 to 1 on an as fed basis. At 60 days prior to expected date of calving each cow (blocks balanced and assigned to treatment by chance) was fed a standard diet for 2 weeks, then placed on experimental diet ad libitum continuously to 90 days past the second parturition. A minimum of 6 cows per treatment were planned. The experimental grain mixtures were formulated so as to provide in the diet dry matter on a percentage basis: crude protein, 16; Ca, low .29, high .70; P low, .25, high .39; Mg, low .14, high .26; K .8; S .15; Fe .011; Cu .001; Co .00001; Zn .002; and Mn .0043.

Two cows, one each on rations low in Mg, were removed from the experiment, posted, and tissues obtained. Both animals had degenerative changes in the smooth muscle of the arch of the aorta. Changes in blood minerals at calving time were numerous. Depressions in minerals on these diets at calving time appeared to be typical in all but first-calf heifers. In one cow with milk fever Ca was 9.8

mg/100 ml at 1 hr after calving. Half hour later it was 3.4. At 1 hr after calving this cow had increased Ca, Mg, and K and lower sodium. One-half hour later (1.5 hr after calving) when the cow was down, all these elements were reduced, and Ca and sodium were reduced to less than half. One hour after treatment with Ca only, P and sodium increased spontaneously. To get an accurate picture of what happens to blood levels during parturition and the onset of milk fever, frequent samples would be necessary. An increase in both Ca and Mg after calving occurred which was enough to suggest that CT release could be involved in the rapid reduction of Ca and P. There is no available physiological explanation for the spontaneous increase in blood P following treatment with Ca.

Three questions relative to the prevention of milk fever arise:

1. Since voluntary consumption of feed at calving time is only a small fraction of normal, would oral supplementation of appropriate mineral elements at the proper amounts at calving time or when voluntary consumption subsides, aid in the prevention of milk fever?

2. Is the target organ, bone, unresponsive to PTH at calving time or would PTH be an effective therapeutic agent in preventing milk fever? The half-life of injected PTH is 20 min, but its effect on blood Ca begins within 30 to 60 min and may persist 12 to 24 hr. Blood P is reduced by PTH and may be contraindicated in hypophosphatemic milk fever.

3. Is the increased blood Mg within hours after calving inhibiting PTH or enhancing CT release or both, thus contributing to milk fever?

Crampiness (95), the downer cow syndrome and reproductive efficiency (2, 36, 49)

TABLE 1. Guide to the inorganic element requirements of lactating dairy cows^a.

Inorganic element		Maintenance ^b		Present per kg milk ^d	Per kg milk	Maintenance +30 kg milk/day		Harmful or toxic
		Daily	Diet ^c			Daily	Diet	
		(g)	(%)	(g)	(g)	(g)	(%)	(%)
Calcium	(Ca)	14.0	.20	1.2	2.8	98.0	.45	
Phosphorus	(P)	14.0	.20	1.0	2.0	74.0	.34	
Sodium chloride	(Na Cl) ^e	25.0	.36		1.5	70.0	.32	
Sodium	(Na)	10.0	.14	0.5	.6	28.0	.13	
Chlorine	(Cl)			1.1				
Potassium	(K)			1.5	Not known ¹			
Magnesium	(Mg)	5.0-25.0	.07-.36	.1				
Iodine	(I)	.001-.02	.00002-.0002	.0000007-.00005		.000025-.0002 ^f	.0076	
Cobalt	(Co)	.0005 ^g	.000007	.0000002-.000001				.001
Iron	(Fe)	.14 ^h	.002	.00015-.0007				
Copper	(Cu)	.05	.0007	.00005-.00045				.003
Molybdenum	(Mo)	.0005	.000007	.00005-.00015				.0005
Manganese	(Mn)	.20	.003	.000037-.00037				
Zinc	(Zn)	.35	.005	.00022-.005				
Sulfur	(S)	8.4	.12	0.5				
Selenium	(Se)	.0007	.00001					.001
Fluorine	(F)	.0007	.00001 [?]	.0002				.0035-.01

^a Insofar as possible, based upon NRC Pub. 1349.

^b 500 Kg body wt.

^c Diets assumed to be air dry containing 90% dry matter, 50% of estimated net energy from concentrate and 50% from roughage for lactating cow, and consisting of 7.0 kg feed for maintenance and an additional 15.0 kg feed for 30 kg milk production per cow per day.

^d Range or value given in Metabolism, FASEB, 1968.

^e Chlorine requirement is approximately half that of sodium.

^f Level of .0076% of salt is effective when stabilized form is added to salt. For goitrogenic feed-stuffs, feed high level.

^g Added to deficient diet will relieve symptoms.

^h Required in chick diet. Usually 30 to 50 mg/.45 kg or .009% iron in the naturally occurring ruminant diet. .0001% = 1 ppm = .000001 = 1 mg in 1 kg.

¹ And for remaining elements in this column.

may also involve these elements. Therefore, feeding desirable amounts of mineral elements may reduce their severity and incidence.

The availability of mineral elements was not included in this paper but is recognized as an important part of the total question. Where biological availability is low, the dietary quantity of any given mineral source should be adjusted accordingly.

Application

The authors' efforts to list mineral requirements and desirable contents are in Tables 1 and 2. The information in the first table and in Figure 1 has been developed over the last several years as the literature was reviewed. Even so quantitative values set down in such a table are somewhat arbitrary. Since the values in Table 1 are intended to represent requirements under experimental conditions, they are not necessarily the same as values recommended for routine use. Therefore, Table 2 was included. The values in this table are even more arbitrary than those of Table 1 but should be much more useful on a practical

TABLE 2. Practical mineral content of diets for lactating cows^a.

Mineral	Content on air dry basis	
	(%)	(ppm)
Ca	.45	4,500
P	.34	3,400
Na Cl	.45	4,500
K	.60	6,000
Mg	.12-.36 ^b	1,200-3,600 ^b
S	.20	2,000
Co	.0001	1
Fe	.01	100
Cu	.0010	10
Mn	.003	30
Zn	.010	100
I	.00003-.0002 ^c	.3-2.0 ^c

^a Some allowance made for availability.

^b Use up to the high level in grass tetany situations.

^c Use high level when feeding goitrogenic feed-stuffs such as soybean meal.

basis. Inorganic element requirements (even where known) are subject to adjustment in diet formulation for: a) milk production; b) relative state of depletion of the animals; c)

TABLE 3. Guide for including the indicated amounts of calcium and phosphorus in a mixture containing primarily corn and soybean meal^a.

Ration	Roughage fed		Concen- trate fed	Amount of mineral ^b to be included in the concentrate to provide adequate phosphorus and a 1.5 to 1.0 Ca:P ra- tio in total diet (90% DM)		
	Kind	Amount		Feed grade		
				limestone	Dicalcium phosphate	Monosodium phosphate
		(kg)	(kg)	(%)	(%)	(%)
1	Excellent alfalfa hay ^c	13.6	8.6	0	0	.7
2	Good alfalfa hay ^d	11.4	10.9	0	0	.6
3	Avg alfalfa hay ^e	9.1	12.3	0	0	.45
4	Poor alfalfa hay	6.8	14.1	0	0	.3
5	Alfalfagrass hay	11.4	10.9	0	.1	.65
6	Good alfalfa hay ^f and corn silage	9.1 15.0	8.6	0	0	.85
7	Avg alfalfa hay and corn silage	4.5 25.9	8.6	0	.25	.6
8	Good orchardgrass hay	9.1	12.3	.85	.8	0
9	Good orchardgrass hay and corn silage	6.8 20.9	8.6	1.2	1.2	0
10	Avg grass hay and corn silage	4.5 26.4	8.6	1.25	1.15	0
11	Corn silage only	35.0	8.6	1.9	1.1	0
12	Corn silage only	29.1	10.9	1.0	.7	0

^a Assuming 20% soybean meal and 75% corn in concentrate mixture, 30 kg milk.

^b Computations based upon feed grade ground limestone (38% Ca, 0% P), dicalcium phosphate (26% Ca, 18% P), and monosodium phosphate (0% Ca, 25% P).

^c Ca:P ratio of total diet would be 4.1 to 1.0 (higher than desired).

^d Ca:P ratio of total diet would be 2.8 to 1.0 (higher than desired).

^e Ca:P ratio of total diet would be 2.1 to 1.0 (still somewhat higher than desired).

^f Ca:P ratio of total diet would be 2.4 to 1.0 (higher than desired).

interference from other elements as shown in Figure 1; d) biological availability of element from source which ranges from zero to 100% for some mineral elements and sources; and e) hormonal and nonmineral dietary influence such as fatty acids and Ca forming soap rendering Ca less available.

Table 3 gives practical suggestions for Ca and P sources and amounts to include in the grain mix for feeding dairy cows with different amounts of roughages and grain. These same computations can and should be made for the other mineral elements as well.

Summary

Though much is known about the inorganic element requirements of lactating dairy cows and how to formulate diets to include the appropriate amount of each, there remains much that is unknown. Today's guidelines are subject to change as research reveals new information. Excessive rather than too little dietary Ca during the dry period prior to calving is likely contributing to the milk fever problem. Basically, blood P must be maintained by absorption from the gut as there is no known specific mechanism for bone P resorption. Therefore, it is important always to include adequate P in the diet. Magnesium may be causing problems that are not well understood, or widely appreciated. Supplemental K is probably indicated on many high concentrate feeding programs.

Not just these minerals but all mineral elements should be considered in ration formulation for high performance and a reduction in mineral nutrition anomalies.

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References

- (1) Alcock, N., and I. McIntyre. 1962. Interrelation of calcium and magnesium absorption. *Clin. Sci.*, 22:185.
- (2) Alderman, G. 1963. Mineral nutrition and reproduction in cattle. *Vet. Record*, 75:1015.
- (3) Anderson, J. J. B. 1970. *Parturient Hypocalcemia*. Academic Press, New York City.
- (4) Bhattacharyya, N. K., and D. N. Mullick. 1963. Effect of magnesium sulphate injection in experimental hypercholesteremia in rabbits. I. On the serum and tissue cholesterol. *Ann. Biochem. Exp. Med.*, 23:515.
- (5) Blaxter, K. L., J. A. F. Rook, and A. M. MacDonald. 1954. Experimental magnesium deficiency in calves. I. Clinical and pathological observations. *J. Comp. Pathol. Therap.*, 64:157.
- (6) Boda, J. M., and H. H. Cole. 1954. The influence of dietary calcium and phosphorus on the incidence of milk fever in dairy cattle. *J. Dairy Sci.*, 37:360.
- (7) Bunce, G. E., K. J. Jenkins, and P. H. Phillips. 1962. The mineral requirements of the dog. *J. Nutrition*, 76:17.
- (8) Campbell, L. D., and W. K. Roberts. 1965. The requirements and role of potassium in ovine nutrition. *Canadian J. Animal Sci.*, 45:147.
- (9) Capen, C. C., C. R. Cole, and J. W. Hibbs. 1968. Influence of vitamin D on calcium metabolism and the parathyroid glands of cattle. *Federation Proc.*, 27:142.
- (10) Care, A. D. 1968. Significance of the thyroid hormone in calcium homeostasis. *Federation Proc.*, 27:153.
- (11) Care, A. D., R. F. L. Bates, and H. J. Gitelman. 1970. A possible role for the adenylyl cyclase system in calcitonin release. *J. Endocrinol.*, 48:1.
- (12) Chandler, P. T., and R. E. Cragle. 1962. Responses of Holstein calves to dietary calcium, phosphorus, vitamin D₃. *J. Dairy Sci.*, 45:680.
- (13) Coates, M. E., and E. S. Holdsworth. 1961. Vitamin D₃ and absorption of calcium in the chick. *British J. Nutrition*, 15:131.
- (14) Converse, H. T. 1954. Calcium requirements of dairy cattle. *U.S. Dep. Agr. Tech. Bull.*, 1092.
- (15) Copp, D. H. 1970. Endocrine regulation of calcium metabolism. *Ann. Rev. Physiol.*, 32:61.
- (16) Copp, D. H., E. C. Cameron, B. A. Cheney, A. G. F. Davidson, and K. G. Henzie. 1962. Evidence for calcitonin — a new hormone from the parathyroid that lowers blood calcium. *Endocrinology*, 70:638.
- (17) Devlin, T. J. 1967. Effect of ration potassium level on fattening steers. *Abstr. J. Animal Sci.*, 26:1488.
- (18) Devlin, T. J., W. K. Roberts, and V. V. E. St. Omer. 1969. Effects of dietary potassium upon growth, serum electrolytes and intramurine environment of finishing beef steers. *J. Animal Sci.*, 28:557.
- (19) Duckworth, John. 1938-9. Magnesium in animal nutrition. *Nutrition Abstr. Rev.*, 8:841.
- (20) Duncan, C. W., C. F. Huffman, and C. S. Robinson. 1935. Magnesium studies in calves. I. Tetany provided by a ration of milk, or milk with various supplements. *J. Biol. Chem.*, 108:35.
- (21) Duncan, Dorothy L. 1958. The interpretation of studies of calcium and phosphorus balance in ruminants. *Nutrition Abstr. Rev.*, 28:3.
- (22) DuToit, P. J., A. I. Malan, and J. W. Groenewald. 1934. Studies in mineral metabolism

- XXXI. Minimum mineral requirements of cattle. Onderstepoort J. Vet. Sci., 2:565.
- (23) Ewer, T. K. 1951. Rickets in sheep. 2. Measurement of phosphorus absorption. British J. Nutrition, 5:300.
- (24) Forbes, R. M. 1966. Effects of magnesium, potassium and sodium nutriture on mineral composition of selected tissues of the albino rat. J. Nutrition, 88:403.
- (25) Garces, M. A., and J. L. Evans. 1971. Calcium and magnesium absorption in growing cattle as influenced by age of animal and source of dietary nitrogen. J. Animal Sci., 32:789.
- (26) Caster, D., E. Havivi, and K. Guggenheim. 1967. Interrelations of calcium, fluorine, and vitamin D in bone metabolism. British J. Nutrition, 21:413.
- (27) Grotebeck, S. H. 1971. Parturient hypocalcemia in dairy cattle. Frontiers in Nutrition Supplement, No. 238:921. Dawe's Lab., Inc., Chicago.
- (28) Hansard, S. L., C. L. Comar, and G. K. Davis. 1954. Effects of age upon the physiological behavior of calcium in cattle. Amer. J. Physiol., 177:383.
- (29) Hansard, S. L., C. L. Comar, and M. P. Plumlee. 1954. The effect of age upon calcium utilization and maintenance requirements in the bovine. J. Animal Sci., 13:25.
- (30) Hansard, S. L., and H. M. Crowder. 1957. The physiological behavior of calcium in the rat. J. Nutrition, 62:325.
- (31) Hemken, R. W., and K. Pradhan. 1968. The potassium requirement of the ruminant. Proc. Maryland Nutrition Conf., 53.
- (32) Hendricks, D. G., E. R. Miller, D. E. Ullrey, J. A. Hoefler, and R. W. Luecke. 1969. Effect of level of soybean protein and ergocalciferol on mineral utilization by the baby pig. J. Animal Sci., 28:342.
- (33) Henry, K. M., S. K. Kon, P. E. Todd, J. Toothill, and D. H. Tomlin. 1960. Calcium and phosphorus metabolism in the rat. Effect of age on rate of adaptation to a low calcium intake. Acta. Biochem. Pol., 7:154.
- (34) Hibbs, J. W., W. E. Krauss, W. D. Pouden, C. F. Monroe, and T. S. Sutton. 1946. Studies on milk fever in dairy cows. II. The effect of vitamin D on some of the blood changes in normal and milk fever cows at parturition. J. Dairy Sci., 29:767.
- (35) Hibbs, J. W., W. D. Pouden, and W. E. Krauss. 1947. Further studies on the effect of vitamin D and of parathyroid extract, "paroidin", on the blood changes of normal and milk fever cows at parturition. J. Dairy Sci., 30:564.
- (36) Hignett, S. L. 1959. Some nutritional and other inter-acting factors which may influence the fertility of cattle. Vet. Record, 71:247.
- (37) Horvath, D. J. 1967. Tetany prevention with supplemental magnesium. Feedstuffs, 39:52.
- (38) Jacobson, D. R. 1969. Where do we stand on mineral research? Dep. Animal Sci., Paper D-35.
- (39) Kemp, A. 1966. Mineral balance in dairy cows fed on grass, with special reference to magnesium and sodium. Proc. X. Int. Grassl. Congr. p. 411.
- (40) Kemp, A., and J. H. Geurink. 1967. Prevention of hypomagnesaemia in milking cows. Agr. Digest 12, p. 23.
- (41) Kemp, A., and J. R. Todd. 1970. Prevention of hypomagnesaemia in cows: The use of magnesium alloy bullets. Vet. Rec. 86:463.
- (42) Kendall, K. A., R. L. Hays, and E. E. Ormiston. 1968. Postpartum serum calcium and phosphorus levels associated with calcium carbonate and monosodium phosphate feeding. J. Dairy Sci., 51:978.
- (43) Kerman, R. P. 1965. Cell K. Butterworths, Washington, D. C.
- (44) Knieriem, H. J., V. C. Y. Kao, and R. W. Wissler. 1968. Demonstration of smooth muscle cells in bovine arteriosclerosis. J. Atheroscler. Res., 8:125.
- (45) Kodicek, E. 1967. The absorption of calcium from the intestine. Proc. Nutrition Soc., 26:67.
- (46) Lane, A. G., J. R. Campbell, and G. F. Krause. 1968. Blood mineral composition in ruminants. J. Animal Sci., 267:766.
- (47) Lazzara, R., K. Hyatt, W. D. Love, J. Cronvich, and G. E. Burch. 1963. Tissue distribution, kinetics, and biologic half-life of Mg^{25} in the dog. Amer. J. Physiol., 204:1086.
- (48) Likar, I. N., and R. W. Robinson. 1966. Bovine arterial disease. I. Localization of lipids in the abdominal aorta in relation to bovine atherosclerosis. Arch. Pathol., 82:555.
- (49) Littlejohn, A. I., and G. Lewis. 1960. Experimental studies of the relationship between the calcium-phosphorus ratio of the diet and fertility in heifers: A preliminary report. Vet. Record, 72:1137.
- (50) Lomba, F., R. Paquay, V. Bienfet, and A. Lousse. 1968. Statistical research on the fate of dietary mineral elements in dry and lactating cows. II. Magnesium. J. Agr. Sci., 71:181.
- (51) McAleese, D. M., and R. M. Forbes. 1961. The requirement and tissue distribution of magnesium in the rat as influenced by environmental temperature and dietary calcium. J. Nutrition, 73:94.
- (52) McKinstry, D. M., Bernard Sass, James L. Cason, and Thomas F. Albert. 1969. Arteriosclerosis in forestomach-bypass calves. J. Dairy Sci., 52:273.
- (53) Martindale, L., and F. W. Heaton. 1964.

- Magnesium deficiency in the adult rat. *The Biochem. J.*, 92:119.
- (54) Mayer, G. P. 1968. Role of the parathyroid glands in cows. *Federation, Proc.*, 27:139.
- (55) Nakamura, M., J. J. Vitale, D. M. Hegsted, and E. E. Hellerstein. 1960. The effect of dietary magnesium and thyroxine on progression and regression of cardiovascular lipid deposition in the rat. *J. Nutrition*, 71:347.
- (56) Nakamura, M., S. Torii, M. Hitamatsu, J. Hirano, A. Sumiyoshi, and K. Tanaka. 1965. Dietary effect of magnesium on cholesterol-induced atherosclerosis of rabbits. *J. Ather. Res.*, 5:145.
- (57) National Research Council, U.S. 1966. Nutrient requirements of dairy cattle. Pub. 1349. Washington, D. C.
- (58) O'Dell, B. L., E. R. Marres, and W. O. Regan. 1960. Magnesium requirements of guinea pigs and rats. Effect of calcium and phosphorus and symptoms of magnesium deficiency. *J. Nutrition*, 70:103.
- (59) O'Dell, B. L. 1960. Magnesium requirement and its relation to other dietary constituents. *Federation, Proc.*, 19:648.
- (60) Packett, L. V., and J. Hauschild. 1963. Relationship of magnesium, calcium, and phosphorus to incidence of urinary calculi in lambs. *J. Animal Sci.*, 22:843.
- (61) Paquay, R., F. Lomba, A. Lousse, and V. Bienfet. 1968. Statistical research on the fate of dietary mineral elements in dry and lactating cows. I. Calcium. *J. Agr. Sci.*, 71:173.
- (62) Payne, J. M., B. F. Sansom, and R. Mans-ton. 1963. Acute experimental hypocalcemia. A.R.C. Field Station, Compton Newbury, Berks., *England Vet. Record*, 75:588.
- (63) Payne, J. M., and F. B. Leech. 1964. Factors affecting plasma calcium and inorganic phosphorus concentrations in the cow with particular reference to pregnancy, lactation and age. *British Vet. J.*, 120:385.
- (64) Pradhan, K., and R. W. Hemken. 1968. Potassium depletion in lactating dairy cows. *J. Dairy Sci.*, 51:1377.
- (65) Rasmussen, H. 1961. Parathyroid hormone: nature and mechanism of action. *Amer. J. Med.*, 30:112.
- (66) Ricketts, R. E., J. R. Campbell, D. E. Weinman, and M. E. Tumbleson. 1970. Effect of three calcium:phosphorus ratios on the performance of growing Holstein steers. *J. Dairy Sci.*, 53:898.
- (67) Roberts, W. K., and A. Driedger. 1966. Effect of various dietary cations (K, Na, Ca) upon growth of lambs. *J. Animal Sci.*, 25:908.
- (68) Roberts, W. K., and V. V. E. St. Omer. 1965. Dietary potassium requirement of fattening steers. *J. Animal Sci.*, 24:902.
- (69) Rook, J. A. F., and J. E. Storry. 1962. Magnesium in the nutrition of farm animals. *Nutrition Abstr. Rev.*, 32:1055.
- (70) Rook, J. A. F. 1963. Experimental magnesium deficiency. *J. Comp. Path. Therap.*, 73:93.
- (71) Sasser, L. B., G. M. Ward, and J. E. Johnson. 1966. Variations in potassium concentration of cow's milk. *J. Dairy Sci.*, 49:893.
- (72) Schmidt, Carl L. A., and David M. Greenberg. 1935. Occurrence, transport and regulation of calcium, magnesium and phosphorus in the animal organism. *Physiol. Rev.*, 15:297.
- (73) Schutte, K. H. 1964. *The Biology of Trace Elements*. 1st ed. p. 41. J. B. Lippincott Co., Philadelphia.
- (74) Scott, D. 1970. Aspects of renal function in ruminants. *Rowett Res. Inst. Ann. Rep.*, 26:98.
- (75) Seelig, M. S. 1964. The requirement of magnesium by the normal adult. Summary and analysis of published data. *Amer. J. Clin. Nutrition*, 14:242.
- (76) Skold, B. H., N. L. Jacobson, and R. Getty. 1967. Spontaneous atherosclerosis of bovine. *J. Dairy Sci.*, 50:1712.
- (77) Smith, A. M., G. L. Holck, and H. B. Spafford. 1966. Re-evaluation of nutrient allowances for high-producing cows. I. Calcium, phosphorus and vitamin D. *J. Dairy Sci.*, 49:239.
- (78) Smith, S. E., and J. St. Laurent. 1970. Calcium metabolism in sheep: Requirements and adaptation to low intakes. *Proc. Cornell Nutrition Conf.*, p. 77.
- (79) Spafford, H. B. 1964. The influence of varied levels and ratios of calcium and phosphorus in the rations of mature dairy cows. M.S. Thesis. University of Vermont, Burlington.
- (80) Steevens, B. J., L. J. Bush, and J. D. Stout. 1971. Effects of varying amounts of calcium and phosphorus in rations for dairy cows. *J. Dairy Sci.*, 54:655.
- (81) Stott, G. H. 1965. Parturient paresis related to dietary phosphorus. *J. Dairy Sci.*, 48:1485.
- (82) Stott, G. H. 1968. Dietary influence on the incidence of parturient paresis. *Federation Proc.*, 27:156.
- (83) Sykes, J. F., and Alfredson. 1940. Studies on the bovine electrocardiogram. I. Electrocardiographic changes in calves on low potassium rations. *Proc. Soc. Exp. Biol. Med.*, 43:575.
- (84) Telle, P. P., R. L. Preston, L. D. Kintner, and W. H. Pfander. 1964. Definition of ovine potassium requirement. *J. Animal Sci.*, 23:59.
- (85) Toothill, J. 1963. The effect of certain dietary factors on the apparent absorption of magnesium by the rat. *British J. Nutrition*, 17:125.
- (86) Ullrey, D. E., E. R. Miller, B. E. Brent, B. L. Bradley, and J. A. Hoefer. 1967. Swine hematology from birth to maturity.

- IV. Serum calcium magnesium, sodium potassium, copper, zinc and inorganic phosphorus. *J. Animal Sci.*, 26:1024.
- (87) Vitale, J. J., H. Veley, C. Guyman, and P. Correa. 1963. Magnesium deficiency in the Cibus monkey. *Circulation Res.*, 12:642.
- (88) Vitale, J. J., P. L. White, M. Nakamura, D. M. Hegsted, N. Zancheck, and E. E. Hellerstein. 1957. Interrelationships between experimental hypercholesteremia, magnesium requirement, and experimental atherosclerosis. *J. Exp. Med.*, 106:757.
- (89) Vitale, J. J., E. E. Hellerstein, D. M. Hegsted, M. Nakamura, and A. Farbman. 1959. Studies on the interrelationships between dietary magnesium and calcium in atherogenesis and renal lesions. *Amer. J. Clin. Nutrition*, 7:13.
- (90) Voisin, A. 1963. Thyroid, lactation, temperature and magnesium requirements. *Grass Tetany*, Chapt. 22:115.
- (91) Ward, G. M. 1966. Potassium metabolism of domestic ruminants. *J. Dairy Sci.*, 49:268.
- (92) Welt, L. G., W. Hollander, and W. B. Myth. 1960. The consequences of potassium depletion. *J. Chronic Diseases*, 11:213.
- (93) Wise, M. B., S. E. Smith, and L. L. Barnes. 1958. The phosphorus requirement of calves. *J. Animal Sci.*, 17:89.
- (94) Wise, M. B., A. L. Ordoveza, and E. R. Barrick. 1963. Influence of variations in dietary calcium: phosphorus ratio on performance and blood constituents of calves. *J. Nutrition*, 79:79.
- (95) Woelffer, E. A. 1964. Crampy cows and bulls. *Hoard's Dairyman*, 109:272.
- (96) Woerpel, H. R., and S. L. Balloun. 1964. Effect of iron and magnesium on manganese metabolism. *Poultry Sci.*, 43:1134.
- (97) Annual report of studies in animal nutrition and allied sciences. 1970. Vol. 26. Rowett Res. Inst., Scotland.