The Mineral Elements in Animal Nutrition.¹

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SINCE the time of Lavoisier, research in nutrition has been directed chiefly to the chemistry and metabolism of organic compounds, *i.e.* proteins, fats, carbohydrates and allied substances, and in tables of rations the food requirements of animals have been expressed in terms of these or their equivalents. During the past half-century, however, an increasing number of workers have become interested in the rôle played by inorganic salts in nutrition. The information being yielded by the researches of these workers is throwing new light on many fundamental problems of biology, and some of it appears to be of potential economic value in animal husbandry.

From 10 to 25 per cent. of living matter consists of organic compounds of which the colloidal material of the protoplasm is formed. The remaining 75 to 90 per cent. consists of water and inorganic salts. In the recent literature of animal husbandry, the elements of these salts have been somewhat loosely termed "the mineral elements," to distinguish them from the carbon, hydrogen, oxygen and nitrogen of the organic compounds. In living matter these mineral elements are present, partly in chemical combination with, and forming an integral part of, organic compounds, and partly free or potentially free, either in solution as salts or ions in the water of the protoplasm, or in a temporary loose union with the colloids.

The fundamental nature of the functions of the so-called mineral or inorganic salts in life processes is at once apparent when we consider the part played by them in the origin of the cycle of energy exchanges which occur in the "organic world." All forms of life depend ultimately upon the transformation of the energy of sunlight into chemical energy. The power of carrying out this fundamental process, which can be regarded as the real origin of life, is possessed by inorganic salts in colloidal solution. Photosynthesis with the production of formaldehyde, which contains the trapped energy of the sunlight, arises from the action of sunlight and inorganic salts on water and carbon dioxide. According to Moore, chlorophyll itself is a product of photosynthesis, and its chief function is probably not the primary one of deoxidising the carbon dioxide and thus charging the carbon with energy, but of changing the formaldehyde into higher carbon compounds. Hence the beginning of life-processes lies in the action of radiant energy on inorganic salts. The carbon atom is harnessed as the most suitable vehicle for conveying the chemical energy formed. The giant molecules and colloidal aggregates with their complex carbon-containing compounds, which have been regarded as the fundamental organic substances, are really secondary developments to secure that degree of stability and complexity required for the evolution of higher forms of life. Thus the true basis of protoplasm is the saline solution which forms from 75 to 90 per cent. of its bulk and still resembles the sea water from which it originated.

It is impossible here to do more than refer briefly to the nature of the functions of the inorganic salts

and ions. As has been already indicated, these functions are intimately connected with colloidal activities. The visible phenomena of life are the resultants of an enormous number of chemical and physical changes in the colloids of protoplasm and of exchanges between masses of protoplasm separated by membranes or interfaces. But these changes in the physical state of colloids are determined by the association and dissociation of colloids and inorganic ions. These ions also affect the permeability of membranes and the tensions at interfaces. Hence, in a real sense, protoplasmic activity is regulated by the action of the mineral elements in solution in the protoplasm or attached to its colloids. Thus, in the contraction of muscle, though the ultimate source of energy is the oxidation of organic compounds, the initiation of the process, the mechanism by which it is carried through and the factors by which it is controlled, depend on the action of the ions and salts present, which involve changes in osmotic pressure and other physical forces.

The foregoing considerations suggest that definite degrees of concentration of the various inorganic ions in the cell fluids are necessary for the maintenance of normal protoplasmic activity. This has been fully demonstrated by work done to determine the effect of changes in the normal concentration of the different ions. The results of experiments with unicellular organisms and with isolated organs such as the perfused heart have shown that slight alterations either in the absolute or relative concentrations of any of the inorganic ions may accelerate, retard, or even reverse processes being carried out by means of the colloidal mechanism.

In the animal body these changes in the concentration of the inorganic ions can be correlated with changes in the functions of the organs. Thus, all the organs regulated by the central nervous system depend for the integrity of their functions upon the maintenance of definite ratios of calcium, potassium, and sodium in the fluids within the nerve tissues. Changes in the relative proportions of these are accompanied by alteration in the excitability of nerve and in the irritability of muscle. The classical experiments of Ringer on the perfused heart show that minute changes in the concentrations of calcium or potassium in the perfusing fluids have a profound effect on the activity of the heart. These examples are merely illustrations of the general law that any disturbance of the normal physiological balance of the salt solution of the body is accompanied by a correlated impairment of function.

The body is remarkably efficient in maintaining this balance, in spite of the fact that there is a continuous loss in the excreta, and the mineral matter of the food is liable to be very different in composition from that found in the blood. Within limits, the elements present in excess tend to be excreted and those deficient to be conserved. The bones act as a reservoir, especially for calcium and phosphorus, the two required in largest amounts. Reserves can be deposited in the bones when the supply is ample, and mobilised in

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times of need. It is probable that this function of the bones, namely, regulating the supply of mineral elements to the body fluids, is as important as the more obvious one of providing a rigid framework. It is probably more fundamental, for, when the available mineral matter is insufficient to maintain both the physiological balance in the blood and the rigidity of the skeleton, it is rigidity which is sacrificed. There is little doubt that in most diseases affecting the bones the skeletal symptoms are only secondary manifestations of the influence of some factor, often a dietary one, which upsets the balance of mineral elements in the blood.

Under experimental conditions it is possible by feeding diets with marked deficiencies or excesses of some of the mineral elements to produce conditions of malnutrition which are so definite and marked that they are as easily recognised as definite diseases; indeed similar conditions occurring in practice are regarded as definite diseases. Thus, primary anæmia, simple goitre and rickets are produced by deficiency of iron, iodine and either calcium or phosphorus respectively. An interesting case of a disease due to an excess of a mineral element is reported by McCollum, who regards an inflammatory condition of the eyes, resembling xerophthalmia, which he calls "salt ophthalmia," as due to excess of chlorine in the food.

In addition to these diseases due to excesses or deficiencies of mineral elements in the diet, in which the symptoms form a definite and easily recognised picture, and the cause is admitted, there are conditions of malnutrition due to the lack of balance of the mineral elements in the diet, where the signs are much less obvious. In young animals there may be retarded growth without any definite pathological symptoms. The only reason for supposing that such animals are not in a perfect state of health is that their rate of growth is not optimal, as is shown by the fact that improvement follows the adjustment of the mineral balance in the food. Thus, Kellner obtained an increased rate of growth in calves by the addition of a calcium salt to a diet on which the animals grew at an average rate and showed no signs of obvious ill-health. In some work, not yet reported, we have found that the addition of traces of iodine to the diet of stall-fed calves in winter increased the rate of growth as compared with that of control animals whose condition would be regarded as normal. Further, it has been shown recently that the supply of minerals in the food of the mother may have a profound influence on the vitality of the young at birth and for some time after, even where there may be no obvious effect on the mother. Thus Hart, Steenbock and Humphrey have noted that deficiency of calcium in the diet of cows may lead to the birth of dead or weakly calves, and Ennis Smith has shown that deficiency of iodine in the food of pigs may lead to the birth of dead young, although there is not, in either case, any obvious pathological condition apparent in the mothers.

Some attention has recently been devoted to the question of an increased susceptibility to certain infectious diseases in cases of malnutrition due to deficiencies of minerals. We have noted in feeding experiments that the mortality from intercurrent infec-

tions is much higher in the groups fed on diets which, for experimental reasons, are ill-balanced or deficient in mineral matter. Meigs has noted a similar increased incidence of diseases in cows on diets deficient in calcium.

It may be of interest to consider some reasons which can be adduced for believing that the danger of deficiencies of minerals in the food of farm animals has been increasing in recent years. During the past half-century, the types of animals after which breeders have been striving are those whose young have a very rapid rate of growth, or whose females have a great capacity for producing the constructive materials required for growth. A remarkable degree of success has attended these efforts of the breeders. Some breeds of pigs will increase in weight from 2 lb. to 2 cwt. in six months. There are dairy cows which can secrete in their milk as much as 10-12 lb. of solid matter per day. There are hens that lay 200 to 300 eggs in a year. Now, the faster the rate of growth, the greater must be both the absolute amount of mineral matter required in a given time and the proportion of mineral matter per unit of energy in the food. The following table shows that the percentage of mineral matter in the milk of different species, and also the amounts relative to the energy values, are in proportion to the rates of growth.

TABLE I.

	Number of Days in which Weight of New-born Animal is doubled.	Milk of Species contains	
		Ash per cent.	Ash per 1000 Calories.
	Days.		Grams.
Man . .	180	0.25	3.7
Cow . .	47	0.72	10.5
Pig . .	14	1.03	10.9
Rabbit .	6	2.50	15

Hence, in modern types of animals the mineral requirements have increased *pari passu* with increased capacity for growth, and the danger of malnutrition through an absolute deficiency of any of the mineral elements, or a lack of balance of these constituents of the food, is correspondingly increased. As a matter of fact, it is found that malnutrition due to disordered mineral metabolism occurs most readily in those animals that are growing fastest. In experiments with both dogs and pigs it has been found that symptoms of rickets tend to appear earliest in those that are growing most rapidly.

Concurrently with the evolution of these faster growing types, with their greater need for each of the essential mineral elements in their food, and for a more perfect balance of these elements, there has been an increasing use of concentrates to support rapid growth. These concentrates, which consist chiefly of commercial by-products of cereal grains and tropical seeds and nuts, are markedly deficient in some of those mineral elements which are required for growth, or for the production of growth material. The following table compares the mineral matter of some of these artificial feeding stuffs with that of milk and good mixed pasture, the only two foodstuffs of which the

mineral content corresponds approximately with the requirements of herbivora.

TABLE II.

	1000 Caloric Portions contain					
	Protein.	Calcium.	Phosphorus.	Sodium.	Potassium.	Chlorine.
Cultivated pasture .	Gm. 65.3	Gm. 2.65	Gm. 1.18	Gm. 0.69	Gm. 9.58	Gm. 3.52
Cow's milk . . .	51.6	1.73	1.52	0.58	2.66	1.39
Potatoes . . .	21.4	0.19	0.65	0.29	4.61	0.32
Maize . . .	28.6	0.02	0.76	0.08	1.13	0.0003
Wheat . . .	35.0	0.13	1.18	0.11	1.32	0.15

It is seen from the table that foodstuffs such as tubers and cereals are deficient especially in calcium, chlorine and sodium. Most concentrates resemble cereals in their mineral composition.

A third factor with an adverse effect on mineral metabolism is the increasing tendency to feed large numbers of animals together. This necessitates for practical purposes the adoption of fixed standard rations, which may be fed with little or no change for months on end, or even through the whole life-cycle of the animal. Unless such rations are almost perfectly constituted with regard to their mineral content, there must be a cumulative effect of any deficiency or lack of balance which would not occur in the case of either single animals or small groups, fed in a more haphazard fashion. As a matter of fact, in practice, the cottager's pig, with a varying diet consisting largely of scraps, differing in kind from day to day, seems less liable to disease and more successful in bearing and rearing large litters than pigs fed in large numbers under what might almost be termed factory conditions.

The reasons adduced above seem valid enough to justify the fear that, under modern conditions of intensive production in animal husbandry, there is a danger of malnutrition and disease arising on account of defects in the inorganic portion of the ration. Acting on this belief, attempts have recently been made to increase the rate of growth and improve the condition of animals by the addition of various mineral salts thought to be present in their rations in insufficient amounts. In many cases marked beneficial effects have been noted. Thus in pig-feeding, the cereal grains and most other foodstuffs commonly used in making up rations are deficient in calcium, sodium, chlorine and, in some cases, iron and iodine, and it has been found that growth, health and reproductive capacity all tend to be improved by the addition to the food of salt mixtures or foodstuffs such as fish meal or meat meal which are rich in these elements.

In poultry it has been found, in experiments carried out at Ohio and at stations in Scotland and Northern Ireland, that even though the birds have access to green food and lime or oyster-shell, egg-production can be increased by the addition to the cereal rations usually fed to poultry of a mixture of those salts which are present in the ration in smaller proportions than in egg.

Of all farm animals, the stall-fed heavy-milking cow

is the one most likely to suffer from depletion of minerals from the tissues and consequent malnutrition, on account of the fact that it loses from its body such relatively large quantities of mineral matter in the milk. In short tests, running for a few days or weeks, the adjustment of the mineral matter of the ration is not usually followed by increased milk production, because the cow will continue to give milk even though the body is being depleted of minerals. But the influence of adjusting the ration is seen towards the end of a long lactation or in a subsequent lactation. In recent tests at Beltsville and Ohio and at Aberdeen, which have been carried over one or more complete lactation periods, it has been found that the adjustment of the ration by the addition of salts present in too small amounts has resulted in a rather greater yield of milk and in an increase in breeding capacity and decrease in disease.

Some interesting cases of deficiencies of one or more minerals in natural pastures have been discovered. In an investigation being carried on partly at the Rowett Institute and partly at the Nutrition Institute at Cambridge, it has been found that there are marked differences in the mineral content of uncultivated pastures grown in different localities, and that there appears to be a correlation between the mineral content of the pasture and its feeding value, as determined by the number of stock it can carry, and the health and breeding capacity of the stock. An interesting fact brought out is that, where the sheep have a choice of pastures, they actually eat the herbage the mineral composition of which most closely approximates to that of good cultivated pasture. As we saw above, good pasture contains the various elements in proportions somewhat similar to those which are found in milk, and might therefore be presumed to be suitable for growth and the maintenance of health, as indeed is found to be the case in practice.

In various countries where the modern type of rapidly growing animal has been put to graze on uncultivated pastures, malnutrition, as shown by stunted growth, low milk yield, or increased liability to disease, has appeared. Thus, in South Africa, Sir Arnold Theiler and his associates have shown that deficiency of phosphorus in the pastures is the cause of pica (depraved appetite), which is prevalent in cattle in certain districts there and leads to the ingestion of the organism which causes lamziekte, and that the condition can be prevented by feeding bone-meal, or any foodstuff rich in phosphorus. Not only does this adjustment of the mineral intake prevent the disease, but the general condition of the animals is also improved.

The two elements most frequently deficient in pasture are probably calcium and phosphorus. Malnutrition due to deficiency of these has been noted in various districts in Australia, New Zealand and India, and in the Falkland Islands. Other minerals may, however, also be deficient. Thus, in the North Island, New Zealand, Aston has found that deficiency of iron is the cause of malnutrition in animals which are grazed continuously on certain areas. The condition is avoided if the animals are transferred for a time to an area where the pasture is richer in iron. The symptoms of the disease can be relieved by feeding iron salts. It is probable that a similar condition

occurs in parts of the Cheviots where soil conditions are similar and the sheep show symptoms which resemble those described by Aston.

These examples of malnutrition in stock, associated with deficiency of one or more mineral elements in the food, are sufficient to show that the dietary conditions which produce such forms of malnutrition are fairly widespread. They also show that there is a possibility of remedying the defects if the nature of the deficiencies be known.

In order to be able to make the necessary adjustments, it is necessary to know the amounts of each of the minerals which should be present in the ration to meet the requirements of the animal. But this depends on the extent to which they are absorbed from the alimentary canal. There might be an abundance in the food, but owing to factors which affect absorption adversely, only a small proportion of what is present in the food may pass through the wall of the intestine into the metabolic field. For example, in the case of calcium, which is probably the element which involves most difficulty in this respect, the amount absorbed, as calculated from the intake in the food minus the output in the faeces, may vary from nil to over 80 per cent. of the amount ingested.

Excess or deficiency of one mineral element may interfere not only with the absorption but also with the utilisation of another. Thus, for example, excess of magnesium interferes with the assimilation of calcium, the ratio of sodium to potassium affects the assimilation of both calcium and phosphorus, either too much or too little oil in the diet decreases the amount of calcium absorbed from the intestine. So the ratios of the different minerals to each other and to the organic constituents of the food are almost as important as their absolute amounts.

Recent work on the ultra-violet irradiation of animals is of great importance in this connexion. The beneficial effects of sunlight have been recognised for many generations. Within the past few years it has been shown that the beneficial effect of sunlight in nutritional diseases such as rickets can be obtained from artificially produced ultra-violet rays.

At the Rowett Institute we have found that when animals are subjected to the influence of these rays the amounts of calcium and phosphorus absorbed from the intestine tend to be increased, or at least the amount excreted in the faeces is decreased, even though at the same time the amount excreted in the urine may be increased. This result, which has an important bearing on mineral metabolism, has also been obtained by other workers. It is of interest to note that the influence of irradiation on the absorption of minerals from the intestine appears to be greatest when the diet is badly balanced.

Ultra-violet irradiation is probably of very great practical importance in milk production. It has been shown by balance experiments that there is difficulty in preventing a loss of calcium from the body of the cow at the height of lactation, when the cow is fed indoors, and there is reason to believe that this loss of calcium is a predisposing cause of some of the diseases prevalent among high-milking cows. It has been found that irradiation at the height of lactation

can decrease the loss of calcium in goats, or even convert a negative balance into a positive. The practical value of irradiation will, however, not be demonstrated until experiments have been carried out with large groups of stall-fed cows in winter, to determine whether the irradiation will favourably affect milk yield, breeding capacity and health.

From what has been said regarding factors which affect the assimilation of minerals, it will be readily understood that, before the mineral content of a ration can be adjusted, it is necessary to consider all the existing dietary factors. Even when all this has been done, it is impossible, in the present state of our knowledge, to do more than make an empirical adjustment by adding inorganic salts containing elements thought to be deficient in the ration. In a few cases we can predict, with some degree of certainty, that beneficial results will follow such adjustments, but in most cases the attempt must be regarded as an experiment, the results of which may or may not justify the continued use of the salt mixture tried.

It is obvious that the use of a stereotyped salt mixture with different rations, and for animals of different ages, and even of different species, is not warranted. In feeding experiments errors arise from the assumption that the addition of such mixtures obviates any necessity for further consideration of the mineral requirements of the animal, or of the influence which may be exercised by inorganic salts present in foodstuffs, the value of which is being tested. Under practical conditions, the use of such fixed mineral mixtures proves beneficial in many cases because they are rich in those inorganic constituents which are most frequently deficient in concentrates, but in cases where the ration is already rich in some of the minerals present in the mixture, the resulting excess may be harmful. No mineral mixture is a panacea.

Our knowledge of this subject is, therefore, still so scanty that it forms a very uncertain guide to the stock-farmer. It is sufficient, however, to warrant his testing, under practical conditions, some of the results which have been obtained under experimental conditions. The results of such tests, if positive, would secure the early application in practice of information which we already possess, and, whether positive or negative, would be a valuable guide to further efforts to increase that part of our knowledge which is of immediate practical value.

Though this practical experimental work is important because it may yield results of immediate economic value, yet with regard to the future it is not more important than academic research. Valuable results are likely to be yielded by further investigations being carried out on the interactions of colloids and inorganic ions, on the influence of the electrical charge and chemical characteristics of the ion on these reactions, on the effects of radiant energy on the processes associated with mineral metabolism, and on the relationship of these to both normal and pathological processes in the body. In this region, which we have only begun to explore, there seems to lie the key to the solution of many obscure problems, both of the normal metabolism of health and the abnormal metabolism of disease.