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Minerals in the animal body

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The minerals in the world today are those which were there when life began. As life evolved more than thirty of them have been incorporated into living matter, and these are listed in Table 1. Some elements are almost universally present in animal bodies, while others have been used by only one or two families. Some elements have known functions, others not, and their presence may be merely fortuitous. Sometimes the same element has been used to fulfil many functions, sometimes the same function has been served by two or more elements. Our own mineral metabolism is the legacy of the ages.

Table 1. *Minerals found in animal tissues*

(Roman numerals refer to group in Periodic Table)

Essential		Useful but probably not essential to vertebrates	Present in animal tissues, but no known function	
Sodium	I	Silicon IV	Lithium	I
Potassium		Fluorine VII	Rubidium	
Copper			Silver	
Calcium	II		Strontium	II
Magnesium			Barium	
Zinc			Beryllium	
			Cadium	
			Mercury	
Phosphorus	V			
Sulphur	VI		Boron	III
Chromium			Aluminium	
Selenium			Tin	IV
Molybdenum			Lead	
Chlorine	VII		Vanadium	V
Iodine			Arsenic	
Manganese				
Iron	VIII		Bromine	VII
Cobalt			Nickel	VIII

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The chemical properties of the mineral elements must always govern their biological behaviour. Of the common ones, sodium, potassium and chloride are freely soluble, whereas calcium is the one with the greatest tendency to form insoluble salts, and the carbonate and phosphate have been widely used as hardening agents. Magnesium is an important constituent of both hard and soft tissues. Iodine forms part of the thyroxine molecule and sulphur of that of two essential amino acids, cystine and methionine. Iron and copper are used for oxygen transport, and both have other functions, particularly as part of enzyme systems. Zinc, manganese and cobalt also form part of enzymes or are specific enzyme activators, and cobalt is an essential component of vitamin B_{12}. Molybdenum occurs in animal tissue flavoenzymes, and its metabolism is interrelated with that of copper and sulphate. Chromium is associated with ribonucleic acid and is also concerned in glucose metabolism, and selenium is essential for the prevention of a form of myopathy in lambs, calves and chickens.

Sodium and potassium

Prehistoric man was a hunter, and lived mainly on the animals he killed, and it was not until he started to lead a settled existence and began to grow plant crops that these became an important item in his dietary. This is not what happened in the evolutionary history of animals, however. Plants must have been the first food of animal life, because plants can and animals cannot synthesize carbohydrate and protein from inorganic materials in the atmosphere and soil. Within every family of animals there are some that have remained plant eaters, others have evolved as eaters of animals, and some, like man, have become omnivorous. Animals are more similar in composition to the bodies of their consumers than are plants, and animals living entirely on the whole bodies of other animals are more likely to get the minerals they require in approximately the right proportions than species that live entirely on plant foods. The element that is in short supply in plant foods is sodium, and it is probably true to say that all herbivores have to have some additional source of sodium from the soil or the drinking water. Creatures that live in the sea have the opposite problem, that of dealing with the excess sodium they take in in the sea water, and they have evolved various means for doing this.

Throughout the animal kingdom sodium and potassium are the elements concerned with osmotic equilibrium in the body fluids. Sodium is always the cation of the fluid outside the cells and potassium is generally the cation of the fluid inside them. The osmolar concentration inside and outside the cells within a body is always approximately the same. The osmolar concentration of the body fluids varies, however, from one form of animal life to another, according to the environment, and according to the excretory arrangements of the animal. This is illustrated in Fig. 1, which compares the osmolar concentrations of the body fluids of invertebrates and vertebrates with those of sea water and river water (Elkinton & Danowski, 1955). The body fluids of marine invertebrates tend to have the same osmolar concentration as sea water, while those of freshwater forms have much lower concentrations. Even in marine invertebrates, however, this similarity to sea water is only relative, for

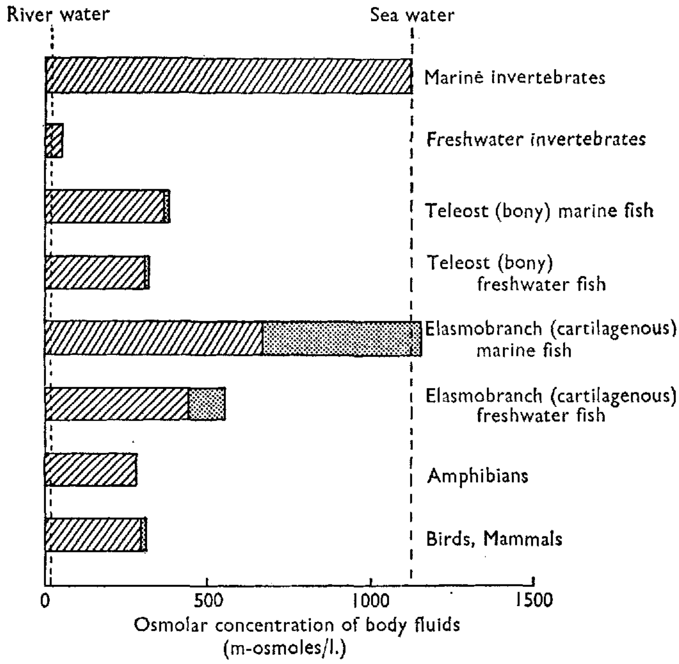

Fig. 1. Osmolar concentration of body fluids of vertebrates and invertebrates living in salt water, fresh water and air. Hatched, inorganic ions; dotted, urea.

the concentrations of the different ions in the extracellular fluid may be quite different, in particular the concentration of magnesium is less and that of sodium greater than it is in sea water.

The teleost or bony fishes evolved in fresh water and many still live there. Other species moved to the sea and developed a new mechanism of osmoregulation—the gills, with cells which actively separate and excrete the sodium and chloride ingested from the sea. Some members of this group, the eel and salmon, move back and forth between fresh and salt water at different stages in their life cycle and much still remains to be discovered about the physiological adjustments involved.

The elasmobranch or cartilaginous fish, the shark family, also evolved in fresh water and then moved to the sea. They developed a different defence against the dehydrating effect of the ingested sea water—a physiological uraemia. The renal tubules actively reabsorb urea and the gills do not excrete it, so that the concentration of urea in their body fluids is more than 2% and the total osmolar concentration of their body fluids slightly higher than that of the surrounding sea water. Some elasmobranchs subsequently moved back to fresh water. They have less urea in their body fluids and they excrete larger volumes of urine.

The amphibians that live in fresh water have body fluids that are similar to those of mammals and birds. Marine mammals and birds have body fluids similar to those of their terrestial counterparts. They achieve this by not drinking sea water, and by having a low evaporative loss of water. The seal feeds on teleost fishes whose body fluids are hypotonic to sea water, and these and the water of oxidation of the protein and fat provide it with the water it needs. The whales live on plankton or cephalopods, which are isotonic with sea water, and they are able to excrete a concentrated urine much as the desert mammals do.

Potassium is not invariably the cation of the cells, and this is illustrated in Table 2. This shows the concentration of potassium and sodium in the red cells of eight species

Table 2. *Electrolyte composition (m-equiv./l. cell water) of erythrocytes of different species*

Species	K	Na	Cl
Man	155	14	70
Horse	140	16	85
Rabbit	142	22	80
Rat	135	28	82
Sheep	46	98	78
Ox	35	104	85
Cat	8	142	84
Dog	10	135	87

of mammal (Widdowson & Dickerson, 1964). The erythrocytes of most mammals, like the other cells of the body, have far more potassium than sodium. The erythrocytes of the cat, dog, goat and certain breeds of sheep do not. A blood-sucking insect feeding on a dog would clearly get much less potassium than one that feeds on man (House, 1958). The mineral requirements of insects are in some ways different from those of mammals. For example a fly, *Pseudosarcophaga affinis*, and the mealworm, *Tenebrio molitor*, have been shown to require almost no potassium (House & Barlow, 1956; Fraenkel, 1958). Sodium may be in short supply in the diet of plant-eating insects, as it is for herbivores, for the cricket *Acheta domestica* only thrives on dried grass if extra sodium is added (Luckey & Stone, 1960).

Calcium

Calcium carbonate has been widely used by the invertebrates for their protective exoskeleton or shell. When it is realized that the shells of oysters, for example, amount to 88% of their weight it can be appreciated what large amounts of calcium the growing oyster requires. In fact, invertebrates with shells only grow in waters in which the concentration of calcium is high. Loss of a shell is a frequent event in the evolution of the invertebrates, and this must have thrown an enormous strain on the mechanisms for excreting calcium. This has not been studied a great deal, but one of the marine nudibranchs, *Archidoris Britannica*, has been found to have 2% of calcium in its body, or 11% of its dry weight (McCance & Masters, 1937). This is not organized into any useful structure, but is present throughout the tissues, mostly in the form of the carbonate. The presence of so much calcium may well be the result of inefficient excretion coupled with the loss of the power to form a shell. Another astonishing thing about Archidoris is the amount of fluoride in its body. This amounts to 3% of the dry weight, which was enough to etch the glassware being used in its analysis.

Birds use calcium phosphate for their bones, and calcium carbonate for the shells of their eggs, and they need a great deal of calcium when they are laying eggs. Calcium, primarily as the phosphate, forms the mineral matter of vertebrate bones and teeth. Man, with his upright habit, has to have bigger long bones than quadrupeds, and calcium makes up 2·2% of his lean body mass in contrast to 1·2 or 1·3% in the pig, cat, rat or rabbit (Widdowson & Dickerson, 1964). His total requirements for calcium per unit body-weight during the period of growth are therefore greater, but man is a slow-growing animal and he has 20 years in which to build his adult skeleton instead of say 3 years for the pig and 6 months for the rat.

Mammals that are born helpless, for example most rodents, carnivores, monkeys, apes and man, depend upon their mother's milk for calcium and other minerals during the period of rapid growth after birth, but mammals that are more highly developed at birth, including most ungulates, are able to get supplementary supplies from the soil and herbage. Some birds, for example the chick, can run and peck as soon as they are hatched, but others remain helpless in the nest for several weeks, and they depend upon the worms and insects their parents bring them for the minerals they need for their very rapid growth. We are investigating this in blackbirds and thrushes at the present time.

Insects have no skeletons or shells, and their calcium requirements are very low. In fact Drosophila seems to need only traces (Sang, 1956). Too much phosphorus can be harmful, and the grasshopper *Melanoplus* has a shorter life and is less fertile if the plants it eats have a high phosphorus content (Smith, 1959).

Iron, copper and zinc

The two respiratory pigments, haemoglobin of vertebrates and haemocyanin of arthropods and molluscs contain iron and copper respectively. Iron, copper and zinc all form part of enzymes, for example iron in heme, cytochromes, catalases and peroxidases, copper in caeruloplasmin and zinc in carbonic anhydrase, and these metalloenzymes are common to many species of mammals. Both copper and zinc are concerned in the formation of melanin, and they are at high concentrations in the iris and choroid, the pigmented parts of the eye. The eyes of the sheep and trout have been reported to have particularly large amounts of copper (Bowness, Morton, Shakir & Stubbs, 1952; Bowness & Morton, 1952), and those of fish and carnivores, above all the fox, have extremely high concentrations of zinc (Weitzel, Fretzdorff & Eberhagen, 1953).

There is a marine mollusc, *Patella athletica*, which has radular teeth made of iron and silica (Jones, McCance & Shackleton, 1935). Sea water contains very little iron, but there is plenty of iron in the seaweed Enteromorphia which forms the main article of diet of this creature. Insects need copper for their cuticle and their whole bodies have been reported to contain 10–60 μg/g of copper (Adelstein & Vallee, 1962). This is to be compared with 2 μg/g in the mammalian body. Copper compounds form the blue colouring matter in the feathers of a South African bird, the turaco.

There are two parts of the body that contain very high concentrations of zinc.

The first is the mammalian male reproductive organs, especially the prostate gland and the sperm (Mawson & Fischer, 1952; Hoare, Delory & Penner, 1956) and a deficiency of zinc in the diet of the male rat leads to degeneration of the reproductive organs (Millar, Fischer, Elcoate & Mawson, 1958). The second is the pancreas, and this has been traced to the α-cells. The α-cells of birds are segregated into visible brownish spots, and those of the duck have been dissected out and found to contain ten times as much zinc as the rest of the pancreatic tissue (Weitzel, Buddecke & Kraft, 1956).

Throughout this paper species differences have been highlighted, but of much greater fundamental importance are the similarities from one family of animals to another. Some species have been studied for one aspect of mineral metabolism, some for another, but the same general principles apply to all, for these ultimately depend upon the chemical properties of the mineral. The same minerals are present and they perform the same sort of functions in the bodies of grasshoppers, mealworms, oysters, trout, duck, and foxes as they do in our own.

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Requirements of different species for vitamins

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The original concept of a vitamin was an accessory food factor required in minute amount to prevent or cure certain deficiency diseases in man or animals. It is now recognized that vitamins have a more fundamental role, since many of them have been shown to be essential participants in metabolic reactions that are widespread

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