7 Minerals

7.1 Foreword

Minerals are the constituents which remain as ash after the combustion of plant and animal tissues. Minerals are divided into:

- main elements,
- trace elements and
- ultra-trace elements

The main elements (Na, K, Ca, Mg, Cl, P) are essential for human beings in amounts $>50\,mg/day$. Sulfur also belongs to this group. However, it will not be discussed here because sulfur requirements are met by the intake of sulfur-containing amino acids. Trace elements (Fe, I, F, Zn, Se, Cu, Mn, Cr, Mo, Co, Ni) are essential in concentrations of $<50\,mg/day$; their biochemical actions have been elucidated. Ultra-trace elements (Al, As, Ba, Bi, B, Br, Cd, Cs, Ge, Hg, Li, Pb, Rb, Sb, Si, Sm, Sn, Sr, Tl, Ti, W) are elements whose essentiality has been tested in animal experiments over several generations and deficiency symptoms have been found under these extreme conditions. For one of these elements, if it is possible to detect a biochemical function in a vital tissue or organ, the element is assigned to the trace elements.

Main and trace elements have very varied functions, e. g., as electrolytes, as enzyme constituents (cf. 2.3.3) and as building materials, e. g., in bones and teeth. Table 7.1 summarizes the content of main elements in the human body.

Table 7.2 shows the content of sodium, potassium, calcium, iron, and phosphorus in some foods. In the same food raw material, the mineral content can fluctuate greatly depending on genetic and climatic factors, agricultural procedures, composition of the soil, and ripeness of the harvested crops, among other factors. This applies to both main and trace elements. Changes in the mineral content usually occur also in the processing of raw materials, e. g., in thermal processes and material separations. Table 7.3 shows data on mineral losses in food processing. Mineral supply depends not only on the intake in food but primarily on the bioavailability, which is essentially related to the composition of the food. Thus, the redox potential and pH value determine the valency state, solubility, and, consequently, absorption. A series of food constituents, e. g., proteins, peptides, amino acids, polysaccharides, sugars, lignin, phytin, and organic acids, bind minerals and enhance or inhibit their absorption.

The importance of minerals as food ingredients depends not only on their nutritional and physiological roles. They contribute to food flavor and activate or inhibit enzyme-catalyzed and other reactions, and they affect the texture of food.

Table 7.1. Main elements in the human body

Element	Content g/kg
Calcium	10–20
Phosphorus	6–12
Potassium	2–2.5
Sodium	1–1.5
Chlorine	1–1.2
Magnesium	0.4–0.5

7.2 Main Elements

7.2.1 Sodium

The sodium content of the body is $1.4\,g/kg$. Sodium is present mostly as an extracellular constituent and maintains the osmotic pressure of the extracellular fluid. In addition, it activates some enzymes, such as amylase. Sodium absorption is rapid; it starts 3–6 min after intake and is completed within 3 h. Daily intake of sodium averages 2.5 g (females) to 3.3 g (males); the adult's average requirement ranges from

Table 7.2. Mineral content (Na, K, Ca, Fe, and P) of some foods

Food product	Na	K	Ca	Fe	P
Milk and dairy products					
Bovine milk,					
raw, high quality	48	157	120	0.046	92
Human milk	16	53	31	0.06	15
Butter	5	16	13	0.02–0.2	21
Cheese					
Emmental (45% fat)	275	95	1020	0.35	636
Camembert (60% fat)	709	95	90	0.13	310
Camembert (30% fat)	669	120	600	0.17	385
Eggs					
Chicken egg yolk	51	138	140	7.2	590
Chicken egg white	170	154	11	0.2	21
Meat and meat products					
Beef, whole carcass, lean	66	342	5.7	2.6	190
Pork, whole carcass, lean	69	397	5	1.0	192
Calf liver	87	316	8.7	7.9	306
Pork liver	77	363	7.6	18	407
Chicken liver	68	218	18	7.4	240
Pork kidney	173	242	7	7.3	260
Blood sausage	680	38	6.5	6.4	22
Fish and fish products					
Herring	117	360	34	1.1	250
Eel	65	259	17	0.9	334
Cereals and cereal products					
Wheat, whole kernel	7.8	381	33	3.3	341
Wheat flour, type 550	2.0	146	15	1.0	108
Wheat flour, type 1050	3.0	203	24	2.2	208
Wheat germ	5	993	49	8.5	1100
Rye, whole kernel	3.8	530	37	2.8	337
Rye flour, type 997	1	285	25	1.9	189
Corn, whole kernel	6	294	8	1.5	213
Breakfast cereals					
(corn flakes)	915	120	13	2.0	59
Oat flakes	6.8	374	48	5.4	415
Rice, unpolished	10	238	16	3.2	282
Rice, polished	3.9	103	6	0.8	114
Vegetables					
Watercress	12	276	180	3.1	64
Mushrooms (cultivated)	8	390	11	1.26	123
Chicory	4.4	192	26	0.74	26
Endive	43	346	54	1.4	54
Peas, green	2	274	24	1.7	113
Lamb's lettuce	4	421	35	2.0	49
Kale	35	451	212	1.9	87
Potatoes	3.2	418	6.4	0.43	50
Kohlrabi	20	322	68	0.48	50
Head lettuce	7.5	179	22	0.34	23
Lentils, dried	6.6	837	65	8.0	412
Carrots	60	321	37	0.39	35
Brussels sprout	7	451	31	1.1	84
Spinach	65	554	117	3.8	46
Edible mushroom (*Boletus edulis*)	6	341	4.2	1.0	85

Table 7.2. continued

Food product	Na	K	Ca	Fe	P
Vegetables					
Tomato	3.3	242	9.4	0.3	22
White cabbage	13	255	46	0.4	36
Fruits					
Apple	1.2	122	5.8	0.25	12
Orange	1.4	165	42	0.19	23
Apricots	2	278	16	0.65	21
Strawberry	1.4	161	21	0.64	29
Grapefruit	1.1	148	24	0.17	17
Rose hips	24	291	257	0.52	258
Currants-red	1.4	257	29	0.91	27
Currants-black	1.5	310	46	1.29	40
Cherries-sour	2	114	8	0.6	19
Plums	1.7	177	8.3	0.26	18
Sea buckthorn	3.5	133	42	0.44	9
Yeast					
Baker's yeast, pressed	34	649	28	3.5	473
Brewer's yeast, dried	77	1410	50	17.6	1900

[a] Data are in mg/100 g edible portion (average values).

Table 7.3. Mineral losses in food processing

Raw material	Product	Loss (%)						
		Cr	Mn	Fe	Co	Cu	Zn	Se
Spinach	Canned		87		71		40	
Beans	Canned						60	
Tomatoes	Canned						83	
Carrots	Canned				70			
Beetroot	Canned				67			
Green beans	Canned				89			
Wheat	Flour		89	76	68	68	78	16
Rice	Polished rice	75	26			45	75	

1.3–1.6 g/day (equal to 3.3–4.0 g/day NaCl). The intake of too little or too much sodium can result in serious disorders. From a nutritional standpoint, only the excessive intake of sodium is of importance because it can lead to hypertension. A low intake of sodium can be achieved by a nonsalty diet or by using diet salt (common salt substitutes, cf. 22.2.5). Table 7.2 provides values for the sodium content of some foods.

7.2.2 Potassium

The concentration of potassium in the body is 2 g/kg. At a concentration of 140 mmol/l, it is the most common cation in the intracellular fluid. Potassium is localized mostly within the cells. It regulates the osmotic pressure within the cell, is involved in cell membrane transport and also in the activation of a number of glycolytic and respiratory enzymes. The potassium intake in a normal diet is 2–5.9 g/day. The minimum daily requirement is estimated to be 782 mg. Potassium deficiency is associated with a number of symptoms and may be a result of undernourishment or predominant consumption of potassium-deficient foods, e. g., white bread, fat or oil. The potassium content in food is summarized in Table 7.2. Potatoes and molasses are particularly abundant sources.

7.2.3 Magnesium

The concentration of magnesium in the body is 250 mg/kg. The daily requirement is 300–400 mg. In a normal diet, the daily intake is 300–500 mg. As a constituent and activator of many enzymes, particularly those associated with the conversion of energy-rich phosphate compounds, and as a stabilizer of plasma membranes, intracellular membranes, and nucleic acids, magnesium is a life-supporting element. Because of its indispensable role in body metabolism, magnesium deficiency causes serious disorders.

7.2.4 Calcium

The total amount of calcium in the body is about 1500 g. Because of the large amounts of calcium all over the body, it is one of the most important minerals. It is abundant in the skeleton and in some body tissues. Calcium is an essential nutrient because it is involved in the structure of the muscular system and controls essential processes like muscle contraction (locomotor system, heartbeat) blood clotting, activity of brain cells and cell growth. Calcium deficiency causes serious disorders. The desirable calcium intake (g/day) is stipulated as: birth to 6 months (0.4), 6 to 12 months (0.6), 1 to 5 years (0.8), 6 to 10 years (0.8–1.2), 11 to 24 years and pregnant women (1.2 to 1.5), 25 to 65 years (1.0) and above 65 years (1.5). The main source of calcium is milk and milk products, followed at a considerable distance by fruit and vegetables, cereal products, meat, fish and eggs. Table 7.2 provides data on the calcium content of some foods. An adequate supply of vitamin D is required for the absorption of calcium.

7.2.5 Chloride

The chloride content of human tissue is 1.1 g/kg body weight and the plasma concentration is 98–106 mmol/l. Chloride serves as a counter ion for sodium in extracellular fluid and for hydrogen ions in gastric juice. Chloride absorption is as rapid as its excretion in the urine. The minimum intake of chloride largely corresponds on a molar basis to the sodium requirement.

7.2.6 Phosphorus

The total phosphorus content in the body is about 700 g. The daily requirement is about 0.8–1.2 g. The Ca/P ratio in food should be about 1. Phosphorus, in the form of phosphate, free or bound as an ester or present as an anhydride, plays an important role in metabolism and, as such, is an essential nutrient. The organic forms of phosphorus in food are cleaved by intestinal phosphatases and, thereby, absorption occurs mostly in the form of inorganic phosphate. Polyphosphates, used as food additives, are absorbed only after prior hydrolysis into orthophosphate. The extent of hydrolysis is influenced by the degree of condensation of the polyphosphates. Table 7.2 includes a compilation of the phosphorus content of some foods.

7.3 Trace Elements

7.3.1 General Remarks

There are 11 trace elements present in hormones, vitamins, enzymes and other proteins which have distinct biological roles. A deficiency in the trace elements results in metabolic disorders that are primarily associated with the absence or decreased activity of metabolic enzymes.

7.3.2 Individual Trace Elements

7.3.2.1 Iron

The iron content of the body is 4–5 g. Most of it is present in the hemoglobin (blood) and myoglobin (muscle tissue) pigments. The metal is also present in a number of enzymes (peroxidase, catalase, hydroxylases and flavine enzymes), hence it is an essential ingredient of the daily diet. The iron requirement depends on the age and sex of the individual, it is about 1.5–2.2 mg/day. Iron supplied in the diet must be in the range of 15 mg/day in order to meet this daily requirement. The large variation in intake can be explained by different extents of absorption of the various forms of iron present in food (organic iron compounds *vs* simple

Table 7.4. Trace elements in the human body and their daily intake[a]

Element	Content (mg/kg body weight)	Adequate Intake[b] (mg/day)
Fe	60	15
F	37	2.9–3.8
Zn	33	10–15
Cu	1.0	1.0–1.5
Se	0.2	0.03–0.07
Mn	0.2	2–5
I	0.2	0.2–0.26
Ni	0.1	0.025–0.03
Mo	0.1	0.05–0.1
Cr	0.1	0.003–0.1
Co	0.02	0.002–0.1

[a] Average values.
[b] Estimated for adults.

salts). The most utilizable source is iron in meat, for which the extent of absorption is 20–30%. The absorption is much less from liver (6.3%) and fish (5.9%), or from cereals, vegetables and milk, from which iron absorption is the lowest (1.0–1.5%). Eggs decrease and ascorbic acid increases the extent of absorption. Bran interferes with iron absorption due to the high content of phytate. Apparently, the absorption of iron present in food is, in a healthy organism, regulated by the requirement of the organism. Nevertheless, in order to provide a sufficient supply of iron to persons who require higher amounts (children, women before menopause and pregnant or nursing women), cereals (flour, bread, rice, pasta products) fortified with iron to the extent of 55–130 mg/kg are recommended. Extensive feeding tests with chickens and rats have shown that $FeSO_4$ is the most suitable form of iron, but ferrous gluconate and ferrous glycerol phosphate are also efficiently absorbed. Two food processing problems arising from mineral fortification are the increased probability that oxidation will occur and, in the case of wheat flour, decreased baking quality. Generally, iron is an undesirable element in food processing; for example, iron catalyzes the oxidation of fat or oil, increases turbidity of wine and, as a constituent of drinking water, it supports the growth of iron-requiring bacteria. The iron content of various foods is shown in Table 7.2.

7.3.2.2 Copper

The amount of copper in the body is 80–100 mg. Copper is a component of a number of oxidoreductase enzymes (cytochrome oxidase, superoxide dismutase, tyrosinase, uricase, amine oxidase). In blood plasma, it is bound to ceruloplasmin, which catalyzes the oxidation of Fe^{2+} to Fe^{3+}. This reaction is of great significance since it is only the Fe^{3+} form in blood which is transported by the transferrin protein to the iron pool in the liver. The daily copper requirement is 1–1.5 mg and it is supplied in a normal diet. Copper is even less desirable than iron during food processing and storage since it catalyzes many unwanted reactions. Cu^{2+}-Ions are taste bearing. The threshold value 2.4–3.8 mg/l was determined with aqueous solutions of $CuSO_4$ or $CuCl_2$.

7.3.2.3 Zinc

The total zinc content in adult human tissue is 2–4 g. The daily requirement of 5–10 mg is provided by a normal diet (6–22 mg zinc/day). Zinc is a component of a number of enzymes (e. g., alcohol dehydrogenase, lactate dehydrogenase, malate dehydrogenase, glutamate dehydrogenase, carboxypeptidases A and B, and carbonic anhydrase). Other enzymes, e. g., dipeptidases, alkaline phosphatase, lecithinase and enolase, are activated by zinc and by some other divalent metal ions. Zinc deficiency in animals causes serious disorders, while high zinc intake by humans is toxic. Zinc poisoning has been reported as a result of consumption of soured food kept in zinc-plated metal containers (e. g., potato salad from institutional catering services).

7.3.2.4 Manganese

The body contains a total of 10–40 mg of manganese. The daily requirement, 2–5 mg, is met by the normal daily food intake (2–48 mg manganese/day). Manganese is the metal activator for pyruvate carboxylase and, like some other divalent metal ions, it activates various enzymes, such as arginase, amino peptidase, alkaline phosphatase, lecithinase or enolase. Manganese, even in higher amounts, is relatively nontoxic.

7.3.2.5 Cobalt

The total cobalt content of the body is 1–2 mg. Since it was discovered that vitamin B_{12} contains cobalt as its central atom, the nutritional importance of cobalt has been emphasized and it has been assigned the status of an essential element. Its requirement is met by normal nutrition.

7.3.2.6 Chromium

The chromium content of the body varies considerably depending on the region; the range is 6–12 mg. The daily intake also varies greatly from 5 to 200 µg. The supply is considered suboptimal. Chromium is important in the utilization of glucose. For instance, it activates the enzyme phosphoglucomutase and increases the activity of insulin; therefore, chromium deficiency causes a decrease in glucose tolerance. And the risk of cardiovascular disease increases. Chromium, as the chromate ion, proved to be nontoxic when used at 25 ppm in a long-term feeding experiment with rats.

7.3.2.7 Selenium

The selenium content in humans is 10–15 mg, while the daily intake is 0.05–0.1 mg. Depending on the region, it can vary greatly because of the varying content of selenium in the soil. Selenium is an antioxidant and can enhance tocopherol activity. The enzyme glutathione peroxidase contains selenium. It catalyzes the following reaction, protecting membranes from oxidative destruction:

$$ROOH + 2GSH \rightarrow ROH + H_2O + GSSG \qquad (7.1)$$

Selenium toxicity, for example, its strong carcinogenic activity, is well known from numerous animal feeding studies and from diseases of cattle grazing in pastures on selenium-rich soil. For adults, an adequate intake is estimated at 30–70 µg Se/day.

7.3.2.8 Molybdenum

The body contains 8–10 mg of molybdenum. Daily intake in food is approx. 0.3 mg. It is a component of aldehyde oxidase and xanthine oxidase. The bacterial nitrate reductase involved in meat curing and pickling processes contains molybdenum. High levels of the metal are toxic, as has been shown by cattle grazing on molybdenum-enriched soil. The grass on such soil contains 20–100 µg molybdenum/g dry matter.

7.3.2.9 Nickel

Nickel is an activator of a number of enzymes, e. g., alkaline phosphatase and oxalacetate decarboxylase, which can also be activated by other divalent metal ions. Nickel also enhances insulin activity. The essential role of nickel has been established by inducing deficiency symptoms in feeding experiments with chickens and rats. These symptoms include changes in the liver mitochondria. The daily intake in food amounts to 150–700 µg. The nickel requirement is estimated to be 35–500 µg/day.

7.3.2.10 Fluorine

The body contains 2.6 g fluorine. It plays an essential role, as indicated by feeding experiments with rats and mice – deficient diets containing less than 2.5 ppm and 0.1–0.3 ppm respectively, resulted in disorders in growth and reproduction. The positive effect of fluorine on teeth caries is well established. The addition to drinking water of 0.5–1.5 ppm fluorine in the form of NaF or $(NH_4)_2SiF_6$ inhibits tooth decay. Its beneficial effect appears to be in retarding solubilization of tooth enamel and inhibiting the enzymes involved in development of caries. Toxic effects of fluorine appear at a level of 2 ppm. Therefore, the beneficial effects of fluoridating drinking water are disputed by some and it is a controversial topic of mineral nutrition.

7.3.2.11 Iodine

The content of iodine in the body is about 10 mg, of which the largest portion (70–80%) is covalently bound in the thyroid gland. Iodine absorption from food occurs exclusively and rapidly as iodide and is utilized in the thyroid gland in the biosynthesis of the hormone thyroxine (tetraiodothyronine) and its less iodized form, triiodothyronine. In this process, the iodide ion is first oxidized, then iodization of the tyrosine residues of thyroglobulin occurs. Diiodotyrosine condenses with itself or with monoiodotyrosine to form thyroglobulin-bound thyroxine or triiodothyronine. Both active hormones are released from thyroglobulin by the action of a proteinase. Also released are several peptides which, however, lack activity. The iodine requirement of humans is 100–200 µg/day; pregnant and nursing women require 230 and 260 µg/day respectively. Iodine deficiency results in enlargement of the thyroid gland (iodine-deficiency induced goiter). There is little iodine in most food. Good sources are milk, eggs and, above all, seafood. Drinking water contributes little to the body's iodine supply. In areas where goiter is found, the water has 0.1–2.0 µgI/l, while in goiter-free districts, 2–15 µgI/l are present in drinking water. To avoid diseases caused by low iodine supply, some countries with iodine-deficient districts employ prophylactic measures to combat the deficiency symptoms. This involves iodization of common salt with potassium iodate, with 100 µg iodine added to 1–10 g NaCl. Higher amounts of iodine are toxic and, as shown with rats, disturb the animal's normal reproduction and lactation. In humans, diseases of the thyroid can develop.

7.3.3 Ultra-trace Elements

7.3.3.1 Tin

Tin occurs in all humans organs. Although a growth-promoting effect was detected in rats, it is disputed. The natural level of tin in food is very low, but it can be increased in the case of foods canned in tinplate cans. Very acidic foods can often dissolve substantial amounts of tin. Thus, the concentration of tin in pineapple and grapefruit juice transported in poorly tin plated cans was 2 g/l. The tin content of foods in tinplate cans is generally below 50 mg/kg and should not exceed 250 mg/kg. In the form of inorganic compounds, tin is resorbed only to a low extent and, therefore, it is only slightly toxic. In comparison, organic tin compounds can be very toxic.

7.3.3.2 Aluminum

The body contains 50–150 mg of aluminum. Higher levels are found in aging organisms. The daily average intake of aluminum is 2–10 mg. It is resorbed in only negligible amounts by the gastrointestinal tract. The largest portion is eliminated in feces. Excretion of aluminum in urine is less than 0.1 mg/day. It is not secreted in milk. Animal feeding tests with high levels of aluminum in the diet through several generations showed that aluminum is nontoxic. This seems to be true also for humans. Hence, the reluctance to use aluminum cookware in food processing is unfounded. Some recent studies, however, have revealed that a pathologically caused accumulation of aluminum in humans can cause significant damage to the cells of the central nervous system.

7.3.3.3 Boron

Boron is found in humans and animals. The concentrations in the organs and tissues vary. In human beings, the highest concentrations are found in the heart (28 mg/kg), followed by the ribs (10 mg/kg), spleen (2.6 mg/kg) and liver (2.3 mg/kg). Muscle tissue contains only 0.1 mg/kg. Boron seems to be an essential nutrient, which promotes bone formation by interaction with calcium, magnesium and vitamin D. In addition, there are indications that boron is involved in the hydroxylation of steroids, e. g., in the synthesis of 17β-estradiol and testosterone. The daily requirement is estimated to be 1–2 mg. Apples (40), soy flour (28), grapes (27), tomatoes (27), celery (25) und broccoli (22) are rich in boron (mg/kg solids). Important sources also include wine (8) and water.

7.3.3.4 Silicon

Silicon, as soluble silicic acid, is rapidly absorbed. The silicon content of the body is approx. 1 g. The main source is cereal products. Silicon promotes growht and thus has a biological role. The toxicity of silicic acid is apparent only at concentrations $\geq$100 mg/kg. The intake in food amounts to 21–46 mg/day.

7.3.3.5 Arsenic

Arsenic was shown to be an essential trace element for the growth of chickens, rats, and goats. Its metabolic role is not yet understood. It appears to be involved in the metabolism of methionine. Choline can be replaced by arsenocholine in some of its functions. The possible human requirement is estimated to be 12–25 μg/day. The intake in food amounts to 20–30 μg/day. The main source is fish.

7.4 Minerals in Food Processing

The contribution of minerals to the nutritive/physiological value and the physical state of food has been covered in the Foreword of this Chapter and under the individual elements.

However, there are metal ions, derived from food itself or acquired during food processing and storage, which interfere with the quality and visual appearance of food. They can cause discoloration of fruit and vegetable products (cf. 18.1.2.5.8) and many metal-catalyzed reactions are responsible for losses of some essential nutrients, for example, ascorbic acid oxidation (cf. 6.3.9.3). Also, they are responsible for taste defects or off-flavors, for example, as a consequence of fat oxidation (cf. 3.7.2.1.6). Therefore, the removal of many interfering metal ions by chelating agents (cf. 8.14) or by other means is of importance in food processing.

7.5 References

Bohl, C.H., Volpe, S.L.: Magnesium and exercise. Crit. Rev. Food Sci. Nutr. *42*, 533 (2002)

Deutsche Gesellschaft für Ernährung (DGE): Referenzwerte für die Nährstoffzufuhr. 1. Auflage. Umschau Braus Verlagsgesellschaft, Frankfurt a.M., 2000

Devirian, T.A., Volpe, S.L.: The physiological effects of dietary boron. Crit. Rev. Food Sci. Nutr. *43*, 219 (2003)

Lang, K.: Biochemie der Ernährung, 4. Aufl., Dr. Dietrich Steinkopff Verlag: Darmstadt. 1979

Pfannhauser, W.: Essentielle Spurenelemente in der Nahrung. Springer Verlag: Berlin, 1988

Smith, K.T.: Trace Minerals in Foods. Marcel Dekker: New York, 1988

Wolfram, G., Kirchgeßner, M. (Eds.): Spurenelemente und Ernährung. Wissenschaftl. Verlagsgesellschaft: Stuttgart, 1990