15 ZINC

Henry C. Lukaski

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I. INTRODUCTION

The growing awareness of the synergy between diet and physical activity to promote health and boost performance fuels an expanding interest in the role that micronutrients can play in attaining one’s genetic potential. Although the public press emphasizes the value of certain foods and nutritional products for

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health and fitness enhancement, the findings from valid scientific studies to support these claims are limited. Information about the needs of mineral elements, particularly zinc (Zn), for physically active individuals is accumulating.\(^1\) Data from epidemiological surveys reveal that many adults and children may not consume adequate dietary Zn, with the mean Zn intake of the U.S. population less than one half of the recommended amount.\(^2\) Furthermore, low Zn intake is common among individuals who regularly participate in aerobic activities,\(^3,4\) including those recommended to promote health and well-being.\(^5\)

As a transition element, Zn has the ability to form stable complexes with side chains of proteins and nucleotides, with a specific affinity for thiol and hydroxyl groups and for ligands containing nitrogen; Zn generally forms complexes with a tetrahedral arrangement of ligands around the metal. Thus, the Zn ion acts as a good electron acceptor, but does not participate in direct oxidation-reduction reactions. These characteristics serve to explain the principal biological function of Zn, that is, its varied roles in regulation of body metabolism.

Zn is essential for the function of more than 200 enzymes in various species.\(^6\) At least one Zn-containing enzyme is found in each of the six major categories of enzymes designated by the International Union of Biochemistry Commission on Enzyme Nomenclature.\(^6,7\) Zn has several recognized functions in Zn-metalloenzymes, including catalytic, structural and regulatory roles.\(^7\) Catalytic function specifies that Zn participates directly in facilitating the action of the enzyme. If the Zn is removed by chelates or other agents, the enzyme becomes inactive. Carbonic anhydrase is an enzyme in which Zn plays a catalytic role.\(^8\)

In a structural role, Zn atoms are required to stabilize the quaternary structure of the enzyme protein and to maintain the integrity of the complex enzyme molecules, but not impact enzyme activity. Zn plays a structural role in the enzymes superoxide dismutase and protein kinase c.\(^6\)

The importance of Zn in biological systems is reflected by the numerous functions and activities on which Zn exerts a regulatory role.\(^9\) Zn is involved extensively in macronutrient metabolism. It is required for nucleic acid and protein metabolism and, hence, the fundamental processes of cell differentiation, particularly replication. Similarly, Zn is needed for glucose utilization and the secretion of insulin. Because of this role in glucose homeostasis, Zn also affects lipid metabolism; Zn-deficient animals display decreased \textit{de novo} lipid synthesis.\(^10\) Thus, Zn status impacts energy substrate utilization.

Zn exerts regulatory actions in various aspects of hormone metabolisms.\(^9\) Zn is required for the production, storage and secretion of individual hormones, including growth and thyroid hormones, gonadotrophins and sex hormones, prolactin and corticosteroids. Zn status also regulates the effectiveness of the interaction of some hormones at receptor sites and end-organ responsiveness.

Integrated biological systems also require Zn for optimal function.\(^11\) Adequate dietary Zn is necessary for proper taste perception, reproduction, immuno-competence, skin integrity, wound healing, skeletal development, brain development, behavior, vision and gastrointestinal function in humans. It is apparent, therefore, that Zn is a nutrient that regulates many physiological and psychological functions and is required to promote human health and well-being.

II. **ZINC METABOLISM**

A. **ZINC IN THE HUMAN BODY**

Zn is present in all organs, tissues, fluids and secretions of the body. More than 95% of Zn in the body is found within cells. Zn is associated with all organelles of the cell but only 60 to 80% of cellular Zn is localized in the cytosol; the remainder has been shown to be specifically bound to membranes that may be important in defining the effects of Zn deficiency on cellular function.\(^12\) The concentration of Zn in extracellular fluids is very low; plasma Zn concentration is approximately 0.65 µmol/l. If the body plasma concentration is 45 ml/kg body weight,\(^13\) then a 70-kg man has about 3 l of plasma, which contains only 3 mg of Zn, or about 0.1% of the body Zn content.

The Zn concentration in various organs and tissues of the body is variable (Table 15.1). Although the concentration of Zn in skeletal muscle is not large, the substantial mass of skeletal muscle
makes it the principal reservoir of Zn in the body. Bone and skeletal muscle account for almost 90% of the body’s Zn content.

The Zn concentration in muscles varies with their metabolic functions. The highest Zn concentrations are found in skeletal muscles, which are highly oxidative, with a large proportion of slow-twitch fibers. The rat soleus muscle, composed of 63% slow-twitch fibers, contains about 300 µg Zn per gram dry weight. Conversely, the extensor digitorum longus, which is primarily a fast-twitch glycolytic muscle, has only 100 µg Zn per gram dry weight. The Zn concentration of skeletal muscles generally is not reduced with restricted dietary Zn, except for small decreases (~5%) in the soleus. The size and number of various types of muscle fibers, however, may be reduced and their relative distribution altered, with a characteristic decrease of the slow-twitch oxidative and an increase in the fast-twitch glycolytic fibers. Thus, skeletal muscle is relatively unresponsive to changes in dietary Zn.

Because the concentration of Zn in bone is quite large relative to other body tissues and organs, and the amount of bone is very substantial, the skeleton is the major depot of Zn (Table 15.1). Bone Zn is impacted adversely by dietary Zn restriction, particularly in growing animals. The decline in bone Zn is more responsive to dietary Zn intake than that of other tissues and may better reflect the gradual decline in overall Zn status of the body than plasma Zn concentration. Studies in growing rats fed Zn-deficient diets found a 50% reduction in bone Zn; short-term Zn supplementation of Zn-deficient rats significantly increased bone Zn. In adult male rats, however, bone Zn responded only to a minor degree to dietary Zn.

### TABLE 15.1

<table>
<thead>
<tr>
<th>Tissue or Organ</th>
<th>Zinc Concentration (µmol/g)*</th>
<th>Total Zn Content (µg/g)*</th>
<th>Percentage of Body Zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal muscle</td>
<td>0.78 51 24 1.53 57.0</td>
<td>Bone</td>
<td>1.54 100 2 0.77 29.0</td>
</tr>
<tr>
<td>Skin</td>
<td>0.49 32 2 0.16 6.0</td>
<td>Liver</td>
<td>0.89 58 2 0.13 0</td>
</tr>
<tr>
<td>Liver</td>
<td>0.17 11 0.6 0.04 1.5</td>
<td>Brain</td>
<td>0.85 55 0.3 0.02 0.7</td>
</tr>
<tr>
<td>Kidneys</td>
<td>0.35 23 0.15 0.01 0.4</td>
<td>Heart</td>
<td>2.30 150 &lt;0.15 &lt;0.01 0.1</td>
</tr>
<tr>
<td>Hair</td>
<td>0.02 1 &lt;0.15 &lt;0.01 0.1</td>
<td>Plasma</td>
<td>0.17 11 0.6 0.04 1.5</td>
</tr>
</tbody>
</table>

Source: Adapted from International Commission on Radiological Protection, Report on the Task Group of Reference Man. * Wet weight

### B. ZINC HOMEOSTASIS

#### 1. Absorption

The amount of Zn in the body represents a dynamic balance between the Zn intake and losses (Figure 15.1). Zn is absorbed principally along the small intestine, with only negligible amounts absorbed in the stomach and the large intestine. The quantity of Zn in the intestines is a combination of dietary Zn and Zn-containing endogenous secretions that aid in digestion. Pancreatic secretions are a major source of endogenous Zn. Other sources include biliary and gastro-duodenal secretions, transepithelial flux of Zn from mucosal cells into the small intestine and mucosal cells sloughed...
Thus, the amount of Zn in the lumen of the small intestine after a meal exceeds the quantity of Zn from the meal because of endogenous secretions. During digestion, secreted enzymes release Zn from the food and endogenous Zn from various ligands. The free Zn can form coordination complexes with various exogenous and endogenous ligands such as amino acids, organic acids and phosphates. The amino acids, histidine and cysteine, are preferred amino acid ligands. It has been shown that Zn-histidine complexes are very efficiently absorbed, more so than Zn sulfate. Other compounds such as iron and phytate, found in the intestinal milieu, can compete with Zn for mucosal binding sites or form insoluble complexes that inhibit Zn absorption.

Zn enters mucosal cells by a mechanism that is not well understood. It is thought that Zn enters the mucosal cell by a carrier-mediated process, saturable at higher luminal Zn concentrations and by diffusion. Within the mucosal cell, Zn is released at the serosal surface and into the blood, where it binds with albumin then is transported by the portal blood to the liver. Functional evidence reveals that at least 24 specific transporters are responsible for either Zn influx or efflux in mammalian cells. These transporters are designated as two gene families: the ZnT proteins and the Zip family. ZnT transporters reduce intracellular Zn availability by promoting Zn efflux from cells, whereas Zip transporters increase intracellular Zn availability by promoting extracellular uptake of Zn. Information about the actions of these transporters in muscle or other tissues in response to physical activity is lacking.

The total body content of Zn is partially controlled by the regulation of the efficiency of intestinal absorption of Zn. Numerous studies in animals and humans have reported an inverse relationship between Zn intake and absorption. Thus, the regulation of Zn absorption by the mucosal cell provides a general control of total body Zn.

2. Excretion

Control of Zn excretion in feces represents another regulatory mechanism for maintenance of body Zn. In normal dietary circumstances, the feces are the major route of Zn excretion. In healthy humans with an average intake of 10 to 14 mg of Zn per day, more than 90% of dietary Zn is excreted in the feces. Some of the Zn in the feces is from endogenous secretions. Studies indicate that 2.5 to 5 mg of Zn are secreted into the duodenum after a meal. Much of the Zn secreted...
into the lumen of the gut is absorbed and returned to the body. The amount of Zn secreted into the gut varies with the Zn content of the meal. Endogenous fecal Zn excretion is directly related to dietary Zn intake. In humans, endogenous fecal Zn losses may range from 1 mg/d with very low Zn intakes to more than 5 mg/d with extremely large Zn intakes. In contrast to absorption, endogenous fecal Zn excretion represents a sensitive control to balance Zn retention to metabolic needs.

Other routes of Zn excretion are present in humans. About 0.4 to 0.5 mg of Zn are excreted daily in the urine. Urinary Zn originates from the ultrafilterable portion of plasma Zn and represents a fraction of previously absorbed dietary Zn. Dietary Zn affects urinary Zn losses only under conditions of extreme intakes and results in corresponding changes in Zn output in the urine.

Zn also is lost from the skin and in various secretions. Surface losses, which include sloughing of the skin, sweat and hair, contribute up to 1 mg of Zn loss daily. Surface losses range from 0.3–0.4 to 0.4–0.5 and 0.7–0.8 mg at intakes of 3–4, 8–9 and 33–34 mg/d, respectively. A marked change in Zn intake results in parallel changes in surface Zn loss. Other sources of Zn loss include seminal and menstrual secretions. An ejaculum of semen includes about 1 mg of Zn. Total menstrual losses of Zn may reach 0.5 mg per menstrual period.

The elimination of absorbed Zn from the body has been modeled with a two-component model. In humans, an initial or rapid phase has a half-life of 12.5 d and a slower turnover phase of about 300 d. The initial rapid phase represents liver uptake of circulating Zn and its quick release into the circulation. The slower turnover rate reflects the different rates of turnover in various organs, excluding the liver. The most rapid rates of Zn uptake and turnover are found in the pancreas, liver, kidney and spleen, with slower rates in erythrocytes and muscle. Zn turnover is slowest in bone and the central nervous system.

Manipulation of dietary Zn impacts zinc turnover. In rats, dietary Zn restrictions promote retention of Zn in soft tissues and organs but not in bone. In humans, the turnover of the slow Zn pool is increased by ingestion of pharmacologic amounts (100 mg) of Zn. These homeostatic actions maintain soft tissue Zn concentrations despite variations in dietary Zn.

3. Transport

Distribution of absorbed Zn to the extrahepatic tissues occurs primarily in the plasma, which contains approximately 3 mg of Zn or about 0.1% of total body Zn. Zn is partitioned among α₂-macroglobulin (40%), albumin (57%) and amino acids (3%) in plasma. Zn is bound loosely to albumin and amino acids; these fractions are responsible for transport of Zn from the liver to tissues. The amino acid-bound Zn constitutes the ultrafilterable fraction that is filtered at the kidneys and excreted in the urine. Because the total amount of Zn present in tissue is far greater than the Zn in the plasma, relatively small changes in tissue Zn content, such as in the liver, can have striking effects on the plasma Zn concentration. Importantly, because all absorbed Zn is transported from the plasma to tissues, the exchange of Zn from plasma into tissues is very rapid to maintain relatively constant plasma Zn concentrations (Figure 15.1).

III. ASSESSMENT OF HUMAN ZINC NUTRITIONAL STATUS

A deficiency of Zn progresses in a pattern that is different from that for most nutrients. In general, an insufficient intake of a nutrient initially induces a mobilization of body stores or functional reserves. As depletion persists, tissue nutrient concentrations decrease, which results in deterioration in one or more nutrient-dependent metabolic functions. Therefore, growth reduction is a late manifestation of the nutritional deficiency. In contrast, when dietary Zn is decreased, the initial response is a reduction in growth by children and a decrease in endogenous losses of Zn as a means to conserve tissue Zn. If the dietary deficiency is mild, homeostasis may be reestablished after adjusting growth and Zn excretion, with no further impairment of function or biochemical changes. When dietary Zn is severely restricted, however, the body cannot restore homeostasis by adjusting...
endogenous losses and growth, consequently generalized impairment of organ and tissue function develops quickly.

Although severe dietary Zn deficiency can be induced in animals, it is rarely present in humans, with the exception of infants and children with acrodermatitis enteropathica, patients fed total parenteral nutrition solutions lacking Zn and experimental human Zn depletion. Evidence of moderate or mild Zn deficiency is difficult to demonstrate because of the lack of a sensitive and specific indicator of human Zn nutriture.  

Two general approaches have been used to assess human Zn status. One strategy has been to measure static indices, including concentrations of Zn in tissues or body fluids or measurements of biochemical surrogates for Zn nutriture in the form of Zn-containing enzymes and proteins. Another approach involves the measurement of dynamic indices that reflect the biological performance of Zn-dependent physiological or psychological functions.

Although frequently measured, plasma and serum Zn concentrations have been shown to be relatively insensitive to modest changes in dietary and body Zn. Because whole-body Zn content is conserved in Zn deficiency, plasma and serum Zn are not reliable indicators of human Zn status. Further, plasma Zn is unresponsive to changes in dietary Zn unless the Zn intake is low and homeostasis cannot be reestablished. It is more realistic to describe plasma Zn as a component of a labile, nutritionally available pool of total body Zn. Any decrease in plasma Zn concentration, therefore, should be interpreted as a decrease in the size of the labile Zn pool. Use of this concept is limited, however, by the findings that metabolic factors also influence the labile Zn pool. Infection, food intake, stress, brief-duration fasting and hormonal status can alter the distribution of Zn among the tissues and thus influence the amount of Zn in the plasma.

Other static indices of human Zn status have failed to be useful. Red blood cell (RBC) Zn concentration is relatively unresponsive to mild or moderate Zn deficiency. The Zn concentration in various populations of leukocytes also is not sensitive to changes in Zn status. Timed urinary Zn excretion rates are decreased in severe Zn deficiency but are not responsive to more moderate changes in dietary Zn. Therefore, current biochemical methods of assessment of human Zn status remain a limitation for routine clinical evaluation of Zn nutritional status.

IV. ZINC NUTRITURE OF PHYSICALLY ACTIVE ADULTS

Attempts to evaluate the Zn status of physically active individuals have been complicated by the use of different experimental designs and reliance on indirect indices of Zn nutritional status. The lack of an integrated assessment of factors affecting Zn homeostasis contributes to the deficit of knowledge about Zn requirements during periods of increased physical activity.

A. Plasma Zinc Concentration

Awareness of potentially adverse effects of physical activity on human Zn nutritional status began with the observation that some endurance runners had significantly decreased serum Zn concentrations as compared with non-training men. About 25% of 76 competitive male runners had serum Zn concentrations less than 11 µmol/l, the lower limit designated for the range of normal values. Importantly, serum Zn concentration was inversely related to weekly training distance. The investigators speculated that dietary habits, including avoidance of animal products and consumption of carbohydrate-rich foods, which are low in Zn, and possible increased losses of Zn in sweat, may have predisposed the runners to hypozincemia.

Similar findings of reduced plasma Zn concentrations have been reported for some, but not all, groups of highly trained athletes. In a survey of elite German athletes, there was no difference between mean serum Zn concentrations of athletes and sex-matched non-athletes. Hypozincemia, defined as serum Zn concentration less than 11 µmol/l, was observed in about 25% of the athletes. Among female marathon runners, plasma Zn values were clustered at the low end of the range of
normal values, with 22% of the values less than 11 \( \mu \text{mol/l} \). In contrast, no differences in plasma Zn concentrations were found in comparisons of male and female collegiate athletes with age-matched non-training students. One explanation for these divergent results is that Zn intake may have been inadequate in the athletes with decreased circulating Zn concentrations.

### B. Dietary Zinc

Based on self-reported food and beverage consumption (Table 15.2), athletes generally consume Zn in amounts exceeding the estimated average requirement (EAR)\(^{40}\) of 9.4 and 6.8 mg/d for men and women, respectively. However, a significant proportion of participants in some activities, including long-distance running and gymnastics, may consume less than 10 mg of Zn daily. Marginal intake is more widespread among female, as compared with male, athletes who restrict food intake. This behavior is characteristic among groups of athletes who participate in activities in which physical appearance is a component of performance evaluation.\(^{41-43}\)

A general relationship between dietary Zn and plasma Zn in athletes is evident. On the average, athletes who consume at least the EAR for Zn have plasma Zn concentrations within the range of normal values (Table 15.2). This observation is independent of sex and sporting activity. Thus, if an individual consumes adequate dietary Zn, regardless of activity status, plasma Zn is within normal values.\(^{44}\) Conversely, if dietary Zn is marginal, then plasma Zn concentration declines;\(^{16,41}\) the apparent threshold for plasma Zn to decline is 4 mg of Zn/d.\(^{45,46}\) Thus, low dietary Zn is associated with a reduced labile pool of Zn in the plasma and reflects impaired Zn status.

### C. Zinc Losses

#### 1. Surface Loss

Exercise is a stressor that can perturb body Zn homeostasis because it increases Zn loss. Estimates of whole-body Zn loss in sweat in men consuming controlled dietary Zn at 12.7 mg/d and not involved in vigorous activity were variable at 0.8 ± 0.2 (mean ± SE) mg/d and represented about
5% of daily Zn intake. When acute bouts of submaximal exercise (30 min/d) were coupled with daily heat exposure (7.5 h at 37.8°C) for 18 d, Zn loss estimated from measurements of arm sweat of three men decreased appreciably after the first 4 days of acclimatization from 13.7 to 2.2 mg/d, which represented about 18% of the daily Zn intake of 12.5 mg.

The concentration of Zn in sweat depends on the location from which sweat is collected during exercise and the ambient temperature. Zn concentration in sweat collected from 12 men during 30–40 min of strenuous ergocycle work ranged from 12.7 µmol/l at the abdomen as compared with about 7 µmol/l at the arm, chest and back. Variation in sweat Zn concentration by site was considerable, ranging from 50 to 100% among the participants. Arm sweat Zn concentration after 1 h of low-intensity ergocycle work was lower at 35°C than at 25°C (0.8 vs. 1.3 µmol/l) but sweat Zn losses were similar (1.15 vs. 1.06 µg/min) in male and female athletes during submaximal ergocycle exercise, indicating that differences in rate of sweating tend to normalize surface Zn losses. Exercise intensity and duration, therefore, contribute to differences in estimates of Zn loss in sweat. Furthermore, the large variability in estimates of surface loss of Zn suggests contamination of samples may be a problem when evaluating the reported magnitude of Zn lost during exercise.

Increased excretion of Zn in sweat during exercise coincides with moderate reductions in circulating Zn. Men and women exposed to heat for 1 week have decreased serum Zn concentrations. Similarly, men participating in a 20-d marathon road race demonstrated a tendency toward a decrease in serum Zn concentration. It is unclear whether the slight reductions in serum Zn reflect differences in dietary Zn or a modest expansion of plasma volume as an adaptation to chronic exposure to a stressor.

2. Urinary Excretion

Increased Zn excretion in the urine with exercise also has been reported. Studies of untrained men participating in short-duration activity (10 min of stair climbing to exhaustion) or trained men participating in a 10-mi road race observed a 50–60% increase in urinary Zn loss during the first hour after exercise as compared with a similar period of time before the exercise. Similarly, Anderson et al. reported a 50% increase in urinary Zn excretion on the day of exercise as compared with the day before in men performing a 6-mi run. In contrast, another study found no differences in urinary Zn output when trained and untrained men performed high-intensity (90% peak work capacity), brief-duration bouts of treadmill running (30 s run followed by 30 s rest). Urinary Zn excretion, however, returns to pre-exercise values on the day following the exercise bouts. Thus, acute increases in urinary Zn excretion are homeostatically regulated, with commensurate reductions in urinary Zn on the day following the exercise bout.

D. Zinc Redistribution during Exercise

Exercise is a potent stressor that influences circulating Zn concentrations in the blood. In general, short-duration, high-intensity activities induce an immediate increase in plasma and serum Zn concentrations. Longer-duration activities, such as distance runs or skiing, tend to have no immediate effect on plasma or serum Zn, but decreases have been observed in the hours after the activity. These changes in circulating Zn have been interpreted as evidence of redistribution of Zn in the body despite no reports of Zn intake.

Limited data support the hypothesis that exercise induces Zn redistribution. Plasma Zn concentrations, determined before and immediately after progressive peak ergocycle work-capacity tests, changed in response to dietary Zn. Although pre-exercise plasma Zn concentration values (15 µmol/l) were within the range of normal values, they decreased significantly (10.2 µmol/l) when dietary Zn was reduced and increased significantly (16.3 µmol/l) when dietary Zn was increased. Post-exercise plasma Zn concentrations increased significantly after exercise; they
responded similarly to the pre-exercise values to changes in dietary Zn. As compared with the control period, when dietary Zn was adequate, the change in plasma Zn concentration in response to exercise was significantly smaller (8%) when dietary Zn was restricted and significantly larger (19%) when dietary Zn was increased. To correct for the effects of hemocoencentration, plasma Zn concentrations were adjusted for changes in hematocrit and hemoglobin to yield values of change in plasma Zn content. The adjusted values, which were positive (+1%) when dietary Zn was adequate and negative (~8%) when Zn intake was low, have been interpreted to indicate altered Zn mobilization, presumably a release of Zn from muscle Zn stores in association with exercise-induced catabolism when dietary Zn was inadequate. This postulated explanation is consistent with data from animal studies in which slow-twitch muscle Zn was reduced in response to restricted Zn intake.

Alternatively, exercise-induced changes in plasma Zn may be explained by release of Zn from erythrocytes. Ohno et al. found that red blood cell Zn concentration decreased immediately after short-duration, high-intensity ergocycle exercise and returned to pre-exercise values within 1 h. A significant correlation was reported between erythrocyte Zn and α2-macroglobulin Zn in plasma after exercise. Thus, brief physical exercise apparently induces the movement of Zn into the plasma.

Although it is clear that a transient redistribution of Zn occurs during exercise, the mechanism is unclear. Immune factors, such as cytokines, have been shown to change circulating Zn concentrations of rats. Acute exercise induces metallothionein expression in liver and exerts small but significant increases in hepatic Zn with concomitant decreases in plasma Zn.

V. ZINC SUPPLEMENTATION

Zn supplements are used by some athletes to improve performance. Singh et al. found that 21% of elite female runners, despite consuming diet adequate in Zn, consumed Zn supplements to enhance their performance. Although there is evidence that Zn is needed for optimal muscle function, the effects of supplemental Zn on performance are equivocal.

A. PERFORMANCE-ENHANCING EFFECTS

Ex vivo studies of frog skeletal muscle found that Zn added to the media increased muscle strength. This ergogenic effect was associated with increased tension without tetanus and prolonged contraction and relaxation periods of the muscle twitch. The effects of supplemental Zn on muscle function were examined in adult male rats fed a chow-based diet and supplemented with Zn (2 or 4 mg/d) dissolved in water for 30 days. Rats supplemented with 4, as compared with 2 mg Zn, had a greater time to fatigue (19.8 ± 1.0 vs. 16.2 ± 0.8 s). These findings should be viewed with caution because there is no indication that the observed change in performance resulted from an improvement in Zn status or increased activity of Zn-dependent enzymes.

There is limited information about the effects of Zn supplementation on human muscle strength and endurance. Sixteen middle-aged women received a Zn supplement (30 mg/d) and a placebo in a double-blind cross-over design study for 14-d periods. Muscle strength and endurance were measured with an isokinetic one-leg exercise test using a standardized dynamometer before and after each treatment. As compared with placebo, Zn supplementation significantly increased dynamic isokinetic strength and isometric endurance. Because these types of muscular strength and endurance require recruitment of fast-twitch glycolytic muscle fibers, it can be hypothesized that Zn supplementation enhanced activity of the Zn-containing enzyme lactate dehydrogenase. Neither dietary Zn nor Zn status was determined. Thus, it is unclear that Zn supplementation had a physiological or pharmacological effect on the measured indices of performance.

The effects of graded dietary Zn on physical performance also have been evaluated. In untrained men fed diets containing variable Zn contents (3.6, 8.6 and 33.6 mg Zn daily), Zn status indicators...
and peak oxygen uptake were not affected. Rats fed diets containing 5 compared with 50 mg Zn/kg of diet for 3 wk had significantly reduced serum Zn concentrations (10 vs 19 µmol/l) but no decrease in time to exhaustion during treadmill running at a constant speed and elevation. The lack of an effect on physical performance may be explained by the some limitations in experimental design. The brief duration of the experiment might have impacted only circulating but not tissue Zn, particularly the activities of Zn-containing enzymes. The conditions of the endurance test could have favored the rats fed the lower Zn diet if they had significantly reduced body weight, because the intensity of the exercise would have been reduced, thus enabling longer duration of exercise before exhaustion.

In contrast, recent research shows that low Zn status was associated with decrements in physical performance. Men fed a formula-based diet severely low compared with adequate in zinc content (1 vs. 12 mg/d) had significantly decreased serum zinc associated with significant decreases in knee and shoulder extensor and flexor muscle strength. Also, men fed whole-food diets low in zinc (3–4 mg/d) that were consistent with zinc intakes of endurance athletes demonstrated significantly increased ventilation rates and decreased oxygen uptake, carbon dioxide output and respiratory exchange ratio during prolonged submaximal ergocycle exercise. The low-Zn diet was associated with significantly decreased serum Zn concentration and decreased Zn retention. RBC Zn concentration and the activity of carbonic anhydrase, a Zn-dependent enzyme, decreased significantly when the low-Zn diet was consumed. The attenuated oxygen uptake and carbon dioxide elimination, as well as the decreased respiratory exchange ratio, are consistent with previous findings in Zn-deficient men. Thus, Zn deficiency, evidenced by decreased concentrations of blood biochemical measures of Zn nutritional status, adversely affects muscle strength and cardiorespiratory function.

B. ANTIOXIDANT EFFECTS

Recent studies support the hypothesis that Zn possesses antioxidant properties. Results from some human studies indicate that Zn supplementation may benefit only individuals with impaired Zn status. Insulin-dependent diabetic patients with low plasma Zn concentrations supplemented with 30 mg Zn (as Zn gluconate) daily for 3 months had significant increases in plasma Zn and selenium-dependent glutathione peroxidase, and reductions in plasma thiobarbituric acid reactants and plasma copper. In contrast, Zn supplementation (50 mg/d as Zn sulfate for 28 d) of healthy men with normal serum Zn concentrations increased serum Zn with no measurable changes on in vitro low-density lipoprotein oxidation. Beneficial effects of Zn supplementation on physiological function are manifest, therefore, only when Zn status is reduced.

C. ADVERSE EFFECTS OF ZINC SUPPLEMENTATION

Zn supplements are consumed by 20–25% of athletes, which is similar to the estimate of the rate of use by the general population. There is concern that Zn supplements should be used with caution and under the guidance of a physician or a registered dietician. Copper absorption is impaired by Zn supplements providing 22.5 mg/d, even when the supplement is taken independently of meals. RBC superoxide dismutase activity, an index of copper status, is decreased within 12 days of ingesting 50 mg of supplemental Zn daily. Larger doses of Zn supplements, 160 mg/d, taken for 16 weeks, reduce high-density lipoprotein (HDL) concentrations. It has been suggested that use of Zn supplements ranging from 17 to 50 mg/d is sufficient to prevent an exercise-induced increase in HDL concentration.

Recent evidence shows that Zn supplementation at a pharmacological dose (80 mg Zn as Zn oxide) with copper (Cu; 2 mg) for 5 yr to prevent macular degeneration had no adverse effect on hematocrit, Cu or lipids. This level of supplementation was accompanied by dietary Zn intakes...
of 10 mg/d, which is similar to the general population. Thus, the adverse effects of high-dose Zn supplementation on hematology and lipids is offset with adequate Cu intake.

D. SUPPLEMENTATION AND PERFORMANCE TRIALS

Generalized trials of the effects of vitamin and mineral supplementation on human physical performance have reported negligible results. A group of 30 male, trained long-distance runners participated in a 9-month cross-over design experiment in which supplements or placebos were consumed for 3 months, followed by a 3-month period in which no experimental treatment was given; then the treatments were reversed for the final 3 months. On the basis of laboratory and field performance tests, there was no measurable ergogenic effect of multiple vitamin and mineral supplementation. Analyses of self-reported dietary records indicated that nutrient intakes, exclusive of supplements, were adequate based on recommended dietary intake values. Blood biochemical measurements of nutritional status were within ranges of normal values.

Similar results were reported in other studies of 86 competitive Australian athletes (50 men and 36 women) training in basketball, gymnastics, swimming and rowing, and receiving either a placebo or a commercially prepared vitamin and mineral supplement designed for athletes. During the 7–8-month experimental period there was no significant change in serum Zn concentration in either the supplemented or the placebo group (17.1 and 17.8 µmol/l, respectively). Dietary Zn, exclusive of supplementation, was consistent with recommended dietary intake for Australians. Performance, as assessed with a battery of general and sport-specific tests, was not impacted by the supplementation. Therefore, the results of these well-controlled and extensive trials clearly indicate that general supplementation of individuals with adequate dietary intake of Zn provides no measurable improvement of Zn status or physical performance.

VI. DIETARY ZINC

A. Zinc in Foods

Zn content is a major determinant of the adequacy of various foods as sources of Zn for an individual planning a healthful diet. Commonly consumed foods in the U.S. have a highly variable content of Zn (Table 15.3). Animal products (meat, fish and poultry) have the greatest concentration of Zn and provide the principal source of Zn in the U.S. diet. Oysters are the richest source of Zn. Meat from fish has a smaller concentration of Zn than most animal muscle meats. Milk and milk products are important sources of Zn, particularly for infants and children and contribute 19% of the daily Zn intake. Importantly, adipose tissue or fat in animal and dairy products has negligible Zn content. The content of Zn consequently is high in cheese and low in butter and cream.

Cereals represent significant sources of energy and Zn in many areas throughout the world. Large differences in the Zn content, depending on the cereal type and including the variety, class and location of production have been reported. For example, the Zn content of wheat has been found to range from 15–102 mg/kg depending on the strain and from 219–61 mg/kg for the same variety of wheat grown in different locations and different years. Cereal and grain products provide about 13% of the dietary Zn in the U.S. Data for the Zn content of legumes consumed by humans are limited. As with cereals, factors such as variety, strain and growing location impact the Zn content of legumes.

Fruits and vegetables have modest contents of Zn (1–8 mg/kg) because of the high water content of the produce. Because these products provide limited energy intake, their contribution to total daily Zn intake is minimal.
<table>
<thead>
<tr>
<th>Foods</th>
<th>Serving Size</th>
<th>Zinc (mg)</th>
<th>% RDA&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meats and fish</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chuck blade roast, braised</td>
<td>3 oz (85 g)</td>
<td>8.7</td>
<td>79</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>Beef, ground lean, broiled</td>
<td>3 oz (85 g)</td>
<td>5.3</td>
<td>48</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>Steak, T-bone</td>
<td>3 oz (85 g)</td>
<td>4.6</td>
<td>42</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Beef, eye of round, roasted</td>
<td>3 oz (85 g)</td>
<td>4.0</td>
<td>36</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Pork shoulder blade, broiled</td>
<td>3 oz (85 g)</td>
<td>4.3</td>
<td>39</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Pork loin chop, broiled</td>
<td>3 oz (85 g)</td>
<td>1.9</td>
<td>17</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Chicken, drumstick, fried</td>
<td>3 oz (85 g)</td>
<td>2.7</td>
<td>25</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Chicken, dark meat, fried</td>
<td>3 oz (85 g)</td>
<td>1.8</td>
<td>16</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Chicken, breast meat, fried</td>
<td>3 oz (85 g)</td>
<td>0.9</td>
<td>8</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Turkey, dark meat, roasted</td>
<td>3 oz (85 g)</td>
<td>3.8</td>
<td>35</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Turkey, light meat, roasted</td>
<td>3 oz (85 g)</td>
<td>1.7</td>
<td>15</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Tuna, canned in oil</td>
<td>3 oz (85 g)</td>
<td>0.8</td>
<td>7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Haddock, breaded, fried</td>
<td>3 oz (85 g)</td>
<td>0.5</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Lobster, cooked moist heat</td>
<td>3 oz (85 g)</td>
<td>2.5</td>
<td>23</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Shrimp, boiled</td>
<td>3 oz (85 g)</td>
<td>1.3</td>
<td>12</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td><strong>Dairy products</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yogurt, nonfat/fruit flavored</td>
<td>6 oz (170 g)</td>
<td>1.3</td>
<td>12</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Milk, lowfat, 2%</td>
<td>1 cup (244 g)</td>
<td>0.9</td>
<td>8</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Cottage cheese lowfat, 2%</td>
<td>1/2 cup (113 g)</td>
<td>0.5</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td><strong>Cereals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raisin bran</td>
<td>3/4 cup (38 g)</td>
<td>1.1</td>
<td>10</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Corn flakes</td>
<td>1 cup (25 g)</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Grains</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bagel, whole wheat</td>
<td>3 in (55 g)</td>
<td>1.3</td>
<td>12</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Whole wheat bread</td>
<td>1 slice (28 g)</td>
<td>0.5</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Macaroni, boiled</td>
<td>1/2 cup (70 g)</td>
<td>0.4</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Fruits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Banana</td>
<td>8 3/4 in (114 g)</td>
<td>0.2</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Orange, raw</td>
<td>medium (131 g)</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Vegetables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinach, boiled, drained</td>
<td>1/2 cup (90 g)</td>
<td>0.7</td>
<td>6</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Potato, white, baked w/skin</td>
<td>2–3 in (122 g)</td>
<td>0.4</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Broccoli, chopped, raw</td>
<td>1/2 cup (44 g)</td>
<td>0.2</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Carrots, raw</td>
<td>7.5 in (72 g)</td>
<td>0.2</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Tomato</td>
<td>2 in (76 g)</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Beans and Legumes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pork and beans</td>
<td>1/2 cup (126 g)</td>
<td>7.4</td>
<td>67</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>Kidney beans</td>
<td>1/2 cup (86 g)</td>
<td>1.0</td>
<td>9</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>
B. PROCESSING AND PREPARATION OF FOODS

The amount of Zn present in foods is affected by how the fresh product is processed and prepared. Unfortunately, knowledge of nutrient losses during food processing and preparation is limited and generally restricted to vitamins.

The food process that has a major impact on Zn intake is refinement of cereals and grains. Because Zn is located in the outer layers, the germ and bran of grain and cereal kernels, large losses of Zn occur during milling and extraction. For example, about 80% of Zn in wheat is lost during the milling process.85 Similar losses occur during the polishing of rice and in the refining of sugar.

Other pretreatments of foods before cooking or consumption, and cooking procedures themselves, can influence the Zn content of a meal. Use of galvanized cookware and storage of foods in Zn oxide-lined cans adds Zn to foods.86 Zn losses into the storage media may be significant (20%) from foods prepared in water and from foods stored in cans.87

C. ZINC BIOAVAILABILITY

The quantity of dietary Zn that is absorbed by a human is a function of the Zn status of the individual, the amount of Zn ingested and the bioavailability of the Zn from the meal. Bioavailability refers to the combined effects of various promoters and inhibitors of Zn absorption in the foods present in a meal.17 Various nutrients and food components impact human Zn bioavailability.

The amount and type of protein affects human Zn absorption, which is positively related to the amount of protein in a meal, and Zn bioavailability is generally better from foods of animal than plant origin.22 Factors that impact Zn bioavailability from plant foods are fiber and phytic acid.

Fiber in the form of bran has been found to reduce Zn absorption88,89 or to have no effect.90 Differences in particle size of the bran has been suggested to be a factor in these conflicting results.90 In humans, Zn absorption from whole-meal bread was less than half (17%) of that from whole bread (38%), but the Zn content of the whole-meal bread was three times greater than that of the white bread, so the total Zn absorbed was greater from the whole-meal bread.91

Phytic acid also has been shown to interfere with human Zn absorption. Stable isotope studies in humans showed a 50% reduction in Zn absorption when 3 g/d of sodium phytate was added to the diet.92 Zn absorption is inhibited in humans by the presence of excesses of certain minerals. When inorganic salts of iron and Zn are given, Zn absorption is decreased.93 Zn absorption from food was not affected by large amounts of heme iron.94,95

TABLE 15.3 (Continued)
Content and Estimated Contribution to Meeting the Zn Needs of an Individual [%RDA of Zn] in Selected Foods

<table>
<thead>
<tr>
<th>Foods</th>
<th>Serving Size</th>
<th>Zinc (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed dishes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beef cheeseburger, bun</td>
<td>4 oz (95 g)</td>
<td>6.8</td>
</tr>
<tr>
<td>Chile con carne</td>
<td>1 cup (253 g)</td>
<td>3.6</td>
</tr>
<tr>
<td>Lasagna</td>
<td>1 cup (250 g)</td>
<td>3.3</td>
</tr>
<tr>
<td>Spaghetti, meatball and tomato sauce</td>
<td>1 cup (248 g)</td>
<td>2.6</td>
</tr>
<tr>
<td>Macaroni and cheese, prepared from box</td>
<td>3/4 cup (147 g)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*a English units with metric units in parentheses.
*Values estimated by using data provided by U.S. Department of Agriculture81,82
*RDA for ages 19–70 y; men = 11mg, women = 8 mg80

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VII. RESEARCH NEEDS

Specific aspects of the interaction between Zn nutrition and physical activity merit additional study. Because low Zn intakes are common among children and adolescents, and low Zn status is associated with impaired growth and development, future research should focus on determination of relationships among Zn status (intake and blood markers) and physical and mental function. Surveys and Zn supplementation trials of children and adolescents are needed to establish appropriate Zn intakes for optimal physiological and psychological function, and thus contribute to development of a recommendation for Zn in this segment of the population. 

Previous studies examining the effect of increasing physical activity on Zn status markers are hampered by reliance on static measures of Zn status (e.g., plasma or serum Zn). There is a need to evaluate the specificity and sensitivity of newer biochemical indicators in this model. For example, studies of responsiveness of Zn-containing enzymes, including carbonic anhydrase and lactate dehydrogenase, are needed, particularly in association with determinations of metabolites affected by these enzymes.

The need to determine the interaction between dietary Zn and metabolic pools of Zn in response to increasing and decreasing physical activity is obvious. Although limited evidence suggests that the metabolizable Zn pool is affected by dietary Zn restriction, it is unknown whether this pool is impacted by increasing physical activity or different types of exercise (e.g., aerobic vs. strength training).

These proposed investigations are needed to clearly determine whether current dietary recommendations for Zn are appropriate for the growing segment of the population that is initiating and continuing physical activity to promote health and well-being. In addition, fundamental studies to determine whether excretory losses of Zn (sweat, surface, urine and feces) are affected by physical activity are needed.

VIII. CONCLUSIONS

Zn has biological roles in protein, carbohydrate and lipid metabolism and, hence, is needed for health and optimal performance. Experimental evidence describing the interaction of dietary Zn and physical activity in humans is limited. Recent evidence indicates that restricted Zn intake reduces Zn status indicators (serum and RBC Zn and Zn retention), decreases muscle strength and endurance and impairs cardiorespiratory function. Athletes who consume adequate amounts of dietary Zn have plasma or serum Zn concentrations that are within the range of normal values. Conversely, athletes who restrict food intake and concomitantly dietary Zn, have low concentrations of Zn in the circulation. As compared with nonexercise conditions, exercise induces increased losses of Zn in the sweat and urine that represent a small and perhaps significant percentage of daily Zn intake. Because the body tends to maintain the Zn content by selectively adjusting absorption and endogenous excretion of Zn, and an adaptation in urinary Zn output occurs on the day following a bout of exercise, the losses of Zn associated with heavy exercise probably are compensated. Proper selection of a variety of foods with varied Zn content, including animal products, unprocessed grains and cereals, will ensure an adequate Zn intake. Unequivocal evidence of beneficial effects of Zn supplementation on physical performance of humans is lacking if Zn intake meets population recommendations.

Consumption of Zn supplements by individuals with adequate Zn status might cause harm by inducing copper deficiency. Without biochemical or physical evidence of altered Zn status, individuals should avoid the use of Zn supplements in amounts exceeding 15 mg/d. Consumption of supplemental Zn in amounts of 50–150 mg/d can lead to impaired copper absorption and decreased HDL cholesterol, unless Cu supplements are consumed concomitantly. Because Zn impacts many diverse biological functions, physically active people should attempt to consume a balanced diet to ensure an adequate Zn intake and thus optimize health and physical performance.
REFERENCES


75. Goodwin, J.S., Hunt, W.C., Hooper, P. and Garry, P.J., Relationship between zinc intake, physical activity and blood levels of high-density lipoprotein cholesterol in a healthy elderly population, Metabolism 34, 519–523, 1985.


