INTRODUCTION

Interest in zinc nutrition was aroused 25 years ago when Zn deficiency, related primarily to diet, was shown to be the cause of dwarfism and hypogonadism among adolescents from the lowest social classes of Egypt and Iran (see Prasad, 1984). Since then a considerable amount of research has been carried out on Zn in order to understand its role in human nutrition. This review will attempt to summarize our present-day knowledge of Zn, concentrating primarily on the most active and exciting areas of research that have evolved over the past few years. Where possible, review articles will be cited to which the reader may refer to gain a fuller insight into a particular aspect of Zn nutrition. After a brief description of the biochemistry and metabolism of Zn, the most-recent evidence of problems in Zn nutrition will be presented. The reasons for their existence will be examined, together with a résumé of the various approaches taken to improve our understanding of Zn.

BIOCHEMISTRY AND METABOLISM OF ZN

The total amount of Zn in the human adult has been estimated to be approximately 2 g. More than 80% of this is found in bone, muscle, hair and skin, and a large number of enzymes require Zn for maximum catalytic activity, e.g., alcohol dehydrogenase (EC 1.1.1.1), RNA nucleotidyltransferases and alkaline phosphatase (EC 3.1.3.1). In addition, Zn may have a structural role, e.g. in superoxide dismutase (EC 1.15.1.1), and alcohol dehydrogenase, where it is bound to the apoprotein in fixed stoichiometric ratios. Zn plays a fundamental role in expression of the genetic potential; the synthesis, repair and structural integrity of nucleic acids require Zn. Therefore, it is not surprising that deficiency of Zn reduces growth in almost all biological systems via decreased cell replication. Initially this was attributed to the observation that DNA polymerase (EC 2.7.7.7) contains Zn as a functional component, but more-recent suggestions have been put forward implicating
other enzymes such as thymidine kinase (*EC* 2.7.1.21) (Cousins, 1986). The role of Zn in brain development and function has been reviewed by Sandstead (1985) and Wallwork (1987).

Zn is also involved in stabilizing membrane structures and in protection at the cellular level by preventing lipid peroxidation and reducing free-radical formation (Coppen *et al.* 1985). The latter function probably arises from the fact that the Zn-thiolate clusters in metallothionein are efficient at scavenging free hydroxyl radicals (Thornalley & Vasak, 1985).

Zn absorption has been reviewed by Kirchgessner & Weigand (1983) and Cousins (1985). Reports on the relative contribution of the different sections of the intestine vary, and it has been suggested that the major site of absorption might shift with differences in food matrix and body Zn status. Absorption can occur throughout the total length of the small intestine, but colonic absorption is limited (Sandstrom *et al.* 1986). Fractional Zn absorption falls with increasing dose (Istfan *et al.* 1983), but increases fairly rapidly in response to reductions in dietary Zn intake (Wada *et al.* 1985). Mechanisms of Zn absorption and homeostasis are a topic of debate and are based mainly on rat studies. Recent findings suggest that Zn uptake across the brush-border surface may occur partly by a regulated carrier-mediated diffusion mechanism, which responds homeostatically to the dietary Zn supply. Transport kinetics show evidence of both passive and saturable processes, but with Zn deficiency a greater portion of the total transport is via the saturable component. Above a certain lumen concentration transport may take place by passive diffusion (Menard & Cousins, 1983). The biphasic nature of Zn absorption is discussed by Solomons & Cousins (1984). The control of Zn homeostasis may operate via an increase in intestinal transport (Menard & Cousins, 1983) or a decrease in endogenous secretions of Zn into the intestine (Matseshe *et al.* 1980) and in sweat (Milne *et al.* 1983), or both. Jackson *et al.* (1984) have proposed that small daily variations in Zn intake are dealt with by alterations in gastrointestinal secretion of Zn, which is a rapidly responding mechanism, but that larger changes in Zn intake can only be adequately dealt with by changes in absorption. Although the latter is slower to take effect, it has a greater capacity to cope with large fluctuations in dietary Zn.

There are three stages in Zn absorption. First the Zn is chelated in the intestinal lumen by an endogenous factor before uptake at the brush border. The Zn is then transferred intracellularly by Zn-binding ligands (ZBL), such as low-molecular-weight ZBL, metallothionein (MT), and high-molecular-weight ZBL. Song (1987) suggests that the low-molecular-weight ZBL is a key regulator of intestinal Zn absorption, but the identity of this ligand is a matter of controversy. Seal & Heaton (1987) have isolated two proteins from rat mucosal cytosol that bind Zn. They concluded from their studies with Zn that Zn entering the cytoplasm rapidly binds to a protein of molecular weight 6500 and is then actively transferred to a protein of molecular weight 45000. Finally, the Zn is removed from the basolateral membrane of the epithelial cells to enter the systemic circulation.

Approximately 65% of portal plasma Zn is associated with albumin, and the remainder with other proteins, notably α-2-macroglobulin and transferrin. Once absorbed, substantial amounts of Zn are taken up by the liver, then subsequently redistributed to other tissues, primarily bone and muscle. Since bone mineralization and reabsorption are controlled by the endocrine system which maintains calcium balance, Zn deposited in the mineralized matrix of bone cells is not readily mobilized. In contrast, a substantial amount of Zn may be supplied from the catabolism of muscle tissue for short-term redistribution to appropriate cellular sites. Hepatocytes are in dynamic equilibrium with the plasma Zn supply and contain two intracellular pools, the smaller of which is labile and may serve as an initial intermediate in Zn metabolism by hepatocytes as well as more general aspects of
Table 1. Techniques used to measure zinc absorption

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolic balance</td>
<td>(a) Retention from complete diet can be measured</td>
<td>(a) Measures retention only</td>
</tr>
<tr>
<td></td>
<td>(b) Generates useful information for estimating Zn requirements</td>
<td>(b) Small errors in intake or excretion lead to large errors in calculated retention</td>
</tr>
<tr>
<td>$^{65}$Zn and whole-body counting</td>
<td>(a) Assuming no problems with counting geometry, simple and accurate technique</td>
<td>(a) Correction required for endogenous $^{65}$Zn losses</td>
</tr>
<tr>
<td></td>
<td>(b) Can be used for single foods or meals</td>
<td>(b) Whole-body gamma counter required</td>
</tr>
<tr>
<td>$^{65}$Zn balance</td>
<td>Can be used for single foods or meals</td>
<td>(c) Restricted application because of hazards of ionizing radiation</td>
</tr>
<tr>
<td>Stable-isotope balance</td>
<td>(a) Can be used safely in all human subjects</td>
<td>(a) Correction required for endogenous $^{65}$Zn losses</td>
</tr>
<tr>
<td></td>
<td>(b) Multi-isotope studies possible</td>
<td>(b) Less accurate than whole-body counting</td>
</tr>
<tr>
<td></td>
<td>(c) Time constraints of radioisotope work not applicable</td>
<td>(a) Corrections required for naturally occurring stable isotope, and endogenous losses</td>
</tr>
<tr>
<td>Plasma Zn tolerance curves</td>
<td>(a) Quick, easy method</td>
<td>(b) Measurement of stable isotopes more exacting than radioisotopes</td>
</tr>
<tr>
<td></td>
<td>(b) Expensive hardware not required</td>
<td>(c) Suitable mass spectrometer required</td>
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<tr>
<td></td>
<td></td>
<td>(a) Qualitative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b) Non-physiological doses required</td>
</tr>
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<td></td>
<td></td>
<td>(c) Interpretation of results difficult</td>
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</table>

liver function related to Zn (Pattison & Cousins, 1986). Most of the Zn in the systemic circulation is localized in erythrocytes and leucocytes (80–90%), erythrocyte Zn but not leucocyte Zn being exchangeable with plasma Zn. Wastney et al. (1986) carried out a detailed analysis of the kinetics of Zn metabolism in adult subjects given oral or intravenous $^{65}$Zn, and identified five major sites at which Zn metabolism is regulated, namely absorption in the gut, excretion in the urine, exchange with erythrocytes and muscle, and secretion into the gut.

TECHNIQUES USED TO MEASURE ZINC ABSORPTION

A number of different approaches have been used to study Zn absorption. These are summarized in Table 1, together with an indication of their major advantages or disadvantages.

Metabolic balance studies tend to underestimate absorption since a considerable portion of faecal Zn is endogenous, derived from pancreatic juice, bile and intestinal secretions (Mateshe et al. 1980), rather than unabsorbed dietary Zn.

Zn retention can be accurately measured using $^{65}$Zn and a whole-body gamma counter (see Lykken, 1983), but does not usually equate with absorption because of the complexities of Zn metabolism. However, retention values can be corrected for endogenous excretion of absorbed radioactivity by a simple mathematical operation (Arvidsson et al. 1978). Payton et al. (1982) have developed an alternative method whereby Zn absorption can be measured from a single stool specimen collected 24–72 h after an oral dose of a $^{65}$Zn-labelled Zn salt.
ingested with a non-absorbed radioactive marker, namely \(^{51}\text{Cr}\). The two isotopes have similar intestinal transit times, thus allowing correction for endogenous \(^{65}\text{Zn}\) losses, and the method has been successfully used to measure \(\text{Zn}\) absorption from turkey meat (Flanagan \textit{et al.} 1985).

Interest in the use of enriched sources of stable isotopes of \(\text{Zn}\) to study \(\text{Zn}\) absorption has increased during the last few years. Three of the stable isotopes can be measured by neutron-activation analysis (Janghorbani \& Young, 1982), but this method requires direct access to a neutron source plus pre- and post-irradiation sample clean-up to remove interfering isotopes. These difficulties have stimulated research into alternative methods using mass spectrometry. All the stable isotopes can be measured by mass spectrometry, e.g. thermal ionization (Turnland \textit{et al.} 1984), fast atom bombardment (Fairweather-Tait \textit{et al.} 1988; Peirce \textit{et al.} 1987) and inductively-coupled plasma mass spectrometry (Date \& Gray, 1983).

The plasma \(\text{Zn}\)-tolerance method has been criticised because the plasma \(\text{Zn}\) levels reflect the rate of oral \(\text{Zn}\) entering the circulation and removal of \(\text{Zn}\) from the plasma to the tissues. Molokhia \textit{et al.} (1980) circumvented the problem of giving non-physiological doses of \(\text{Zn}\) by using the short-lived radioisotope \(^{69}\text{Zn}\) to calculate \(\text{Zn}\) absorption by deconvolution after oral and intravenously-administered doses.

**EVIDENCE OF PROBLEMS ASSOCIATED WITH ZINC NUTRITION**

It is apparent from the literature that certain groups of people are at risk with regard to \(\text{Zn}\) nutrition. There are a number of reasons for their vulnerability, including inadequate intake or low bioavailability, malabsorption, elevated losses (particularly associated with certain clinical conditions), or elevated requirements to support growth, pregnancy and lactation. The diagnosis of \(\text{Zn}\) deficiency is not easy as there is no single definitive test that can be used to assess \(\text{Zn}\) status (as discussed in detail, see p. 30). The case for \(\text{Zn}\) deficiency or the risk of it occurring, therefore, rests in many instances on circumstantial evidence, such as growth retardation which is reversed with \(\text{Zn}\) supplements, or low plasma \(\text{Zn}\) levels.

A number of clinical conditions predispose individuals to \(\text{Zn}\) deficiency. Clearly, the anorexia associated with some malignant illnesses results in a low intake of \(\text{Zn}\), and the administration of total-parenteral-nutrition solutions not containing \(\text{Zn}\) will precipitate \(\text{Zn}\)-deficient states (Takagi \textit{et al.} 1986). Anorexia nervosa leads to a low tissue \(\text{Zn}\) state, but is unlikely to cause overt \(\text{Zn}\) deficiency except in extreme cases (Ainley \textit{et al.} 1986). Alcoholics and patients with liver disease generally exhibit hyperzincuria (Sullivan \& Lankford, 1965), have low leucocyte \(\text{Zn}\) levels (Keeling \textit{et al.} 1982), and a reduced absorptive capacity for \(\text{Zn}\) (Dinsmore \textit{et al.} 1985). Preliminary findings suggest that patients with pancreatic insufficiency also have impaired \(\text{Zn}\) absorption (Watson \textit{et al.} 1988). Renal patients have been shown to have reduced serum \(\text{Zn}\) concentrations, particularly with severe renal failure (Burge \textit{et al.} 1984), but no explanation has been given for this observation. There is accumulating evidence that diabetes mellitus may lead to mild \(\text{Zn}\) deficiency (Mooradian \& Morley, 1987), which is currently thought to be due to the combination of hyperzincuria and slightly impaired \(\text{Zn}\) absorption. Finally, the effect of trauma on \(\text{Zn}\) metabolism must be mentioned. Patients with burns or other skin disorders have a high dermal loss of \(\text{Zn}\). In addition, any stress or trauma that causes loss of body protein, such as operative procedures, will at the same time result in loss of body \(\text{Zn}\), mainly via the urine. At the same time there is a fall in serum \(\text{Zn}\) which is thought to reflect the movement of \(\text{Zn}\) to the liver and wound areas. The usefulness of therapeutic doses of \(\text{Zn}\) to maintain serum \(\text{Zn}\) levels is under debate since most research groups find that the fall
in serum Zn is not prevented even when the Zn is administered before the operation (Jiang et al. 1985).

Two genetic disorders have been linked to Zn deficiency. Acrodermatitis enteropathica, a recessive trait that is more commonly found amongst infants of Italian, Armenian or Iranian lineage, develops in the early months of life, and is fatal if untreated. The symptoms can be reversed with Zn supplementation, since the underlying cause of Zn deficiency is malabsorption. Patients with sickle-cell anaemia are often Zn deficient, probably due to an inadequate intake coupled with hyperzincuria.

Apart from people with genetic or clinical disorders, certain apparently-healthy members of the population may be susceptible to Zn deficiency. These include infants, growing children, and pregnant and lactating women, whose requirements are especially high in order to support growth. The elderly are also at risk, but for different reasons, namely low intakes of Zn and a reduced efficiency of absorption (Turnland et al. 1986). The latter observation may of course merely reflect a lower requirement for Zn by the elderly. However, Thomas et al. (1988) carried out duplicate diet analyses of long-stay hospital patients, aged 63–89 years, and found the mean Zn intake to be 5.5 mg d, which they concluded was low in comparison with levels of intake from healthy elderly people in metabolic equilibrium. The leucocyte Zn concentrations of long-stay patients were also low, particularly in those with leg ulcers or pressure sores, implying suboptimal Zn status.

Infants, especially those born prematurely, are susceptible to Zn deficiency (for review see Hambidge, 1986). Zn in human milk has a higher bioavailability than cow’s milk, but infant formulas generally contain a much-higher level of Zn than that found in breast-milk in order to compensate for the lower absorption. Friel et al. (1985) examined nutrient intakes and growth in preterm and full-term infants, and found that Zn intake played a more-important role in explaining the height at 3 months and weight at 12 months than did any of the other measured variables. Walravens et al. (1988) found that infants aged 6–24 months with failure to thrive of primarily nutritional origin benefited from a daily 5 mg Zn supplement in terms of weight-for-age (males and females) and height-for-age (females only). Golden et al. (1985) demonstrated that inadequate Zn intake may be a limiting factor in the growth of severely malnourished infants, and Castillo-Duran et al. (1987) found that marasmic infants given Zn supplements (2 mg/d) had an enhanced weight gain during recovery which was unrelated to food intake. Zn also had a beneficial effect on infectious morbidity and host defence, a finding that has important clinical implications for the treatment of protein–energy malnutrition in developing countries.

Suboptimal Zn nutriture has been found in preschool children in Canada (Vanderkooy & Gibson, 1987). Boys with low hair Zn concentrations had a lower mean height-for-age percentile, and consumed less meat and fish but more Ca in their diet. Meat is considered to be one of the best sources of available Zn, and Ca may interfere with Zn absorption. Thus an inappropriate diet at this critical age may cause some problems associated with poor Zn nutrition. The second National Health and Nutrition Examination Survey (Pilch & Senti, 1985) found that 3.3% of 3–8-year-old boys had low serum Zn levels, and that this was the age-group most at risk amongst males. A greater percentage of girls aged 3–8 years had lower Zn levels than 9–19 year olds, although amongst females the age-range with the highest percentage of low serum Zn levels was 20–44 years. It appears that boys have a higher requirement for Zn than girls, possibly related to their faster growth rate. Zn supplements have been used with success in 7–13-year-old children in the USA of short stature with significantly-retarded bone age (Ghavami-Maibodi et al. 1983), when it was noted that hair Zn levels, which were initially low, increased during the course of supplementation. Unfortunately, no information regarding dietary Zn intakes was given.
There is considerable interest in the role of Zn in reproduction (Apgar, 1985). Since the drastic effects of severe maternal Zn deficiency on the rat fetus were demonstrated (Hurley, 1985), attempts have been made to assess the effect of suboptimal Zn nutriture on fetal development in humans. Although it is extremely unlikely that pregnant women ever undergo Zn depletion as severe as that used in the earlier studies on laboratory animals, several studies support the hypothesis that low birth weight is in some way linked to poor Zn nutrition during pregnancy (Simm & Thompson, 1986).

Intrauterine growth retardation has been linked to low polymorphonuclear (PMN) Zn concentrations, and 85% of mothers having small-for-gestational-age infants were selected from low maternal PMN Zn levels or smoking during pregnancy, or both (Simm & Thompson, 1985). When nutrient intake during the last trimester of pregnancy was assessed by dietary recall in mothers shortly after birth, low Zn intake was found to be significantly associated with intrauterine growth retardation (Simm et al. 1987). Maternal plasma Zn levels have been shown to be negatively correlated with birth weight in vegetarian women (Abu-Assal & Craig, 1984) and also women in Australia (McMichael et al. 1982), but the validity of assessing Zn status by means of plasma Zn levels in pregnancy is questionable. Ward et al. (1987) analysed placentas from 100 women who had obstetrically normal births and found that placental Zn concentrations were positively correlated with birth weight and head circumference over the lower end of the 'normal' range.

Oral Zn supplements (20 mg/d from the 12th week onwards) have been shown to reduce the overall complication rate for both mother and fetus, in particular small- or large-for-gestational-age infants (Kynast & Saling, 1986). However, by 12 weeks the development of most of the fetal tissues and organs is complete and subsequent Zn deprivation will have an adverse effect on fetal growth rather than a teratogenic effect.

The effect of maternal Zn status on pregnancy outcome obviously depends on the degree of deficiency, since a number of investigators have failed to show any link between Zn nutrition and birthweight. Hunt et al. (1985) supplemented low-income teenagers of Mexican descent (mean dietary intake of 10 mg Zn/d) with 20 mg Zn daily throughout pregnancy, but Zn supplementation did not affect the outcome of pregnancy compared with controls. A similar study was performed by Hambidge et al. (1983) who gave a supplement of 11 mg Zn/d but found no effect on pregnancy outcome or birth weight. Tuttle et al. (1985) found no association between intravascular mass of Zn and percentile-birth-weight distribution in women taking in 9 mg Zn/d, and Campbell-Brown et al. (1985) were unable to demonstrate any association between birth weight and Zn status in pregnant Hindu Asians and indigenous Europeans.

Many studies show that women do not increase their Zn intakes during pregnancy, yet the demand for absorbed Zn increases by up to 0·6 mg/d during late gestation (Swanson & King, 1987). Results from rat studies suggest that there is an adaptive response to meet the increased demands of pregnancy in terms of increased absorption (Fairweather-Tait et al. 1984), but there appears to be no conservation of body Zn by means of reduced Zn turnover (Fairweather-Tait et al. 1985). In humans, no evidence for adaptive changes has yet been described and Swanson et al. (1983) found no effect of diet or pregnancy on Zn absorption.

The observed decline in circulating Zn in pregnancy is normal and reflects maternal–fetal transfer of Zn and expansion of maternal plasma volume. Zimmerman et al. (1984) contend that each of the major transport proteins for Zn has a specific role in Zn homeostasis, and that the pool of loosely bound Zn carried by albumin and amino acids (principally histidine and cysteine) is likely to provide rapid exchange of Zn to the placenta and fetus. Thus total plasma Zn levels are probably not a very useful measure of Zn metabolism in pregnancy.

Another area of concern is the effect of iron supplementation in pregnancy on Zn status. Meadows et al. (1983) demonstrated a fall in Zn absorption as a result of previous
administration of Fe. The fact that the Fe and Zn were not administered together led the authors to suggest that the Fe was interfering with Zn absorption at the level of the intestinal mucosa rather than in the lumen, but the doses of Zn used for the absorption test were well above dietary levels. More recently, this research group has confirmed their original findings using smaller doses of Zn (25 mg), and at the same time have shown that folate also interferes with Zn absorption (Simmer et al. 1987b). However, they used plasma Zn changes to give a quantitative estimate of absorption, which is not the method of choice. Sheldon et al. (1985) found that Fe supplements did not influence the changes in serum Zn levels seen in healthy or insulin-dependent diabetic mothers, but it is not known to what extent serum Zn represents metabolically-active Zn.

Following birth, maternal plasma Zn concentrations gradually return to pre-conception values, but in lactating women they are still lower than non-pregnant controls 9 weeks after birth (Qvist et al. 1986). Clearly, lactation imposes a drain on maternal Zn, but the fact that breast-milk Zn concentrations progressively fall over time may reflect a homeostatic mechanism for conserving maternal Zn (Krebs & Hambidge, 1986).

**BIOAVAILABILITY OF ZINC**

Zn is not fully absorbed from the diet, the actual amount being dependent on a number of dietary and physiological variables. Estimates of bioavailability are generally made from studies of absorption and retention, and a comprehensive review on this topic has been published recently (Solomons, 1982). The reader is also referred to a symposium sponsored by the American Chemical Society which was held on nutritional bioavailability of Zn in 1982 (Inglett, 1983).

The physicochemical form of Zn in a food is an important determinant of its bioavailability, but may be significantly modified by certain dietary constituents, as indicated in Table 2. Most substances reduce Zn availability by combining with soluble Zn in the intestinal lumen to form an unabsorbable complex. The most-potent inhibitor of Zn absorption of practical significance is probably phytic acid (myo-inositol hexaphosphate), found in most cereal grains and seed legumes.

A number of studies have shown that wheat bran reduces Zn absorption (e.g. Farah et al. 1984), which is thought to be primarily due to its high phytate content, since Zn absorption increases when the phytate content of bread is reduced by fermentation (Navert et al. 1985). The effect of phytate on Zn absorption largely depends on the phytate:Zn molar ratio as illustrated by the work of Turnland et al. (1984). Although Ca per se probably does not affect Zn bioavailability (Spencer et al. 1983), Ca is important in the presence of phytate since Ca–Zn–phytate complex is more insoluble than that formed by either element when combined separately with phytate. Ellis et al. (1987) have suggested that the critical values of phytate:Zn and phytate×Ca:Zn molar ratios are > 10 and > 200 respectively. Most omnivorous diets have ratios well below these, but certain diets may exceed this threshold, notably lacto-ovo vegetarian diets. Foods which may make a significant contribution towards reaching these critical ratios include unleavened wholemeal chapatti bread, tanok, untoasted muesli, soya-bean flour, health-food snack bars, and dairy products (Bindra et al. 1986; McKenzie-Parnell & Guthrie, 1986). Since meat is an important source of Zn in the diet, the substitution of meat with soya-bean products, usually high in phytate, may create problems with Zn nutrition, but this depends on the degree of replacement (Sandstrom et al. 1987b), and the composition of the rest of the diet. Cossack & Prasad (1983) concluded from their studies that 15 mg dietary Zn may not be sufficient to meet the daily requirement for adults if soya-bean protein is the major source of protein.

Other dietary constituents that significantly reduce Zn availability include oxalic acid,
Table 2. Dietary factors affecting zinc bioavailability

<table>
<thead>
<tr>
<th>Inhibitors</th>
<th>Enhancers</th>
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<tr>
<td>Phytate (plus calcium)</td>
<td>Congeners in red wine</td>
</tr>
<tr>
<td>High-fibre foods, especially bran</td>
<td>Histidine</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>Animal protein</td>
</tr>
<tr>
<td>Oxalate</td>
<td></td>
</tr>
<tr>
<td>Orange juice (ascorbic acid?)</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td></td>
</tr>
<tr>
<td>Maillard reaction products</td>
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</table>

but probably only in the presence of dietary fibre (Kelsay, 1983), hemicellulose (Drews et al. 1979), orange juice, (active constituent ascorbic acid?) (Flanagan et al. 1985), and other inorganic elements that compete with Zn for absorption, e.g. Fe (Solomons & Jacobs, 1981), and tin (Solomons et al. 1983). Processing of food can also affect Zn bioavailability. The observation that Zn absorption was lower from browned cornflakes than the untoasted product was thought to be due to the presence of Maillard reaction products (Lykken et al. 1986). Extrusion cooking of a high-fibre cereal product reduced Zn availability in ileostomy subjects (Kivisto et al. 1986), which was attributed to the deactivation of bran phytase (EC 3.1.3.26) on extrusion cooking, but not in normal adults (Fairweather-Tait et al. 1988). The different results obtained in the latter two studies are probably due to chemical differences in the cereal products or physiological differences between the two groups of subjects.

A few substances have been shown to increase Zn availability, and these include the congeners of red wine (McDonald & Margen, 1980), the amino acid histidine (Scholmerich et al. 1987), and animal proteins such as those present in milk and cheese (Frohlich & Sandstrom, 1983).

DIAGNOSIS OF ZINC DEFICIENCY AND ASSESSMENT OF STATUS

There is a wide spectrum of clinical manifestations of Zn deficiency, depending on the degree of severity (Prasad, 1985). Laboratory diagnosis of severe deficiency is relatively simple, but marginal Zn deficiency is extremely difficult to confirm due to the lack of suitable methods of assessing Zn status. Various attempts have been made to develop a sensitive and reliable measure of Zn status as summarized in Table 3, but as yet there is no single method available. At present, the best indication of Zn deficiency is the biochemical and clinical response made to Zn supplements, but this is essentially retrospective. The level of Zn in plasma (or serum) does not always reflect body Zn status. Apart from diurnal fluctuations, there are other conditions, unrelated to Zn nutrition, that cause changes in plasma levels, e.g. the fall associated with infection, and with the use of oral contraceptives (King, 1987). Therefore, plasma Zn concentrations must be interpreted cautiously. Leucocyte Zn is a very-useful indicator of Zn status (Patrick & Dervish, 1984), but requires technical skill and a fairly large volume of blood. Bunker et al. (1984) have published values for leucocyte Zn in a group of elderly people which should serve as a useful reference standard. Serum alkaline phosphatase is low in Zn deficiency and rises following Zn therapy, indicating that serial determinations may be a useful aid in diagnosing Zn deficiency (Weismann & Hoyer, 1985; Baer et al. 1985). An alternative approach to the
Table 3. Some of the techniques used to assess zinc status

<table>
<thead>
<tr>
<th>Useful indices</th>
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<tbody>
<tr>
<td>Biochemical and clinical response to Zn supplements</td>
</tr>
<tr>
<td>Plasma or serum Zn</td>
</tr>
<tr>
<td>Leucocyte Zn</td>
</tr>
<tr>
<td>Plasma or serum alkaline phosphatase (EC 3.1.3.1)</td>
</tr>
<tr>
<td>Erythrocyte metallothionein</td>
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<tr>
<td>Urinary metallothionein</td>
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Less-reliable measures

| Erythrocyte Zn                                      |
| Hair Zn                                            |
| Salivary Zn                                        |
| Fingernail Zn                                      |
| Urinary Zn                                         |
| Sweat Zn                                           |
| Erythrocyte carbonic anhydrase (EC 4.2.1.1)        |
| Platelet aggregation                               |
| Zn tolerance tests                                 |
| Taste acuity                                       |
| Dark adaptation                                    |

problem of assessing Zn status lies in the recent development of a radioimmunoassay to measure metallothionein in rats (Bremner et al. 1987a). Metallothionein is an important metal-binding protein that occurs in varying amounts in a wide range of tissues (Bremner, 1987a) its concentration being affected by exposure to many elements. The biological function of metallothionein is still a matter of considerable conjecture (Bremner, 1987b), but experiments to date have shown that the concentration of metallothionein in the blood and urine of rats appears to reflect body Zn status, unaffected by food restriction or cold stress (Bremner et al. 1987b). It may, therefore, be a useful aid in the diagnosis of Zn deficiency, once suitable radioimmunoassays are available for human studies.

The usefulness of other measures of Zn status is open to some debate (see Solomons, 1979). Medeiros et al. (1987) failed to show any effect of Zn supplementation on hair Zn levels in men of adequate Zn status, thereby eliminating hair Zn as an indicator of status in non-Zn-deficient subjects. Hair Zn concentrations depend not only on the delivery of Zn to the root, but also on the rate of hair growth, and Zn deficiency itself may impair the growth of hair, and actually result in increased Zn concentrations. Platelet aggregation has been shown to be impaired when plasma Zn levels are low following Zn deprivation, but is restored to normal within 19 h of Zn supplementation (Gordon et al. 1982). Further work is required to assess the importance of this finding. Zn tolerance tests (Fickel et al. 1986), taste acuity (Bales et al. 1986), and dark adaptation (Sandstrom et al. 1987a) are not good measures of Zn status.

REQUIREMENTS FOR ZINC

Human Zn requirements and recommended dietary allowances are controversial issues. The USA is one of the few countries at present that publishes official values for Zn (National Academy of Sciences, 1980) (see Table 4) and these are currently under review. Requirements for Zn are assessed by means of balance studies, from measurements of tissue endogenous losses, and from the functional response to a marginal Zn intake. Recommended allowances are then calculated from the estimated requirements, to be adequate to meet the known nutritional needs of practically all healthy persons. It is
important to remember that they are set at levels sufficiently above the average physiological requirement to just exceed the upper range of needs of almost all individuals of a given age and sex category, i.e. two standard deviations above the mean value of requirements, and encompassing all but 2.5% of the range of individual requirements.

Regarding the question of bioavailability, an expert committee set up by the World Health Organization (1973) suggested three levels of Zn intake for each age-group, depending on the bioavailability of Zn in the diet. Thus, they categorized diets as containing Zn of 10, 20 or 40% bioavailability. The highest value is roughly equivalent to a Western diet, and the lowest value is that found in a diet containing substantial amounts of inhibitors, such as phytate from wheat bran, plus low intakes of meat. This approach serves to emphasize the importance of bioavailability and illustrates how dietary bioavailability may be the predisposing factor in determining whether or not the Zn intake of a group of people satisfies their requirements.

King (1986) presents preliminary evidence to suggest that tissue Zn status influences endogenous losses, and therefore the dietary need. Thus individuals in good status may require higher amounts of Zn in their diets than individuals in poor status. In addition, there is clear evidence that man can adapt to reductions in Zn intake by reducing urinary and faecal excretion. There are many dietary studies in which the mean Zn intake of an apparently healthy group of subjects is well below the recommended level (Record et al. 1985; Thomas et al. 1986). The high intakes recommended for pregnancy appear to present a particular problem, and it is unlikely that they can be achieved without dietary supplementation of the whole female population (Taper et al. 1985), an option that has been rejected by Hytten (1985). Allowances for lactation are even higher. Krebs & Hambidge (1986) found that women receiving 25 mg Zn/d had a slower rate of decline in milk zinc concentration than those receiving 11 mg/d but only after 6 months, which is the

Table 4. Recommended daily dietary allowances for zinc (mg)

<table>
<thead>
<tr>
<th>Category</th>
<th>Age (years)</th>
<th>Zn (mg)</th>
<th>WHO (1973)</th>
<th>Bioavailability of Zn in the diet (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infants</td>
<td>0-0.5</td>
<td>3</td>
<td>10</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>0.5-1.0</td>
<td>5</td>
<td>20</td>
<td>11.0</td>
</tr>
<tr>
<td>Boys</td>
<td>1-10</td>
<td>10</td>
<td>40</td>
<td>16.0</td>
</tr>
<tr>
<td>Girls</td>
<td>1-10</td>
<td>10</td>
<td>1-9</td>
<td>15.5</td>
</tr>
<tr>
<td>Males</td>
<td>11-14</td>
<td>15</td>
<td>11-17</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td>15-18</td>
<td>18</td>
<td>18+</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>19+</td>
<td>15</td>
<td>14+</td>
<td>26.5</td>
</tr>
<tr>
<td>Females</td>
<td>11+</td>
<td>15</td>
<td>10-13</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14+</td>
<td>22.0</td>
</tr>
<tr>
<td>Pregnant</td>
<td>—</td>
<td>20</td>
<td>0-20 week</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20-30 week</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30-40 week</td>
<td>30.0</td>
</tr>
<tr>
<td>Lactating</td>
<td>—</td>
<td>25</td>
<td>—</td>
<td>54.5</td>
</tr>
</tbody>
</table>

NAS, National Academy of Sciences; WHO, World Health Organization.
time by which most infants are weaned. In fact, Ruz (1984) contends that it is impossible for infants up to 6 months to achieve the recommended level of 3 mg/d from breast-milk alone. It will not be possible to settle the arguments surrounding Zn requirements until there are reliable measures of Zn status that can be routinely used. Clearly, a great deal more research is needed in order improve our understanding of the role of Zn in human nutrition.

REFERENCES


