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*Chapter 13*

# Boron in human and animal nutrition

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**Abstract**

This review describes the findings from human and animal studies indicating that B is a dynamic trace element which, in physiological amounts, can affect the metabolism or utilisation of numerous other substances involved in life processes including macrominerals, energy substrates such as triglycerides and glucose, nitrogen containing substances such as amino acids and proteins, reactive oxygen species, and estrogen. Through these effects, B can affect the function or composition of several body systems, including the brain, skeleton and immune system, generally in a beneficial fashion. Moreover, homeostatic mechanisms apparently exist for B because it is rapidly excreted in the urine, does not accumulate in tissues, and is maintained in a relatively narrow range of concentrations in blood of healthy individuals. Thus, even though B has not been conclusively established as essential because a biochemical function for it has not been identified, its beneficial actions suggest that an intake of over 1 mg $day^{-1}$ (but probably not more than 13 mg $day^{-1}$) is desirable; diets low in fruits, vegetables, legumes and nuts may not provide this amount of B. Boron may be of more practical nutritional importance than currently acknowledged.

## Brief introduction and early history of boron in food and nutrition

Since 1857, B has been known to be present in plants (Ploquin, 1967). Thus, B is a constant constituent of foods. The recognition that there are benefits and detriments to having B present in foods apparently began in the 1870s. At that time it was discovered that borax (sodium borate) and boric acid could be used to preserve foods. For about the next 50 years, borate addition was considered one of the best methods of preserving or extending the palatability of foods such as fish, shellfish, meat, sausages, bacon, ham, cream, butter and margarine. According to a brief historical review (Gordon, 1987) of B as a food preservative, an English Royal Commission appointed in 1899 to investigate preservatives and colourings in foods recognised in 1901 that borates were used to preserve all foodstuffs except milk. Also in England, an act in 1907 named borax and boric acid as the only permitted preservatives in butter and margarine. Boron had a vital role as a preservative in preventing food crises during World War I. In other words, for the last 30 years of the past century and the first part of this century, B was considered a beneficial element only, and medical opinion was that B was rather innocuous because no corpses resulted from the use of B as a preservative.

As early as 1902, however, German and American scientists began to question the orthodox view that large amounts of borates in foods were innocuous. Foremost among the works that changed perceptions about B was a report by Wiley (1904) in which it was stated that consumption of boric acid in doses greater than 0.5 g $day^{-1}$ for 50 days resulted in disturbances in appetite, digestion and health in human volunteers. Wiley (1904) concluded that 0.5 g $day^{-1}$ of boric acid was too much for a normal man to receive regularly, and 4.0 g $day^{-1}$ of boric acid was the limit beyond which a normal man cannot go without harm. Subsequent to his report, the opinion that B posed a risk to health gained momentum; by the mid-1920s, many countries of the world began legislating against the addition of borates to food. Only during World War II were the restrictions involving B in foods eased; food shortages were making food preservation a major concern in many countries (Gordon, 1987). After the war, restrictions were gradually reimposed; by the middle 1950s, B as a food preservative was essentially for-

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bidden throughout the world. This was also the time when B began to receive attention from toxicologists. Because of some accidental poisonings and inappropriate uses in the medical profession, boric acid and borates became important in human health only from the toxicological point of view between 1950 and 1980.

About 15 years after Warington (1923) and Sommer and Lipman (1926) showed that B was an essential nutrient for plants, attempts were made to show that B is essential for higher animals. However, these attempts were apparently unsuccessful (Hove et al., 1939; Orent-Keiles, 1941; Teresi et al., 1944). It was reported in 1945 that high dietary B, 100 to 1000 $\mu g\ g^{-1}$ diet, enhanced survival, and increased body fat and liver glycogen in potassium deficient rats (Skinner and McHargue, 1945). However, attempts to confirm these findings using a different diet with an unknown B content and with different amounts of B supplementation were unsuccessful (Follis, 1947). Thus, the inability to produce a B deficiency in animals in these early studies apparently resulted in generations of students of biochemistry and nutrition being taught that B was a unique element in that it was essential for plants but not for higher animals including humans.

In the early 1980s, the dogma about B in animal and human nutrition began to change; this is when studies of the nutritional importance of B in my laboratory began. These were stimulated by a rather serendipitous finding. In an arsenic study, chicks grew about 50% slower than expected and exhibited leg abnormalities. Examination of the diet which had been recently reformulated revealed that the routine additions of B, fluoride and nickel to the diet had been eliminated and a new source of cholecalciferol (vitamin $D_3$) was used. Thus, a preliminary study with chicks was performed to ascertain whether supplemental B, fluoride or nickel would improve the performance of the chicks fed the basal diet used in the arsenic studies. As the result of the surprising finding, that B seemed to stimulate growth of these chicks and partially prevented the occurrence of leg abnormalities, further studies of the importance of B in nutrition were, and continue to be, performed.

Further study of the diet used in the first B experiment revealed that it contained inadequate cholecalciferol because the indicated potency of the supplement used apparently was not correct. This led to the study of the possible interaction between B and cholecalciferol; in 1981, the first results of this study appeared (Hunt and Nielsen, 1981). This report showed that B deprivation depressed the growth of chicks with the effect seemingly more marked when dietary cholecalciferol was deficient. Morphological examination of the tibias of the chicks indicated that an interaction between B and cholecalciferol affected bone formation. When dietary cholecalciferol was low, rachitic long bones were found in 17 of 21 B deprived chicks, but only 9 of 22 B supplemented chicks exhibited rachitic long bones; moreover the lack of calcification generally was more severe in the B deprived chicks. In the 15 years since this report, circumstantial evidence has been accumulating which strongly suggests that B is an essential nutrient for higher animals and humans.

## Nutritional importance of boron for animals

Findings from numerous experiments indicate that chicks and rats fed low dietary B ($<0.3\ \mu g\ g^{-1}$) exhibit altered bone development, brain function, macromineral metabolism, energy substrate utilisation, immune function and insulin secretion. In these experiments, the responses to low dietary B were most marked when the experimental animals were exposed to a stressor that adversely altered hormonal or macromineral metabolism, possibly at the cell membrane level, such as calcium, cholecalciferol or magnesium deprivation. Some of these findings are described here.

### *Bone development*

Boron deprivation was found to exacerbate gross bone abnormalities in chicks caused by a diet deficient, but not completely lacking, in cholecalciferol (Hunt and Nielsen, 1981; Hunt et al., 1994). At the microscopic level, B deprivation exacerbated the distortion of marrow sprouts caused by cholecalciferol deprivation and delayed the initiation of cartilage calcification (Hunt, 1989). Boron deprivation also decreased chondrocyte density in the zone of proliferation of the growth plate in cholecalciferol deficient chicks (Hunt et al., 1994). It also has been found that *in ovo* injections of B reduced the abnormal height of the growth plate of chicks hatched from cholecalciferol deficient eggs (King et al., 1991). Based on these findings, Hunt et al. (1994) have suggested that B enhances the maturation of the growth plate in the long bones.

### *Brain function*

Boron deprivation was found to systematically influence brain electrical activity assessed by an electrocorticogram in mature rats; the principal effect was on the

frequency distribution of electrical activity (Penland and Eberhardt, 1993). This finding suggests that B may play an important role in the maintenance of brain activation. Brain mineral composition also is affected by B deprivation. Calcium concentrations in total brain and in brain cortex, as well as the phosphorus concentration in the cerebellum, were found to be higher in B deprived than in B supplemented rats fed a cholecalciferol deficient diet (Hegsted et al., 1991). Penland (1990) found that B deprivation increased the copper concentration in brain.

*Macromineral metabolism*

In the cholecalciferol deficient rat, B deprivation was found to decrease the apparent absorption and balance of calcium, magnesium, and phosphorus (Hegsted et al., 1991). Boron deprivation also has been found to alter the plasma concentrations of substances involved in macromineral metabolism. Boron deprivation exacerbated the abnormally elevated plasma concentration of total alkaline phosphatase activity in chicks caused by cholecalciferol deficiency (Hunt and Nielsen, 1981; Hunt et al., 1994). Also in cholecalciferol deficient chicks fed low dietary B (about 0.3 $\mu g\ g^{-1}$), B supplementation (about 1.4 $\mu g\ g^{-1}$) markedly increased plasma 25-hydroxycholecalciferol (Bai and Hunt, 1995b) and 1,25-dihydroxycholecalciferol (Bakken and Hunt, 1995) concentrations. In the cholecalciferol adequate chick, low dietary B increased plasma 1,25-dihydroxycholecalciferol concentrations (Bakken and Hunt, 1995). Regardless of cholecalciferol status, Hunt et al. (1994) found that B supplementation of B deficient chicks significantly increased femur calcium, phosphorus and magnesium concentrations.

*Energy substrate utilisation*

Hunt (1997) reported that B supplementation (about 1.3 mg $kg^{-1}$ diet) of chicks fed a low B diet (about 0.2 mg $kg^{-1}$) increased the concentration of 2-phosphoglycerate and decreased the concentration of dihydroxyacetone in liver. These findings suggest that B intake has an influence on the hepatic glycolytic pathway and thus affects energy substrate metabolism. Further evidence for B affecting energy metabolism is the findings that B deprivation exacerbates the elevation in plasma glucose caused by cholecalciferol deficiency in chicks (Hunt and Nielsen, 1987), and decreases plasma triglycerides in both chicks (Bai and Hunt, 1995b; Hunt and Herbel, 1993) and rats (Aasen and Hunt, 1993; Herbel and Hunt, 1992).

*Immune function*

Evidence is emerging which indicates that B nutriture can affect the immune response or the inflammatory process. Bai and Hunt (1996b) reported that B deprivation depresses the antibody response in rats immunised with bacterial antigens. Moreover, Bai and Hunt (1995a) found that luxuriant amounts of dietary B (20 $\mu g\ g^{-1}$ diet) delayed the onset and severity of adjuvant induced arthritis in rats. Boron as borax also has been reported to have an anti-arthritic effect on formaldehyde induced arthritis in rats (Shah and Vohora, 1990).

*Insulin secretion*

Boron deprivation has been found to increase plasma insulin concentrations in the cholecalciferol deficient rat (Hunt and Herbel, 1991–1992). Additionally, it has been found that peak insulin release was markedly higher from isolated, perfused pancreata from chicks fed a low B diet (about 0.3 mg $kg^{-1}$) compared to chicks fed about 1.4 mg B $kg^{-1}$ diet (Bakken and Hunt, 1995).

## Nutritional importance of boron for humans

Findings indicating that B is of nutritional importance to humans have come mainly from two studies in which men over the age of 45, postmenopausal women, and postmenopausal women on estrogen therapy were fed a low B diet (about 0.25 mg/2000 kcal) for 63 days and then fed the same diet supplemented with 3.0 mg B $day^{-1}$ for 49 days (Nielsen, 1994). The major differences between the two experiments were the intakes of copper and magnesium; in one experiment they were marginal (1.6 mg Cu/2000 kcal) or inadequate (115 mg Mg/2000 kcal), in the other, they were adequate (2.4 mg Cu and 300 mg Mg/2000 kcal). Findings from these experiments, some described in the following, showed that B affects the metabolism of macrominerals, energy, nitrogen, and reactive oxygen in humans; they also showed that B affects brain function, psychomotor performance and the response to estrogen ingestion.

*Table 1.* Examples of findings indicating that boron affects macromineral, nitrogen, reactive oxygen species and estrogen metabolism in humans[1]

| | Dietary B[2] (mg day$^{-1}$) | Serum calcitonin[3,4] (pg mL$^{-1}$) | Blood urea nitrogen[5] (ng mL$^{-1}$) | Erythrocyte superoxide dismutase[6] ($\mu$g haemoglobin) | Serum 17$\beta$-estradiol (pg mL$^{-1}$) |
|---|---|---|---|---|---|
| Men over the age of 45 | 0.25 | 71 | 14.6 | 3091 | 20 |
| | 3.25 | 60 | 12.9 | 3231 | 17 |
| | p value | 0.16 | 0.01 | 0.71 | 0.12 |
| Postmenopausal women | 0.25 | 78 | 13.8 | 2666 | 11 |
| | 3.25 | 52 | 12.6 | 3169 | 11 |
| | p value | 0.02 | 0.08 | 0.04 | 0.86 |
| Postmenopausal women on estrogen therapy | 0.25 | 61 | 13.4 | 2520 | 99 |
| | 3.25 | 55 | 11.5 | 3327 | 157 |
| | p value | 0.02 | 0.03 | 0.03 | 0.02 |
| Above groups combined plus one premenopausal woman | 0.25 | 74 | 13.8 | 2735 | 48 |
| | 3.25 | 59 | 12.2 | 3243 | 69 |
| | p value | 0.0008 | 0.0001 | 0.04 | 0.06 |

[1]Four to five individuals in each group.
[2]After an equilibration period of 14 days when dietary B was about 3.25 mg day$^{-1}$, there was a depletion period of 63 days when dietary B was about 0.25 mg 2000 kcal$^{-1}$ followed by a repletion period of 49 days when the basal diet was supplemented with 3 mg B day$^{-1}$ as sodium borate.
[3]From experiment where magnesium was inadequate (115 mg 2000 kcal$^{-1}$) and copper was marginal (1.6 mg 2000 kcal$^{-1}$) throughout the study (Nielsen et al., 1990).
[4]In experiment where dietary magnesium was adequate (about 300 mg 2000 kcal$^{-1}$) and copper was luxuriant (about 2.4 mg 2000 kcal$^{-1}$) calcitonin values were close to 37 pg mL$^{-1}$, an expected normal-type value, and were not significantly affected by dietary B.
[5]From experiment where magnesium was adequate (about 300 mg 2000 kcal$^{-1}$) and copper was luxuriant (about 2.4 mg 2000 kcal$^{-1}$) (Nielsen, 1994; Nielsen et al., 1991, 1992).
[6]Does not include premenopausal woman.

*Macromineral metabolism*

Evidence that B affects macromineral metabolism includes changes in hormones that are involved in this metabolism. In both experiments, the serum 25-hydroxycholecalciferol concentration was lower during B depletion than B repletion (Nielsen et al., 1990, 1992). In the experiment where dietary copper was marginal and magnesium was inadequate, calcitonin values were much higher than in the experiment where these two elements were adequate. This finding suggests that, because the calcitonin values obtained with adequate copper and magnesium were close to those reported by others as being normal, the combined magnesium-low, copper-marginal diet caused elevated serum calcitonin indicative of an abnormal calcium metabolism. As shown in Table 1, B depletion exacerbated this abnormality (Nielsen et al., 1990). Similar findings were obtained with serum osteocalcin. Further evidence that B affects macromineral metabolism is that plasma ionised calcium and serum magnesium concentrations were lower during B depletion than repletion in the experiment where dietary copper and magnesium were marginal or inadequate.

*Energy substrate metabolism*

Similar to the findings with animals, B deprivation affects circulating glucose and triglyceride concentrations in humans. In the experiment where dietary copper and magnesium were low, serum glucose concentrations were significantly higher during B depletion than B repletion (Nielsen, 1989). Unfortunately, serum glucose was not determined in the other experiment. However, serum triglycerides were determined and were significantly lower during B depletion than repletion (Nielsen, 1992).

*Nitrogen containing biosubstances metabolism*

In both experiments with volunteers, blood urea nitrogen (BUN), serum creatinine and urinary urea were significantly higher during B depletion than B repletion (Nielsen, 1989; Nielsen et al., 1991). In the experiment where dietary copper and magnesium were adequate, urinary hydroxyproline excretion was significantly lower during B depletion than B repletion (Nielsen, 1994). The changes in these nitrogen containing metabolites suggest an alteration in amino acid or protein metabolism. In other words, the utilisation of some amino acids or proteins are affected by B such that the incorporation of amino acids into, or the breakdown of proteins, is changed and results in altered concentrations in nitrogen metabolites in blood and urine.

*Reactive oxygen species metabolism*

Both superoxide dismutase and ceruloplasmin are enzymes involved in the protection against damage caused by reactive oxygen species. In both experiments, erythrocyte superoxide dismutase was significantly lower (Table 2) during B depletion than B repletion (Nielsen, 1989, 1994). The ceruloplasmin findings apparently were modified by dietary copper and magnesium; when these were low, enzymatic ceruloplasmin was significantly lower during B depletion than B repletion. When dietary copper and magnesium were adequate, dietary B did not affect enzymatic ceruloplasmin, but immunoreactive ceruloplasmin was significantly lower during B depletion than repletion. Most likely, B does not directly participate in the conversion of reactive oxygen species into harmless metabolites, but instead affects their formation during normal metabolism of energy (discussed above), which apparently affects the need for enzymes involved in reactive oxygen species metabolism.

*Response to estrogen ingestion*

In both experiments, estrogen ingestion elevated both serum 17$\beta$-estradiol (Table 1) and plasma copper; these elevations were higher during B repletion than B depletion (Nielsen et al., 1992). Dietary B did not affect plasma copper nor serum 17$\beta$-estradiol in men or postmenopausal women not on estrogen therapy. These findings indicate that B can enhance the effects of estrogen ingestion.

*Brain function and cognitive and psychomotor performance*

Penland (1994) has reported that a low B intake results in electroencephalogram (EEG) changes suggestive of reduced behavioural activation (e.g. drowsiness) and mental alertness. In addition, Penland (1994) found that the EEG changes seemed to be in concert with the finding that a low B intake results in poorer performance in tasks that involve psychomotor skills and the cognitive processes of attention and memory. Penland (1994) has stated that the changes induced by low dietary B are similar, but not as severe, as those found with malnutrition or some metal toxicities.

## Physiological (biochemical) function

About the only item lacking for the unequivocal acceptance of B as an essential nutrient for higher animals and humans is a defined biochemical function. This lack should not be surprising because a biochemical function for B in plants is only now emerging, which is over 70 years after it was found essential for plants to complete their life cycle (Sommer and Lipman, 1926; Warington, 1923). A consensus seems to be forming that the specific biochemical role of B in plants is structural and/or functional in the cell wall and probably in the cell membrane. This role supports a hypothesis advanced for the biochemical function of B in higher animals. This hypothesis is that B has a role in cell membrane function or stability such that it influences the response to hormone action, transmembrane signalling, or transmembrane movement of regulatory cations or anions (Nielsen, 1991). This hypothesis is supported by the finding that B influences the transport of extracellular calcium and the release of intracellular

*Table 2.* Changes in rat[1] platelet ionised calcium, $[Ca^{2+}]_i$, in response to thrombin suggesting that boron can influence cell membrane function or transmembrane signalling

| Dietary treatment | | $\Delta$ $[Ca^{2+}]_i$ without external $Ca^{2+}$ | $\Delta[Ca^{2+}]_i$ in presence of 1.0 m *M* $Ca^{2+}$ |
|---|---|---|---|
| B ($\mu g\ g^{-1}$) | K (%) | | |
| 0 | 0.36 | 74 | 627 |
| 3 | 0.36 | 64 | 538 |
| 0 | 1.00 | 71 | 648 |
| 3 | 1.00 | 54 | 582 |
| | | P Values | |
| B | | 0.04 | 0.05 |
| K | | 0.31 | 0.41 |
| B×K | | 0.59 | 0.76 |
| Root MSE | | 16 | 127 |

[1]Data from groups of 12 rats fed their respective diets for 12 weeks. After platelets were obtained they were loaded with the fluorescent marker FURA-2 so that cellular $[Ca^{2+}]_i$ could be measured in the resting stage and after activation with 0.25 units $mL^{-1}$ thrombin.

calcium in rat platelets activated by thrombin (Table 2), and that B influences redox actions involved in cellular membrane transport in plants (Blevins and Lukaszewski, 1994). Another hypothesis which accommodates a large and varied response to B deprivation and the known biochemistry of B is that B acts as a metabolic regulator through complexing with a variety of substrate or reactant compounds in which there are hydroxyl groups in favourable positions (Hunt, 1994). Because this complexing usually results in a competitive inhibition of two classes of enzymes *in vitro*, the regulation by B is hypothesised to be mainly negative.

## Metabolism of boron

One of the criteria often stated for an element to be considered essential is that homeostatic control mechanisms must exist for it. Evidence that B is homeostatically controlled includes the rapid urinary excretion of absorbed B, the lack of accumulation of B in tissues, and the relatively narrow range of B concentrations in blood of apparently healthy individuals.

Because there is no useable radioisotope of B, the study of its metabolism has been made difficult. However, sodium borate, boric acid and most likely food B are rapidly absorbed, and excreted largely in the urine. Most ingested B probably is converted into $B(OH)_3$, the normal hydrolysis end product of most B compounds and the dominant inorganic species at the pH of the gastrointestinal tract. Thus, B probably is absorbed, transported throughout the body and excreted mainly as undisassociated $B(OH)_3$. During transport in the body, the $B(OH)_3$ most likely is weakly attached to biosubstances containing cis-hydroxyl groups.

An inductively coupled plasma mass spectrometry method using the ratio of the two staple isotopes, $^{11}B/^{10}B$, has been developed to study B metabolism (Vanderpool et al., 1994). This method was used to show that B in broccoli, intrinsically enriched with $^{10}B$, was absorbed as well as extrinsic $^{10}B$ in boric acid from a test meal in rats. When 20 $\mu$g of $^{10}B$ isotope were fed to rats, 95% of this isotope was detected in the urine and 4% in the faeces after 3 days. This agrees with other urinary findings indicating that >90% of ingested B is usually absorbed (Jansen et al., 1984). The high urinary excretion indicates that this is the major homeostatic mechanism for controlling body content of B. Moreover, the mechanism probably is something more than just the movement of B down a concentration gradient because the urinary concentration of B apparently can be markedly different from the blood concentration. Hunt et al. (1997) found that in 11 postmenopausal women, an increase in dietary B from 0.36 (probably deficient) to 3.3 mg $day^{-1}$ (luxuriant) increased the mean fasting plasma B concentration only from 64 to 95 ng $mL^{-1}$ whereas the mean daily excretion of B increased from 0.37 to 2.87 mg. Nielsen (1996) found that a B supplement of 2.5 mg $day^{-1}$ given to 43 perimenopausal women consuming a mean of about 1.2 mg B $day^{-1}$ (based upon urinary excretion) increased the mean fasting plasma B concentration from 34 to 53 ng $mL^{-1}$ while mean urinary B excretion increased from 1.19 to 3.29 mg $day^{-1}$. Urine volume was not

apparently affected by the B supplementation in either study.

Boron is distributed throughout soft tissue and fluids of animals and humans at concentrations mostly between 0.015 and 0.6 $\mu g\ g^{-1}$ fresh tissue (Bai and Hunt, 1996a; Ward, 1993; Shuler et al., 1990). Bone, fingernails, hair and teeth usually contain several times these concentrations. Spleen also apparently contains relatively high amounts of B (Bai and Hunt, 1996a). Because the concentration of B in bone increases with increased B intakes, and the increased concentrations are maintained for a period of time after B intake is decreased, bone may be a storage site for B. As with other mineral elements, overcoming homeostatic mechanisms by high B intakes will elevate tissue B concentrations.

## Boron toxicity

Boron has low toxicity when administered orally. Toxicity signs in animals generally occur only after dietary B exceeds 100 $\mu g\ g^{-1}$. Boron toxicity was a focus of a recent symposium (Health Effects of Boron, 1994). In this symposium, it was stated that boric acid has a low, acute oral toxicity of about 4000 mg $kg^{-1}$ body wt in rats. In mice and rats, the threshold toxicity effect of B (about 4500 mg boric acid $kg^{-1}$ diet for mice) was found to be testicular cell damage and atrophy in males. Studies of the effect of high B on development revealed that this was not affected in rabbits fed 125 mg boric acid $kg^{-1}$ body wt, or in mice fed 450 mg boric acid $kg^{-1}$ body wt.

In humans, the signs of acute toxicity include nausea, vomiting, diarrhoea, dermatitis and lethargy (Linden et al., 1986). The signs of chronic B toxicity have been described as including poor appetite, nausea, weight loss, and decreased sexual activity, seminal volume, and sperm count and motility (Hunt, 1993). Two infants who had their pacifiers dipped into a preparation of borax and honey for a period of several weeks exhibited scanty hair, patchy dry erythema, anaemia and seizures (Gordon et al., 1973). The seizures stopped and the other abnormalities were alleviated when the use of the borax and honey preparation was discontinued. It should be noted that high B intake induces riboflavinuria (Pinto et al., 1978); thus high B intakes could possibly exacerbate the consequences of low dietary riboflavin.

The safe daily intake of B is in the process of being determined through the International Programme on Chemical Safety of the World Health Organisation. However, another group analysed both human and animal data for the World Health Organisation (WHO/FAO/IAEA, 1996) and suggested that an acceptable safe B intake could well be 13 mg $day^{-1}$.

## Dietary considerations of boron

In the human depletion-repletion experiments discussed above, the subjects responded to a B supplement after consuming a diet supplying only about 0.25 mg B 2000 $kcal^{-1}$ for 63 or more days. Thus, humans apparently have a dietary requirement higher than this. An analysis of both human and animal data resulted in the suggestion that an acceptable safe range of population mean intakes of B for adults could well be 1 to 13 mg $day^{-1}$ (WHO/FAO/IAEA, 1996).

For most people the major source of B is food. Most of the reported values for the concentrations of B in foods reported before 1985 are of questionable validity because of inadequate analytical methods. Two recent reports (Anderson et al., 1994; Hunt et al., 1991) provide an adequate indication of the amounts of B in various foods (Table 3). The richest sources of B are fruits, vegetables, pulses, legumes and nuts. Dairy products, fish, meats and most grains are poor sources of B. Based on the recent analyses of foods and food products, estimations of daily intakes of various age/sex groups have been made. Rainey et al. (1996) estimated that the median, mean and 95th percentile daily intakes of B for 27 age/sex groups in the United States ranged from 0.29, 0.49 and 1.53 mg $day^{-1}$, respectively, for infants aged 0 to 5 months to 1.02, 1.25 and 3.15 mg $day^{-1}$, respectively, for males aged 60 to 65 years. The estimated median, mean and 95th percentile daily intakes of B were 0.75, 0.93 and 2.19 mg $day^{-1}$, respectively, for all groups, and 0.79, 0.98 and 2.33 mg $day^{-1}$, respectively for adults aged 17 and older. Using foods included in the United States Food and Drug Administration Total Diet Studies, Iyengar et al. (1990) determined the mean adult male daily intake of B to be 1.52 mg $day^{-1}$, whereas Anderson et al. (1994) determined the intake to be 1.21 mg $day^{-1}$. Based on the United Kingdom National Food Survey (UK Ministry of Agriculture, Fisheries and Food, 1991), the dietary intake of B in the United Kingdom ranges from 0.8 to 1.9 mg $day^{-1}$. It should be noted that the increased consumption of specific foods with high B content will increase B intake significantly; for example, one serving of wine or avocado provides 0.42 or

*Table 3.* Boron content of selected foods

| Food | B fresh wt ($\mu g\ g^{-1}$) ICP[1] | PGAA[2] | Food | B fresh wt ($\mu g\ g^{-1}$) ICP[1] | PGAA[2] |
|---|---|---|---|---|---|
| *Fruits, fruit juices* | | | *Meats* | | |
| Apple juice | 1.88 | 2.38 | Beef, ground | <0.015 | <0.05 |
| Apple sauce | 2.83 | – | Chicken | <0.015 | 0.34 |
| Apple, red w/peel | – | 2.73 | Cod/haddock | – | 0.24 |
| Banana | – | 1.04 | Ham | – | 0.20 |
| Cherries | 1.47 | 7.00 | Lamb | – | 0.14 |
| Grapes, purple/green | – | 4.60 | Liver (beef) | – | <0.07 |
| Grape juice | 2.02 | 3.72 | Pork roast | - | 0.06 |
| Orange (naval) | - | 2.17 | Turkey breast | - | 0.09 |
| Orange juice | 0.41 | 0.92 | Milk, eggs | | |
| Peach, canned | 1.87 | 2.06 | Cheese, cream | <0.015 | – |
| Pear, canned | 1.22 | 1.59 | Cheese, cottage | – | 0.19 |
| Pineapple juice | 0.27 | 0.57 | Milk, 2% | <0.015 | 0.23 |
| Wine | - | 3.52 | Eggs | <0.015 | 0.12 |
| *Fruits, dried* | | | *Cereal grain products* | | |
| Prunes | – | 21.5 | Bread, white, enriched | 0.20 | 0.48 |
| Raisins | - | 19.0 | Corn flakes | 0.31 | 0.92 |
| *Vegetables* | | | Flour, wheat, white | 0.28 | – |
| Avocado | - | 11.1 | Oatmeal | – | 0.10 |
| Beans, green | 0.46 | 1.56 | Rice | <0.015 | 0.32 |
| Broccoli, flowers | 1.85 | 2.47 | Spaghetti/ macaroni | <0.015 | 0.14 |
| Carrots | 0.75 | 2.59 | *Miscellaneous* | | |
| Corn | – | 0.49 | Catsup | 0.85 | 1.39 |
| Peas | – | 1.28 | Chocolate powder | – | 4.25 |
| Potato | 0.17 | 1.25 | Honey | – | 6.07 |
| Squash, winter | – | 2.65 | Sugar | <0.015 | 0.29 |
| Sweet potato | – | 1.08 | Vegetable oil, corn | – | <0.04 |
| Tomato | – | 0.75 | | | |
| *Pulses, nuts* | | | | | |
| Cow peas (blackeyed) | – | 4.76 | | | |
| Lima beans | – | 3.43 | | | |
| Red beans | – | 3.14 | | | |
| Peanuts | – | 13.8 | | | |
| Pecans | – | 6.6 | | | |

[1]Inductively coupled plasma emission spectrometric analysis by Hunt et al. (1991).
[2]Neutron capture prompt x-ray activation analysis by Anderson et al. (1994).

1.11 mg, respectively (Anderson et al., 1994). Moreover, for the population obtaining their drinking water from the 10% of the public water systems in the United States which provide water containing 0.4 mg B $L^{-1}$, water used for drinking and cooking may be the major, or significant source of B.

## Clinical considerations

Many people apparently consistently consume less than 1.0 mg B $day^{-1}$, the lower value given for the safe range of intakes above. For example, in a group of 43 perimenopausal women studied in the eastern North Dakota area of the United States, two women apparently consumed an average of less than 0.5 mg B $day^{-1}$, and 14 women consumed between 0.5 and 1.0 mg B $day^{-1}$ over a 90 day period (Nielsen, 1996). Rainey et al. (1996) also reported that many people

consistently consume less than 1.0 mg B $day^{-1}$. These findings suggest that B could be a practical nutritional or clinical concern. Based on the findings from animal and B deprivation studies, it may be of special concern to people exposed to certain nutritional stressors such as vitamin D, copper or magnesium deficiencies.

Although knowledge about B nutrition, biochemistry and metabolism is growing, more is needed before specific clinical disorders can be attributed to subnormal B nutrition. Reports such as those suggesting that low B status may enhance the susceptibility or exacerbate some forms of arthritis (Newnham, 1994; Travers et al., 1990) should be recognised as evidence that further study of the clinical importance of B is urgently needed. Because B clearly is a biologically dynamic element in higher animals and humans, its dietary lack may have a role in some disorders of unknown cause such as arthritis or osteoporosis.

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