DIETARY FIBRE AND MINERAL BIOAVAILABILITY

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INTRODUCTION

It would be comforting to know that by increasing the intake of dietary fibre in order to accrue health benefits only nutritional enhancement would occur. However, such is not the case. There are too many dietary and physiological variables to permit such an unqualified belief. The purpose of the present review is to clarify dietary fibre–mineral interrelationships and to try to assess the kinds and levels of dietary fibre which may be incorporated into diets without impairing mineral status.

Dietary fibre is that portion of a food carbohydrate which cannot be digested by enzymes secreted by the host and normally present in the gastrointestinal tract. Mineral bioavailability is often well below 100 % and this shows that the total amount of a mineral in a food or a biological system is not a reliable index of its nutritional value. This mineral must withstand the rigours of digestion and absorption and be available where and when it is needed. A stumbling block along the route may be dietary fibre.

Unrefined cereal grains have been shown to be the best single food source of both dietary fibre and minerals. The refining of grains, essential for edibility, and desirable for palatability, reduces both the mineral and dietary fibre content of the grains.

Minerals are found in highest concentrations in the germ and outer layers of the grains. Thus, with a higher extraction rate, more minerals and dietary fibre would remain

undisturbed, presumably affording the best possible nutritional advantages. However, these minimally disturbed grain products contain anti-nutrients as well: oxalates, tannins (polyphenols), and phytates, all of which may adversely affect mineral bioavailability.

When attempts are made to remove or minimize the effects of the anti-nutrients, the dietary fibre matrix is often altered or destroyed. Moreover, if dietary fibre fractions are removed, concentrated and then added back, the original food takes on new characteristics, eliciting different metabolic responses. For establishing long-term beneficial effects, it is important to learn what food and what quantities will be most beneficial.

As our environments became more temperature-controlled and society became more mechanized, with numerous and affordable labour-saving devices, it was evident that, in order to maintain normal body-weight, energy intake must be reduced or energy expenditure must increase (preferably both). This necessitated a reformulation of the diet to provide foods with greater nutrient density with no increase in energy. As a part of that development, dietary fibre intake was decreased. It soon became apparent that this was not a desirable trend.

There is overwhelming evidence that dietary fibre is a necessary component of human (Graf & Eaton, 1985; Behall *et al.* 1987; Lanza *et al.* 1987) and animal (Rader *et al.* 1986) diets, and its reduction has led to a number of metabolic disorders in the population. Thus, a gradual reversal in concept has been taking place. Recommended nutrient requirements have remained virtually the same, yet we are trying to increase intakes of dietary fibre. Another aspect, not new but gaining greater prominence as more is learned about dietary fibre, is the need for reassurance that the required nutrients are available in sufficient amounts. We do not have as great a margin as we would like for the free selection of foods on a lowered energy intake. We desire convenience foods that are attractive, high in nutrients and high in fibre. Achieving this balance is difficult.

Nutrient requirements are critical for the segments of the population with the greatest nutrient needs in proportion to energy: pregnant women, children and adolescents (B. F. Harland & S. A. Smith, unpublished results). Vegetarians and persons consuming special diets must also pay strict attention to their dietary intakes to receive the proper balance of nutrients, energy and dietary fibre (Harland *et al.* 1988).

The degenerative diseases of Western society, atherosclerosis, diabetes, hypertension and obesity, are directly related to food intake. They sustain a high incidence in part because there is such a variety of tempting, available and affordable foods. Everyone likes to eat the foods and drink the beverages that taste good, or that make us feel good, at least in the short term. These are the foods high in sugar, fat and alcohol. Unfortunately, these highly processed foods are frequently deficient in the essential nutrients, and are low in or devoid of fibre.

The recommendation to increase fibre in the diet (Department of Health and Social Security, 1978; US Department of Agriculture, 1985) cannot be effected by the simple insertion of a nutrient which could be accommodated without any further changes in the diet. To fulfil the recommendation necessitates three major dietary alterations: (1) changing the type of diet and the amounts of foods consumed, (2) lowering the energy density, thereby increasing the volume of food and (3) increasing the intake of substances associated with dietary fibre in the cell walls, thus inadvertently incorporating some of the anti-nutrients, primarily phytate (Southgate, 1987).

Harland & Morris (1985) published a comprehensive review of the research to date regarding interactions of dietary fibre and mineral absorption in humans and animals. The general hypotheses advanced in 1985 are still valid: (1) increased dietary fibre is recommended for improved general health, (2) foods or diets high in dietary fibre may alter mineral metabolism, and (3) phytate normally present in fibrous foods is the primary cause of alteration of mineral metabolism, rather than the fibre itself.

Table 1. *Effects of dietary modifications to increase dietary fibre intake on mineral intake and the proportion absorbed**

Subjects	n	Dietry fibre intake (g)	Potassium		Calcium		Magnesium		Phosphorus	
			Intake (mg/d)	Proportion absorbed	Intake (mg/d)	Proportion absorbed	Intake (mg/d)	Proportion absorbed	Intake (mg/d)	Proportion absorbed
Young men	12	9·3	2990	0·905	1180	0·258	280	0·393	1660	0·708
	12	21·5	3770	0·815	1130	0·188	411	0·299	1990	0·621
Young women	14	6·2	2560	0·926	769	0·180	160	0·277	1240	0·680
	14	16·2	2910	0·832	740	0·195	294	0·314	1460	0·647
	10	29·9	4340	0·816	964	0·248	391	0·182	1560	0·591
Elderly men	11	9·6	2700	0·874	1020	0·334	207	0·307	1410	0·735
	11	28·3	3000	0·774	969	0·311	381	0·276	1700	0·658
Elderly women	12	7·4	2260	0·852	920	0·360	190	0·415	1190	0·688
	12	20·9	2670	0·739	813	0·330	300	0·274	1500	0·646

* From Southgate (1987). Reprinted with permission.

Interest in this area has been so keen, and there has been such a proliferation of publications, that the current review will be mainly confined to reporting research developments since that publication. Recent research provides much greater clarity and understanding of the mechanisms involved in the interactions of dietary fibre and mineral bioavailability than hitherto.

In Table 1 are listed the effects on the absorption of potassium, calcium, magnesium and phosphorus when dietary fibre is increased. Of thirty-six mean values, only one was improved as a result of increased dietary fibre. The rest showed decreased mineral absorption by the body when dietary fibre was increased. In these Scottish subjects the increased dietary fibre was achieved by the introduction of foods higher in phytate: fruits, vegetables and wholemeal breads (the latter replaced white bread). This confirmed previous studies in which it was concluded that phytate-rich sources produce the most pronounced effects on mineral bioavailability (Franz *et al.* 1980; Andersson *et al.* 1983).

Several types of studies are available to investigators who seek to discover the mechanisms of the role of dietary fibre in mineral bioavailability. The most valuable are those studies involving humans, because that is the ultimate reason for research: how can we improve the human condition? Unfortunately there are major limitations of money, space, willing and suitable subjects and the necessary constraints applied by the various institutional review boards. However, a well-designed and conducted human study should provide important information.

Some human studies involve the use of isotopes. This type of study will provide more detailed and accurate metabolic information by indicating endogenous mineral activity, information which is not available in simple balance studies.

Animal studies permit research which cannot be performed in humans, and in vitro studies have basic research value for establishing mechanisms, preliminary to subsequent testing in animals or in humans.

In the following sections, each of the research designs has been employed to add to our knowledge.

MINERAL-BINDING FACTORS ASSOCIATED WITH DIETARY FIBRE

OXALATES

As mentioned previously, oxalates, tannins and phytate possess anti-nutritional properties, specifically in the binding of minerals, thereby impairing mineral absorption into the body. Oxalates are organic acids found in cauliflower, spinach, rhubarb and chocolate. In a human study by Kelsay & Prather (1983), when a high-fibre, high-oxalate (primarily spinach) diet was fed, mean apparent balances of Ca, Mg and zinc were negative, indicating that this type of diet impaired mineral absorption. The mechanism could be a binding of both oxalic acid and dietary fibre to minerals in a dietary fibre-mineral-oxalate complex. This complex may be less easily broken down in the human digestive tract than an oxalate–mineral or a dietary fibre–mineral bond. Gut microbes normally present have the ability to hydrolyse oxalate complexes. This ability varied from subject to subject producing results which were widely ranged.

TANNINS

Tannins are also organic compounds that can inhibit mineral absorption. Tannins, also known as polyphenols, are responsible for the astringent quality of tea and are found in

certain grains such as sorghum. There is some evidence that if milk is added to tea before it is drunk the mild protein casein will bind with the tannin and lessen the binding of minerals by the tannin. Most tannin research relates to impaired haem-iron bioavailability (Farkas & le Riche, 1987). Tannins in both tea and coffee have been shown to bind Fe by forming insoluble iron tannates within the human gastrointestinal tract.

PHYTATE

Phytate, like oxalates and tannins, is an organic compound (*myo*-inositol hexaphosphate) which occurs in all plants and serves as the storage form of P in the living plant. Phytate is a potent chelator of minerals and, thus, its presence in a food will strongly dictate the outcome of minerals associated with this molecule. Phytase (*EC*. 3 . 1 . 3 . 26) is the enzyme which hydrolyses phytate, thereby releasing the bound mineral or minerals. The role of phytate in biological systems has been alluded to earlier in the present review, and will be described in many of the subsequent reports on dietary fibre and mineral bioavailability.

DIETARY FIBRE AND MINERAL BIOAVAILABILITY

IRON

One of the most common nutrient deficiencies world-wide is that of Fe, not only in geographical areas where food is scarce, but also in areas where food is plentiful. Some developed nations are partially meeting this problem with Fe fortification of cereals. Most nations do not have this technological sophistication available to them, and still other nations choose not to enrich or fortify with Fe, but place emphasis on the forms and combinations of foods in a meal which can enhance bioavailability of nutrients.

Work by Morris & Ellis (1976) identified the Fe form monoferric phytate as being completely bioavailable. However, < 5 % of the phytate in wheat bran is in the monoferric phytate form. Simpson *et al.* (1981) and Hallberg (1987) recognized that there may be another factor or factors in addition to phytate in wheat bran which impair Fe bioavailability. Tannins, naturally present in the bran, may be responsible, and in meals containing animal protein and ascorbic acid a soluble animal protein–tannin complex may be formed which would prevent the interference with Fe bioavailability by tannins (Hallberg, 1987).

The promotion of dietary fibre in the diet often includes the use of wheat bran. When wheat bran was added to a meal the absorption of non-haem-Fe from all foods tested was impaired (Hallberg, 1987). The non-haem-Fe may comprise 100 % of the total Fe intake; thus, it is the primary source of absorbable Fe. The inhibitory effect of bran on Fe absorption may be attributed primarily to its phytate rather than its dietary fibre content. However, if meat (or fish) or ascorbic acid, or both, are present, the binding properties of the phytate in the bran may be lessened or overcome entirely. Table 2 (Frølich, 1986) provides a comprehensive list of foods which enhance the bioavailability of Fe, and of Zn. For a definitive publication on Fe bioavailability, see Monsen (1988). Previous societies in history with albeit higher intakes of dietary fibre (greater energy intakes and no refined foods) were protected by high intakes of ascorbic acid (as much as 400 mg) as well as higher intakes of animal protein.

A survey of 112 children was conducted in Manchester, UK by D'Souza *et al.* (1987) to compare the Fe status of three populations: sixty-five Caucasians, twenty-four West Indians and twenty-three Asians. The children were divided into two groups according to age: (1) 1 week–6 months and (2) 7 months–14 years 5 months. In the younger group,

Table 2. *Effect of addition of other foods on bioavailability of iron and zinc**

Mineral	Fibre source	Addition	Result	Reference
Fe	Rice	Fish	Increased absorption	Hallberg et al. (1978)
Fe	Maize, bread	Vitamin C	Increased absorption	Cook & Monsen (1977)
Fe	Rice	Fruit, meat	Increased absorption 5-fold	Hallberg et al. (1974)
Fe	Maize	50 g meat	Increased absorption 2-fold	Layrisse et al. (1974)
		100 g fish	Increased absorption 2-fold	
		150 g papaya (66 mg vitamin C)	Increased absorption 2-fold	
Fe	Maize	Fish	Increased availability	Layrisse et al. (1968)
Fe	Rice	Vitamin C	Increased availability	Sayers et al. (1974)
Fe	Maize	Tea, vitamin C	Tea reduced absorption from 3·8 to 2·1 % Vitamin C increased absorption 10-fold Inhibitory effect of tea overcome with vitamin C	Derman et al. (1977)
Fe	Maize, wheat	Vitamin C	Increased absorption from maize, but not from wheat	Callender & Warner (1970)
Fe	Cereals	Vitamin C	Increased non-haem-Fe absorption	Erdman (1978)
Fe	Whole-grain bread	Tea, orange juice	Tea reduced absorption 0·5-fold, Orange juice increased absorption 2-fold	Rossander et al. (1979)
Fe	Wholemeal bread	Fruit juice	Increased absorption	Elwood et al. (1968)
Fe	Rice	Fish	Increased absorption	Aung-Than-Batu et al. (1976)
Fe	Wheatbread	Orange juice	Increased absorption	Callender & Warner (1968)
Fe	Wholemeal bread	Vitamin C	Increased absorption	Dobbs & Baird (1977)
Zn	Wholemeal bread	Animal protein, milk	Increased absorption	Faridi et al. (1983)

* Table and references from Frølich (1986). Reprinted with permission.

haemoglobin values, mean corpuscular volumes and serum ferritin levels were similar. In the older group, haemoglobin values and mean corpuscular volumes were similar but serum ferritin levels were lower in both the West Indian and Asian groups. All children with lower height centiles, regardless of ethnic origin, had reduced ferritin levels. A nutritional survey of the older children revealed similar intakes of energy, protein and Fe for all three ethnic groups. However, there were higher intakes of dietary fibre and phytate (with mineral-binding characteristics) among the West Indian and Asian children, attributed to frequent consumption of pulses and unleavened chapatis and rare consumption of red meats (excellent sources of readily available minerals). Fe status was being compromised and full growth was not being achieved.

In most of the previous discussions, phytate has been given a negative image because of its impairment of Fe absorption. However, Graf & Eaton (1985) have shown phytate in a more favourable light. They postulated that although dietary fibre is recommended as a preventive against certain types of cancer (the rationale being that dietary fibre reduces transit time, enhances the excretion of potentially harmful free fatty acids (cholic and deoxycholic) and acts as a fat diluent, the protective action may very well be due to phytate. According to Graf & Eaton (1985), it is the phytate within the dietary fibre which acts as a potent inhibitor of the Fe-mediated generation of the hazardous hydroxyl radical. Therefore, the apparent beneficial effects of fibre may in part be attributed to phytate.

Using the intrinsic tag technique and two different radio-Fe tracers, Rossander (1987) compared in the same subjects Fe absorption from meals with and without added dietary fibre. Fe absorption was normalized to 40 % in the subjects. A standard dose of 3 mg Fe (as ferrous ascorbate) was given to each fasted subject as a reference dose in order to measure the subject's ability to absorb Fe before the addition of various fibres. To test the effect of the fibre from citrus pectin on Fe bioavailability, two types of pectin were fed: high methoxylation (71–75 %) and low methoxylation (29–36 %). In all cases, Fe absorption was high with no significant difference between pectins. When pectin was mixed into a chocolate pudding, Fe absorption was decreased, but this was attributed to the cocoa in the pudding. A slight but significant inhibition was seen with ispaghula, a hemicellulose preparation, but when guar gum was incorporated into rolls, the absorption of Fe was not affected.

In marked contrast, wheat bran strongly inhibited the absorption of non-haem-Fe from wheat breads. The correlation between the mean absorption ratio with added bran: without added bran was highly significant (r 0·99; Rossander, 1987).

Fairweather-Tait & Wright (1985), in an attempt to increase the dietary fibre and nutritional value of white bread, conducted an experiment in which pea (*Pisum sativum*) testa was added to the bread ingredients before baking. (Pea testa is the outer coating of the seed and because of its location and composition is believed to be low in phytate and tannins.) This bread is being developed because there have been some objections by the British public to the addition of brans to white bread because of unfavourable appearance and palatability. In this experiment, the bread, extrinsically labelled with 0·25 μCi ^{59}Fe, was fed to rats to determine the bioavailability of Fe by whole-body counting. Results showed acceptable Fe retention in adult male rats as well as adequate whole-body deposition of Fe. In many instances, locally grown peas offer an alternative to imported soya bean for use by the food industry in high-dietary-fibre products. Because peas and pea products are lower in phytate than soya-bean products, there would be greater mineral bioavailability from the pea products.

In an attempt to elucidate the detailed mechanism of intestinal Fe uptake, Reinhold *et al.* (1986) injected ferrous- or ferric-Fe combined with maize or wheat fibre, with or without ascorbic or citric acids, into intact jejuno-ileal segments of rat intestine. After careful in vitro experimentation to find suitable ferric and ferrous buffers, injection sites,

flushing techniques and conditions for regulation of intestinal pH, the following conclusions were drawn.

1. Solutions could be injected into intact rat intestines at 10 min intervals and the unabsorbed Fe could be measured in the effluent.

2. Fe retention was effective over a broad pH range, from 5 to 7·8.

3. Ascorbic acid did not increase retention of Fe under these conditions, contrary to that shown in humans. It should be recalled that the rat has no dietary requirement for ascorbic acid.

4. A 5 mM concentration of sodium citrate released Fe from the mucosa.

5. The retention of ferrous- and ferric-Fe in the mucosa was impaired both by maize and by wheat fibres. The authors postulated the mechanism to be binding with the formation of poorly soluble Fe polymers by autoxidation.

The uptake of Fe by isolated loops of rat duodenum isolated in situ was studied by Swindell & Johnson (1987). The purpose of the experiment was to determine the effects of guar gum supplements on Fe bioavailability. At intervals of 12, 36, 60 and 84 h after a dietary challenge with low- and high-Fe meals, the Fe uptake was measured. In a 10-week experiment, 'no effect of feeding guar gum on Fe retention nor Fe status at any level of Fe intake was observed'. It was concluded that, although guar gum led to a slight reduction of Fe uptake rate and to an impairment of the regulation of uptake, there was no significant nutritional impairment in the capacity of animals to maintain Fe status.

ZINC

Unlike Fe, Zn status in humans is difficult to assess; there is no reliable biochemical marker. Due to a normally large endogenous intestinal excretion of Zn, at times greater than or equal to that absorbed, the technique of apparent balance, in which the intake of Zn is compared with urinary and faecal excretion of Zn, poorly represents Zn status. It is likely that a number of 'at risk' population groups may be exhibiting borderline deficiencies which impair such normal functions as tissue growth, wound healing and immune response. Indeed, the latter was demonstrated by Kaplan et al. (1988) in a study of mildly Zn deficient elderly subjects who showed significantly impaired interleukin-2 production compared with subjects of normal Zn status. Interleukin-2 is a lymphokine of central importance to cellular immune function. This elderly population consisted of twenty-three relatively healthy subjects age 65–85 years (thirteen blacks, ten whites, eight males and fifteen females), all of lower socio-economic status. Nutritional histories were obtained by the 24 h dietary recall method. Dietary intakes provided 6·69 MJ (1600 kcal) with daily mean intakes of 7·8 mg Zn. None of the subjects had plasma Zn levels $< 100 \mu g/l$ (normal), but eight of the twenty-three had 'mild' Zn deficiency as defined by intracellular Zn levels > 1 SD below the mean of normal subjects in at least two of the three cell lines examined. The elderly, as well as pregnant women, children and adolescents, are susceptible to mild Zn deficiencies because of reduced intakes of the Zn-containing protective foods such as meats and shellfish, particularly when these persons have low energy intakes.

In further studies of the relationship of phytate and fibre to Zn bioavailability, Sandstrom et al. (1987) fed meals to humans containing rye, barley, oatmeal and triticale (a wheat–rye cross-blend). In all the experiments the amount of phytic acid in the meal was the primary determinant of Zn absorption. In contrast, when fibre-rich vegetables, e.g. carrots, peas, turnips, cabbage and potatoes, were added in 225 g amounts to a meal with chicken as the primary protein source, the Zn absorption from these vegetable meals was minimally affected. Although vegetables as a category are higher than grains in uronic acids, also known to bind minerals, vegetables are lower in phytate.

Most investigators seek an experimental diet that will increase the dietary fibre intake and produce beneficial metabolic effects such as a reduction of blood levels of cholesterol, triglycerides and glucose, without impairing mineral status.

By direct contrast, Rabbani et al. (1987) deliberately produced Zn deficiency in five male subjects by keeping the dietary Zn intake low (4·8 mg/d) and phytate intake high (phytate: zinc molar ratio 21). Dietary fibre intakes were 8·5 g/d (neutral-detergent fibre; NDF). After an experimental period of 28 weeks, a mild Zn deficiency state was achieved. The administration of Zn supplements was initiated to reverse the effects of Zn deficiency. A period of 20 weeks of feeding 30 mg Zn/d were required to totally reverse the symptoms of Zn deficiency. To show the effects of maize dietary fibre (low in phytate) on Zn metabolism, six normal, free-living adults were given two types of maize products, cornflakes and grits, intrinsically labelled with ^{65}Zn, by Lykken et al. (1986). Each volunteer absorbed more ^{65}Zn from the maize grits than from the cornflakes. The processing of cornflakes probably caused the formation of resistant starch which is only minimally digested by host enzymes and chelates minerals as it passes the length of the gastrointestinal tract. The cornflakes had also undergone the Maillard reaction (producing a colour ranging from light yellow to deep brown) resulting in a complex of minerals and glucose formed (presumably) during autoclaving or toasting. Continued ingestion of browned foods may accelerate faecal Zn excretion through chelation of endogenous Zn.

The use of radioisotopes has improved our understanding of Zn mechanisms. With respect to dietary fibre and Zn availability, 'The type and amount of cereal fibre has less influence on Zn absorption than the presence of phytate' (Sandstrom, 1987). At intakes of 8–10 g untreated wheat bran by humans Zn absorption was < 10%. However, when the phytic acid content was reduced, absorption of Zn increased to 25%. A Zn intake of > 20 mg/d would be required if Zn absorption were only 10%—recommended dietary allowance (RDA) for Americans is 15·0 mg/d (Munro, 1980). As with Fe, Zn absorption may be improved by increasing the consumption of animal protein in the meal (Sandstrom et al. 1987).

Young chicks served as the animal model for a study by Baker & Halpin (1988). The purpose of the experiment was to demonstrate Zn bioavailability by the measurement of Zn in tibia, pancreas and liver. Fish meal, wheat bran or a maize–soyabean meal mixture (100 g/kg diet) was added to a casein – D-glucose basal diet. Zn was fed at two levels: 68 and 318 mg/kg diet. The results showed that at both levels of Zn intake there was severe depression of Zn absorption from all three supplements (fish meal, wheat bran and the maize–soyabean meal mix). At 318 mg dietary Zn/kg without supplementation, chicks had three times more Zn in the tibia and twice as much Zn in the pancreas than with feed supplements. It was concluded that Zn utilization was markedly reduced by feeding the high-fibre, high-phytate supplements.

CALCIUM

In a study by Behall et al. (1987), designed to compare the effects on mineral bioavailability of wheat bran v. purified dietary fibres, two males and five females (59–76 years) consumed self-selected diets. After a stabilization period of 10 d, 30 g wheat bran was added to their diets during two periods of 10 d each. The addition of wheat bran increased their NDF intakes from 8·5 to 20·9 g/d. Dietary Ca intakes were calculated and faecal Ca was analysed during the last 8 d of the study. Apparent Ca absorption decreased in all subjects as a result of feeding the wheat bran. The authors then studied the effects of the addition of 24 g/d of four purified dietary fibres (cellulose, carboxymethylcellulose, locust bean (Ceratonia siliqua L.) gum and karaya (Sterculia urens Roxb.) gum) on the mineral balances of eleven

men. These purified fibres did not cause a decrease in the apparent absorption of Ca, Mg, Fe, Zn, or copper, because the phytate content is much lower than that of wheat bran.

In a study by Cree *et al.* (1986), rats were housed in four types of cages; two that permitted normal ambulation ((1) regular and (2) metabolic) and two anticoprophagy cages ((3) a short, linear tube cage and (4) a long tube cage). Weight gains (3 d) were greater in groups housed normally despite similar food intakes in all groups. Wet faecal weights were greater in rats housed in anticoprophagy cages. Neither faecal NDF (g/kg dry weight) nor apparent NDF digestibility was affected by caging conditions. However, groups in anticoprophagy cages showed decreased Ca balances. Those animals which had the opportunity to consume their faecal waste were able to recapture previously excreted Ca.

COPPER

To study Cu bioavailability, Turnlund *et al.* (1985) confined young men to a metabolic ward for 63 d. Cu absorption was determined with ^{65}Cu, a stable isotope, during each of three dietary treatments (basal diet, basal diet + α-cellulose or basal diet + phytate). Absorption of Cu was slightly but not significantly depressed by the treatments (%): basal diet 35·0, α-cellulose 34·1, phytate 31·4. A total of 2·34 g phytate was added daily (three times the usual adult intake). However, there was great individual variation in Cu absorption, ranging from 29·5 to 44·1 % among the subjects.

The bioavailability of Cu in the presence of dietary fibre was studied in mice and rats by Rockway *et al.* (1987). The following diets were tested: (1) wheat-bran-bound Cu, (2) adequate Cu (unbound), (3) deficient Cu with cellulose and (4) deficient Cu with wheat bran. In mice, when adequate Cu was fed, increased dietary fibre had no effect on Cu deposition in cardiac and hepatic tissues. However, in rats, hepatic Cu was decreased with bran-bound Cu. Tissue Cu was lower in animals fed on wheat bran compared with those fed on cellulose. Bioavailability of Cu was assessed by body-weight, tissue weight, food consumption and tissue content of Cu. The mice were fed on a wheat bran–Cu complex containing 52·5 μg Cu/g bran and the rats, 259 μg Cu/g bran. Copper sulphate was used as the control. The results demonstrated that Cu utilization differed between species and was reflective of the fibre source. In Cu-deficient diets, wheat bran had a more pronounced ability to impair Cu bioavailability than did cellulose. However, when dietary Cu was adequate, or in excess, no difference in Cu bioavailability could be traced to the dietary fibre source.

CHROMIUM

In contrast to most nutrient minerals studied, Cr was not bound by phytate in a rat experiment conducted by Keim *et al.* (1987). Twenty Sprague–Dawley rats (ten per group) were fed on a basal, semi-purified casein-based diet or the basal diet with soft red winter wheat bran added at a level of 350 g/kg. To determine Cr absorption and uptake by tissues, rats were incubated with 100 μCi ^{51}Cr and killed after 24 h. Of the variables examined, urinary Cr excretion, and Cr levels in liver, spleen, jejunum and blood, none showed altered uptake of Cr as a result of dietary wheat bran.

MINERAL INTERACTIONS

The effects of dietary fibre on the absorption of Ca, Fe, Mg, P and Zn were studied in seven ileostomy patients by Kivisto *et al.* (1986). These volunteers were fed on a low-fibre diet with either 54 g of a bran–gluten–starch mixture or the corresponding extruded product/d. Apparent absorption of Mg, P and Zn was significantly decreased during the period of feeding the extruded product, compared with ingestion of the bran–gluten–starch

mixture. During this same period, no difference in absorption was exhibited by Ca or Fe. Although the negative effect of an extruded product containing phytic acid was small, infant formulas or foods of this nature which are consumed frequently may pose a problem for mineral nutrition. Ileostomates are generally very suitable and reliable subjects. They are of considerable value because to duplicate this experiment in normal subjects might require a feeding study of from 1 to 2 months (the time span necessary for complete adaptation to an experimental diet in humans). Moreover, ileal excretion of ileostomates shows much less day-to-day variation than is found in faecal excretion of normal subjects (Kivisto *et al.* 1986). There was greater excretion of phytate when the extruded product was fed. The high temperatures required for extrusion cooking may inactivate the phytase in the foods. Thus, larger amounts of phytate might have a greater effect on the mineral binding.

Hallfrisch *et al.* (1987) conducted a study with twenty men, nineteen premenopausal women and twelve post-menopausal women in which apparent mineral balances of Ca, Cu, Fe, Mg, Mn and Zn were monitored. The subjects consumed either self-selected or high-fibre diets consisting of either simple or complex carbohydrates. The simple carbohydrate diets contained added sucrose, granola, coconut, pickle relish and lemon–lime soda. The high-fibre diets contained additional cracked wheat and Vienna breads, oatmeal and noodles. Most dietary intakes of the groups were below the RDA for Ca, Mg, Cu and Zn recommended by the National Academy of Sciences (Munro, 1980). The premenopausal women consumed less than two-thirds of the RDA for Fe. Apparent balances for all men and women were negative during the self-selection period for Ca, as were Mg and Zn for the women. High-fibre diets did not cause the apparent balances of Fe, Mn or Zn to become more negative. Excretion of Cu was increased in the premenopausal women consuming the simple-carbohydrate, high-fibre diet. Ca and Mg balances were negative for women even on adequate intakes of these minerals during the high-fibre period, leading to the recommendation that intakes of Ca and Mg should be increased above present RDA when a high fibre diet is consumed. An effective means of increasing bioavailable forms of Ca and Mg would be to increase consumption of dairy products.

An experiment using rats was conducted by Jiang (1986) in which cellulose and xylan were fed at levels of 30, 60 and 120 g/kg and diets contained 10 μg Zn and 4 μg Cu/kg. It was shown that (1) there was significant binding by cellulose of dietary Zn and Cu, and (2) mineral absorption by young rats on high-fibre diets was greater than that of their older counterparts. The Zn and Cu levels provided have been shown previously to be adequate for 1-month-old rats. After 26 weeks, the rats were killed and plasma, liver, kidney and intestinal mucosa were analysed for Zn and Cu. Of the cellulose 86% passed through the gastrointestinal tract and was recovered in the faecal contents, whereas only 18% of the xylan remained undigested. At a dietary inclusion level of 60 g cellulose/kg, Zn absorption was impaired, while diets containing 120 g cellulose/kg led to lowered apparent absorption of both Zn and Cu. The feeding of cellulose also resulted in lower plasma Zn and lower liver and kidney Cu. Xylan exerted no effects at any of the three levels. We may conclude that the indigestible cellulose was binding Zn and Cu which was subsequently excreted, whereas the xylan was more digestible, exerting a negligible effect upon mineral bioavailability.

Brock *et al.* (1988) examined the intergenerational effects of high dietary fibre and phytate on Ca and Zn in pregnant rats and their offspring. In addition to the control diet, there were four experimental diets containing (g/kg): 2 Ca, 150 maize bran; 2 Ca, 150 wheat bran; 10 Ca, 150 maize bran; 10 Ca, 150 wheat bran. Phytate levels in the wheat bran were fourteen times greater than in the maize bran. The content of dietary fibre was similar in the four experimental diets. Ca and Zn status were measured in the pregnant dams and offspring by assessing body-weights, normal pregnancies, litter size and viability of young. Femurs and jawbones were removed from the pregnant dams after death, and pups were analysed for total body Ca and Zn. The most sensitive indicators of Ca and Zn

status were the jawbones of the dams and the pup homogenates. Even with the higher intakes of Ca in two of the experimental diets, Ca content of femurs and jawbones was lower than in controls; this was true of pup homogenates as well. Thus, diets high in phytate and Ca can impair the bioavailability of Zn and Ca not only in pregnant dams, but in their offspring as well.

Cellulose and the hull and cell-wall materials isolated from rape (*Brassica napus*) and soya beans were fed at the 120 g/kg diet level to growing male Wistar rats by Ward & Reichert (1986). Transit time and Ca, Cu, Fe, Mg, Mn, P and Zn concentrations were measured in intestinal segments at the termination of the 16 d experiment. Apparent absorption of Ca, Cu, Fe and P was lower on the fibre-containing diets. Mg absorption was lower after feeding cellulose and rape hulls; Zn was lower after feeding cellulose and rape cell walls. Overall, cellulose bound all the minerals poorly, and rape hulls were the strongest chelator of the minerals. The following four factors were believed to be the primary determinants of reduced mineral bioavailability.

1. Shortened transit times, providing less time for mineral absorption to occur.
2. Dilution of intestinal contents and faecal bulking.
3. Chelation of minerals to dietary fibre matrices.
4. The property of dietary fibre to influence active and passive transport of minerals (Ward & Reichart, 1986).

Vahouny *et al.* (1987) studied the bioavailability of Ca, Fe, Mg and Zn to male albino rats fed on insoluble dietary fibres at the 100 g/kg diet level, and soluble fibres at the 50 g/kg diet level. Only Zn exhibited apparent negative balance when wheat bran was fed in this 4-week experiment. Additional dietary fibres tested were: cellulose, Fibyrax (a commercially prepared mix of fibrous materials), lucerne (*Medicago sativa*), pectin, guar gum, psyllium and cholestyramine (anion-exchange resin).

Ca, Mg, P and Zn absorption in five groups each of four growing pigs (35–40 kg) were studied by Bagheri & Guéguen (1985). A basal diet or the basal diet plus 200 g coarse wheat bran/kg was fed for 3 weeks. Mg and P were well absorbed; Ca and Zn were not. The authors attributed this impairment to the phytate in the wheat bran. In a second experiment, a basal diet, a basal diet + 25 g high-methoxylated (HM) apple pectin or a 25 g low-methoxylated (LM) apple pectin was fed. HM pectin had little effect on mineral absorption; however, the feeding of LM pectin resulted in negative apparent balances of Ca, Mg and Zn. The authors concluded that the degree of pectin esterification was the primary factor impairing mineral bioavailability.

Poor Fe bioavailability appears to be associated primarily with the content of phytate and fibre in the diet. However, in vitro experiments by Garcia-Lopez & Lee (1985) demonstrated that the presence of other minerals such as cobalt, Cu, Mg and Zn in the medium can also affect the Fe-binding capacity of fibre. Their investigations showed decreased Fe binding by NDF when Cu and Zn were present, yet increased Fe binding by acid-detergent fibre in the presence of Cu. The authors postulated multiple binding sites on the dietary fibres for the minerals tested.

PHYTATE:MINERAL RATIOS

Most recent research continues to support the concept that phytate even more than dietary fibre impairs mineral bioavailability. The use of phytate:mineral molar ratios has become more widespread as a method for predicting the risk of mineral deficiency, particularly Zn. A phytate:Zn molar ratio of 10 has withstood the test of time as that ratio for both animals and humans above which Zn deficiency may be predicted (Oberleas, 1975).

After summarizing fifty-two rat experiments, Davies *et al.* (1986) proposed the application of a phytate × Ca:Zn ratio as a more accurate predictor of the risk of Zn

Table 3. *Comparison of phytate:zinc and phytate × calcium:Zn millimolar ratios above critical level*†

| | Phytate:Zn | | | | Phytate × Ca:Zn | | | |
| | Female | | Male | | Female | | Male | |
Diet	%‡	No.§	%‡	No.§	%‡	No.§	%‡	No.§
Omnivorous (US)	6	16	0	13	11	16	31	13
Vegetarian (US)	83	12	82	11	66	12	91	11
Vegetarian (Asian Indian)	85	13	76	17	46	13	71	17
Vegetarian (Nepalese)	96	26			58	26		

* From Ellis *et al.* (1987). Reprinted with permission.
† Suggested critical level for phytate:Zn and phytate × Ca:Zn molar ratios are > 10 and > 0·2 respectively.
‡ Percent above critical level.
§ No. of subjects.

deficiency. Bindra *et al.* (1985) applied it to humans, proposing that the critical molar ratio be 0·2. Since then, Ellis *et al.* (1987) reported dietary intakes of American, Asian and Nepalese vegetarians which for the most part exhibited higher ratios than those previously accepted (Table 3).

Subsequently, Harland *et al.* (1988) measured the ratios of the dietary intakes of twenty-one male lacto-ovo vegetarians. The mineral status of this population as judged by the normal variables of general health was excellent, with phytate: Zn molar ratios just under 10, and phytate × Ca:Zn ratios of 0·51. This finding indicates that the upper limit for phytate × Ca: Zn molar ratios in humans may be more nearly 0·5 as had been predicted by Davies *et al.* (1986).

For a comprehensive review of the phytate–mineral mechanisms as well as a list of phytate values in approximately 200 foods, see Harland & Oberleas (1987). For a further discussion of phytate: mineral ratios, see Fordyce *et al.* (1987).

CONCLUSIONS

As may be observed from the research discussed here, dietary fibre can have an adverse effect on mineral bioavailability. However, when the conditions are clearly described one can conclude that most of the effects of dietary fibre on mineral binding are due to the presence of phytate. When adequate vitamin C and animal or fish protein are present, the impairment of Fe and possibly other mineral absorption is minimized. For a healthy adult, a dietary fibre intake of 10 g/4·18 MJ (1000 kcal) seems to be acceptable (Life Sciences Research Office, 1987). Lanza *et al.* (1987) found that the average intake in the United States is 11 g/d; the US National Cancer Institute recommends a doubling of this value for optimimum health benefits. Pregnant women, children, adolescents, the elderly, strict vegetarians or those with special dietary needs are the groups which may require specific directions for combining the kinds and amounts of foods which can supply their recommended dietary fibre intakes without impairment of mineral bioavailability.

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