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Total Dietary Fiber and Mineral Absorption

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Introduction

Dietary Fiber Hypothesis

The dietary fiber hypothesis states : "A diet that is rich in foods that contain plant cell walls is protective against a range of diseases, in particular those prevalent in affluent Western Communities". Conversely, the hypothesis implies that "in some instances a diet providing a low intake of plant cell walls is a causative factor in the etiology of the disease, and in others it provides the condition under which other etiological factors are more active"(Southgate, 1982).

This hypothesis, which represents dietary fiber as a very important component of the diet, was based on the pioneering observations of Burkitt and Trowell(1975), Burkitt et al. (1979), Trowell (1976), A.R.P. Walker, and N.S. Painter. Since these early observations, little has happened to diminish the importance of dietary fiber in health and disease. In fact, the positive image of dietary fiber continues to increase(Talbot, 1980 ; Committee on Diet, Nutrition, and Cancer, 1982 ; Life Sciences Research Office, 1987 ; Koop, 1988).

Total Dietary Fiber

Scientific advancements that have been accomplished to help elucidate the dietary fiber hypothesis are best found throughout the present volume and the two previous books in this series (Vahouny and Kritchevsky, 1982, 1985). One advancement has been the finding that from an analytical perspective, total dietary fiber(TDF) consists of insoluble and soluble components(Southgate, 1969, 1981 ; Furda, 1981 ; Prosky et al., 1984 ; Becker et al., 1986). The classification of major components comprising plant cell wall TDF is shown in Fig. 1. From a physiological standpoint, the insoluble and soluble fractions appear to function differently in the gastrointestinal tract(Haber et al., 1977 ; Eastwood et al., 1983 ; Judd and Truswell, 1985 ; Leeds, 1987 ; Ink and Hurt, 1987). The current estimate of TDF intake is 11 to 23 g/day in the United States, and it has been recommended that the intake of TDF be increased to 20~35 g/day(Life Sciences Research Office, 1987). This same committee recommended that the TDF intake consist of 70~75% insoluble dietary fibers(IDF) and 25~30% soluble dietary fibers(SDF). Dreher(1987) has reviewed the TDF intake in different countries, which ranged from 13.9 g/day in Iceland to 45.1 g/day in Portugal.

Total Dietary Fiber and Minerals

Three factors have contributed to the scientific community's and consumer's belief and acceptance of TDF as possibly the single most healthful component in the diet. These factors are(1) real and perceived health benefits of TDF as indicated by epidemiologic, clinical, and animal studies ; (2) recommendations that TDF intake can and should be increased ; and (3) the lack of any

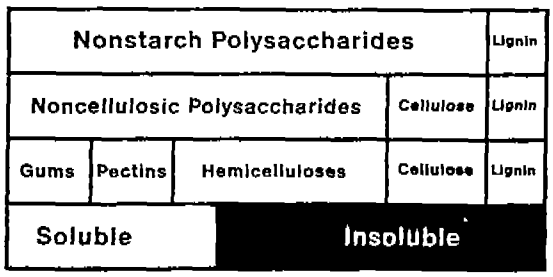

Fig. 1. The distribution of major plant cell wall components comprising total dietary fiber. Gums and pectins are normally considered sources of soluble dietary fibers. Cellulose, lignin, and a majority of hemicellulose are insoluble. Some hemicelluloses are soluble.

strong and convincing scientific evidence that TDF causes any harmful effects. In turn, the food industry is accommodating consumer demand by incorporating more and different sources of TDF into foods. However, in the scientific community, there are concerns that high intakes of TDF(i.e., >20~35 g/day) may impair mineral absorption and nutriture(Kelsay, 1978, 1981, 1982, 1986 ; Harland and Morris, 1985 ; Toma and Curtis, 1986). In regard to the relationship between minerals and TDF, the recent Committee reporting on the physiological effects and health consequences of dietary fiber(Life Sciences Research Office, 1987) provided the following qualifying statement : "Given the possibility that there is likely to be an adaptation to any alteration in mineral availability resulting from an increased fiber intake, a moderate level of fiber intake of 20~25 g/day NDF(or insoluble fiber) does not appear to pose a problem." Long-term studies of the effect of TDF on mineral nutriture have not been done. It is interesting to note that no known pathology has ever been associated with either a deficiency or excess of TDF.

The purpose of this review is to integrate mineral nutrition with TDF consumption. More specifically, the effects of various types and amounts of TDF and its major insoluble and soluble components on mineral nutrition are presented. The apparent benefits of higher intakes of TDF appear to justify increased consumption of foods rich in TDF. The author takes the position that although TDF does affect mineral absorption, these are not negative effects, and TDF does not impair mineral health.

Essential Minerals and Sites of Absorption

The minerals essential for human health are indicated in Table 1 along with the four most common toxic elements in the human diet. From the standpoint of the interaction between TDF and mineral absorption, the minerals presented in Table 1 have significance for a number of reasons. Insufficient information is available as to whether TDF affects the absorption of all minerals uniformly or whether only specific minerals or groups of minerals(i.e., the transition elements, Fe, Zn, and Cu) are affected. A second considera-

Table 1. Essential and toxic minerals in the diet along with their highest recommended dietary allowance(RDA) or estimated safe and adequate daily dietary intake(ESI)

Essential					
RDA (mg/day)[a]		ESI mg/day		No exact requirement/intake established	Toxic
Ca	1200	Na	1100-3300	Ni	As[b]
P	1200	K	1875-5625	Mo	Hg
Mg	400	Cl	170-5100	As[b]	Cd
Fe	18	Cu	2.3-3.0	Co	Pb
Zn	15	Mn	2.5-5.0	Cr	
I	0.15	F	1.5-4.0	Si	
		Cr	0.05-0.2	Sn	
		Se	0.05-0.2	V	
		Mo	0.15-0.5		

[a]Maximum RDA(National Academy of Sciences, 1980).

[b]Essential in only trace amounts but toxic in higher amounts.

tion is the site of each mineral's absorption along the alimentary tract. As knowledge is gained that the insoluble and soluble dietary fibers act differently in the major sections of the intestine, the question can be asked : What fibers affect what minerals in what sections of the gastrointestinal tract ?

Most minerals are absorbed in the small intestine(Fig. 2), with a majority of the uptake occurring in the duodenum and less along the remainder of the small intestine(Mertz, 1987). There is information to suggest that copper(Van Campen and Mitchell, 1965) and selenium are partially absorbed from the stomach. Adequate information on the role of the stomach in mineral absorption is not available. Electrolytes are exchanged between the intestinal lumen and the body along the entire intestine, with a majority of this exchange taking place in the colon. There is debate as to the magnitude and importance of the colon

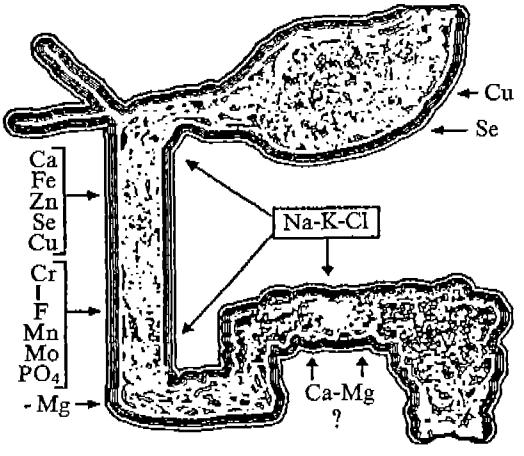

Fig. 2. Generally accepted sites of absorption of selected essential minerals along the gastrointestinal tract. The exact magnitude and significance of copper and selenium absorption from the stomach is unknown. Calcium and magnesium absorption from the colon is only speculated. All known essential minerals are reported in Table 1.

as a site of mineral absorption other than for the electrolytes. Absorption of calcium from the colon has received significant attention(Favurs et al., 1980 ; Lee et al., 1980 ; Ammann et al., 1986). Because TDF has been implicated in impaired calcium utilization(McHale et al., 1979 ; Slavin and Marlett, 1980 ; Godara et al., 1981), possibly by decreasing absorption at sites in the small intestine, having a second area for absorption of calcium would be advantageous.

Mineral Bioavailability

The area of nutrition that has possibly received the greatest amount of attention this past decade has been nutrient bioavailability. Bioavailability is defined as that proportion of the total amount of a nutrient that is absorbed and utilized by the body(O'Dell, 1984). With minerals, the first use of this term was probably by James Fritz(Pla and Fritz, 1971), then with the Food and Drug Administration. His studies were instrumental in showing that certain forms of iron were more available to the body(e.g., ferrous sulfate) than others, which were almost totally unavailable(e.g., ferric orthophosphate).

Although the study of nutrient bioavailability remains a commendable endeavor, a major difficulty arises in obtaining a meaningful response or index that accurately reflects mineral status without conducting invasive techniques. For selected minerals, the relationship between physiological/biochemical functions and current measurements to assess status and bioavailability are reported in Table 2. Because of the lack of sensitive indices, coupled with the fact that there are no overt mineral deficiencies in populations or in clinical research studies evaluating the effect of TDF on mineral nutrition, unequivocal conclusions can only be inferred as to any possible ad-

Table 2. Selected physiological/biochemical functions of minerals and indices to assess status or bioavailability in animals and humans

Mineral	Physiological/biochemical function	Index of status
Ca	Bone	Bone density
Mg	Neuromuscular transmission	Serum Mg
Fe	Hemoglobin	Blood ferritin
Zn	RNA polymerase	Serum Zn
Cu	Superoxide dismutase	Serum Cu
Se	Glutathione peroxidase	Glutathione peroxidase activity

Table 3. Factors affecting nutrient-mineral bioavailability

Intrinsic	Extrinsic
Age	Protein
Gender	Fat
Health/disease	Carbohydrate
Pregnancy	Total dietary fiber
	Others :
	Maillard products
	Phytic acid
	Ascorbic acid

verse affects of TDF on mineral accretion. It is interesting to note that little mention is ever made of TDF enhancing mineral utilization or bioavailability.

The bioavailability of nutrients' minerals is affected by two sets of factors, and these are listed in Table 3. Those physiological changes that occur in the living system are referred to as intrinsic factors. The second set of factors, extrinsic factors, are those directly associated with the diet. Total dietary fiber is considered an extrinsic factor. Changes in the amount or ratios of the carbohydrate, protein, and fat to TDF concentration in the diet may be important in mineral nutriture. An adequate understanding of the intrinsic and extrinsic factors that affect mineral bioavailability and long-term mineral nutriture represents a formidable challenge for the researcher.

Plant cell walls are rich in minerals(Crosby, 1978 ; Johnson et al., 1985). For this reason, whole-grain products and bran can contribute minerals to a food product and ultimately the human diet. This has led numerous investigators to evaluate the bioavailability of minerals from fiber sources, and these studies have been reviewed(Erdman, 1982 ; Frolisch, 1986). The conflicting findings suggest both that sources of TDF such as brans provide minerals with varying degrees of bioavailability and, conversely, that TDF impairs mineral bioavaiability, a dilemma that should be resolved.

Epidemiologic Studies

Although the dietary fiber hypothesis was developed from epidemiologic studies, there was not, nor is there now, a concern about any adverse effect of TDF on mineral utilization among populations(Trowell et al., 1985). In his review on dietary fiber and mineral utilization, Walker(1987) provided an excellent discussion of the rationale that TDF should not be considered to change mineral status adversely. Walker also made the point that increased consumption of TDF and the benefits for human nutrition and health to be achieved by these changes should be viewed holistically and not in isolation.

Possibly the best long-term studies of the effects of high-TDF diets on mineral nutriture are obtained from vegetarians. These individuals have not been found to have impaired mineral status(King et al., 1981 ; Anderson et al., 1981 ; Gibson et al., 1983 ; Abdulla et al., 1984). Freeland-Graves et al. (1980) have reported alterations in zinc absorption among lacto-ovo-vegetarians. Vegetarians adapt to high TDF(>35 g/day) intakes, which in turn help them mainatain normal mineral nutriture. The adaptation in human and ani-

mal studies caused by changes in diet is important and has significant implications in clinical studies.

Clinical Studies

Many clinical trials have focused on possible adverse effects of TDF on mineral absorption and nutriture with the preponderance of results suggestive of a negative influence. These studies have been reviewed(Kelsay, 1978, 1981, 1982, 1986 ; Harland and Morris, 1985 ; Toma and Curtis, 1986). Current research studies continue to support the concept of adverse affects of TDF on mineral absorption(Hallberg, 1987). However, more recent reviews on this subject(Munoz, 1986 ; Southgate, 1987) have begun to challenge the negative effect of TDF on mineral utilization.

McCance and Widdowson(1942) found that Ca, Mg, and P were less efficiently absorbed in subjects who consumed diets containing 40~50% of their calories from brown bread compared to subjects who consumed white bread. Since this early report, approximately one-half of all clinical studies have indicated a negative impact of TDF on minerals ; the other reports indicate no change. Along with iron and zinc, the mineral that appears to be most frequently cited as being negatively affected by TDF is calcium(Walker et al., 1984 ; Cullumbine et al., 1950 ; Reinhold et al., 1976 ; Cummings et al., 1979), but the mechanism is not known. It would be worthwhile to clarify this possible relationship between TDF intake and calcium balance in light of the Surgeon General's Report on Nutrition and Health(Koop, 1988), which advocates increased TDF intakes and also indicates osteoporosis to be one of the major skeletal diseases in this country.

As chronicled in cited reviews, evaluations of the effect of TDF on mineral nutrition have primarily been accomplished with balance trials, a few of which have employed isotopes(Schwartz et al., 1984 ; Turnlund et al., 1985). The balance technique has long been used to assess nutrient requirements for humans. Most of the current recommended dietary allowances(National Academy of Sciences, 1980) for essential nutrients have been determined using balance trials. There are advantages and disadvantages of the method when used for humans or animals(Hegsted, 1976), with each species providing its own difficulties. Until better analytical technques are developed and better methods of assessing nutrient status in animals and man become available, the balance technique will continue to be used(Beisel, 1979).

In the case of minerals, the balance method appears accurate because minerals are not degraded as are organic nutrients. Duncan(1967) made an important observation when she stated that it is wrong to use balance data to reflect absolute rather than relative change. Positive balance does not necessarily mean accretion of a mineral in the body, nor does negative balance mean mineral depletion. Inherent with the balance technique are sampling and analytical errors, which will normally overestimate positive balance results(Forbes, 1973).

To achieve good balance data may take months of steady observation to overcome changes that could be the result of adaptation alone. Isaksson and Sjogren(1967) have indicated that for calcium balance data, adaptation to a new intake level may take months to achieve in studies on calcium balance. However, reproducible balance results for calcium and phosphorus in humans have been reported(Hargreaves and Rose, 1965) in studies lasting only for months.

One of the longest and best-controlled metabolic studies evaluating the effect of TDF on mineral

balance was conducted by Sandstead et al.(1978, 1979). Subjects were fed similar diets plus an additional 26 g of TDF per day for periods ranging from 4 to 8 months. The TDF provided at monthly intervals included wheat bran, corn bran, soy bean hulls, dehydrated apple powder, or dehydrated carrot powder. Among the minerals assayed in these studies were calcium, magnesium, phosphorus, zinc, copper, and iron. None were found to be adversely affected by the different sources of TDF, and the subjects were not in negative balance.

Insoluble Dietary Fibers

The IDFs in the plant cell wall serve as structural components(Selvandran, 1984, 1985). Plant species, age, and growing conditions affect the amounts and ratios of the three major IDFs-cellulose, hemicellulose(s), and lignin-that are present in plant cell walls. Naturally occurring as in brans or as isolated, relatively pure polymers(i.e., cellulose), IDFs are added to foods to provide both bulk and water-holding capacity. These insoluble polymers can be expected to exhibit the same properties in the intestine.

Two theories have been suggested as to how IDF may decrease mineral utilization. First, IDF accelerates the movement of the digesta through the intestine. Although IDF has been shown to increase movement of luminal contents(Read, 1985), it has not been demonstrated that this phenomenon affects mineral absorption. The second theory suggests that IDF acts as a chelator, holding numerous metal ions and preventing their absorption(Reinhold et al., 1975 ; Ismail-Beigi et al., 1977 ; Eastwood and Kay, 1979).

Cellulose is the one source of IDF that has been frequently cited as impacting negatively on Ca nutriture(McHale et al., 1979 ; Slavin and Marlett, 1980 ; Godara et al., 1981). If cellulose affects calcium absorption, it appears to do so through a mechanism other than binding, as cellulose has no ionic charge. If decreased transit time is the explanation, then the question should be asked why other types of IDF that decrease transit time do not decrease calcium absorption and why other minerals are not also affected.

In vitro binding : Cation-Exchange Capacity

In discussing the physicochemical properties of TDF, water absorption, water holding capacity, and cation-exchange capacity have been considered(McConnell et al., 1974 ; Eastwood and Mitchell, 1976 ; Rasper, 1979). The cation-exchange capacity of TDF has been defined as the number of milliequivalents of hydrogen ions held per gram TDF(mEq/g). Basically, a sample of TDF is allowed to become saturated with hydrogen ions. With sodium chloride the hydrogen ions are then stripped from the TDF and titrated. Alternatively, solutions of mono- or polycations are added to the TDF-hydrogen ion mixture, and the cations bound to the TDF are measured. This *in vitro* procedure has variation in experimental protocols among different laboratories. The cation-exchange capacity of TDF represents the foundation behind the idea that TDF adversely affects mineral nutrition via a binding or chelation mechanism. The unsubstituted uronic acid residues contained primarily in pectin and to a lesser degree in hemicellulose polymers are believed to be involved primarily in TDF cation-exchange capacity.

Eastwood and Mitchell(1976) reported that the cation-exchange capacity of dried vegetable fibers ranged from 0.6 to 2.3 mEq/g. With the highest figure measured, and assuming a TDF intake of

35g per day, estimates by calculation are that vegetable fiber could theoretically bind 3220mg of calcium, which is well above the maximum RDA (Table 1). Calculations of this nature add support for the binding theory as a mechanism by which some kinds of TDF affect mineral absorption.

Rasper(1979) measured the cation-exchange capacity of 11 cereal and noncereal sources of TDF. Nine samples had cation-exchange values that ranged from 0.07 to 0.21mEq/g(mean 0.10 mEq/g). Soybean hulls and peanut red skins had values of 0.68 and 0.55mEq/g, respectively. Rasper found the following correlations between the components of the nine cereal fibers and their cation-exchange capacity : hemicelluloses 0.56 ; cellulose −0.49 ; and lignin −0.33. For the combined 11 samples, the correlation coefficients were : hemicellulose 0.46 ; cellulose 0.44 ; and lignin 0.17. The latter correlation values suggest that cellulose may bind minerals, although levels of significance were not provided. Extension and clarification of this work by Rasper would appear to be appropriate. Frolich(1986) and Dreher(1987) review numerous *in vitro* studies on the ability of various sources of TDF to bind different cations.

The number of studies in which both *in vitro* and *in vivo* binding have been investigated and compared is limited. Fernandez and Phillips(1982 a, b) in comparison studies observed *in vitro* ^{59}Fe binding to various sources of TDF(in order of decreasing affinity, lignin>psyllium>cellulose>pectin) on addition to these fibers with or without ascorbate, citrate, cysteine, fructose, or ethylenediaminetetraacetic acid. Then they perfused these polymers along with ^{59}Fe into the duodenal-jejunal section of the dog small intestine. These results showed that lignin and psyllium were potent inhibitors of iron absorption, with less effect by pectin and no effect by cellulose. More *in vitro* and *in vivo* binding comparisons of this nature are needed.

Nontraditional Sources of Total Dietary Fiber

The recommendation for increasing the amount of TDF in the human diet calls for increasing the intake of foods rich in fiber. A gray area of this recommendation is the addition of isolated fibers to the diet in processed foods. Isolated fibers include a variety of cereal and oilseed brans and purified polymers such as cellulose, guar gum, psyllium, pectin, and polydextrose, to mention only a few. Investigators have used these isolated fiber sources to help prove and understand the dietary fiber hypothesis. Specifically, these individual fiber sources are being used to identify the mechanism(s) by which TDF acts in the body.

Mineral absorption in rats

As mentioned, TDF has been reported to have a negative effect on calcium absorption(Marlett, 1984). How TDF specifically affects calcium nutriture is unclear. In an attempt to address the question of whether charged functional groups on TDF affect mineral absorption, three sources of conventional dietary fibers and three nonfood polymers were evaluated in the rat. Mineral balance was determined for phosphorus, calcium, magnesium, iron, zinc, and copper(Schroeder and Gordon, 1985).

Groups of rats(n=5) were fed an AIN-76 diet (American Institute of Nutrition, 1972) containing cellulose, chitin, chitosan, pectin(brown N.F. pectin, CECA, Inc., St. Louis, MO), cholestyramine, or wheat bran(American Association of Cereal Chemists) at dietary concentrations of 2.5, 5, 10, 20, or 40%. These polymers were selected because they possess different charged(e.g., ionic)

groups. Cellulose and chitin were neutral, and pectin had a negative charge because of its uronic acid content(28% of galacturonic units had a free carboxylic group). Chitosan is the deacylation product of chitin, and cholestyramine is a bile-acid-sequestering drug(Questran®, Mead Johnson and Co., Evansville, IN). Both of these latter two polymers contain positively charged amino groups.

Growth rates of animals with cellulose, chitin, and wheat bran were similar at dietary levels of 20% and lower. At 40% dietary fiber levels, growth was reduced because of inadequate energy intake. Pectin impaired growth at 10% concentration in the diet. Animals consuming diets with 10% or more chitosan and 20% or more cholestyramine died of septicemia during the last 10 days of the 21-day feeding period.

Mineral absorption among the groups of animals fed these different polymers at different dietary concentrations were not significantly different except for chitosan and cholestyramine. The absorption of all minerals, especially iron, was impaired in animals consuming diets with the latter two amino polymers. Percentage mineral absorption in animals consuming diets with increasing amounts of cellulose(2.5 to 40%) and 2.5 % chitosan are reported in Table 4.

Three important findings resulted from this study. Calcium balance was not impaired in growing rats fed diets containing cellulose or wheat bran. In addition, the two sources of dietary fiber containing negatively charged groups, pectin and wheat bran, had no adverse effect on calcium balance or any of the other five elements. The action of the amino polymers was unique in that both chitosan and cholestyramine dramatically reduced iron utilization. We have documented this adverse effect of chitosan on iron absorption in two previous studies in which significantly lowered blood hemoglobin and liver iron concentrations were demonstrated(Gordon and Besch-Williford, 1983, 1984). Chitosan, because it is partially dissolved in the stomach acid, produces a viscous bolus in the stomach and small intestine. This physical property is believed to be responsible for reduced growth by impairment of nutrient absorption. The binding of iron by the two amino polymers is thought to take place through the formation of a coordinating complex that appears specific for iron relative to the other transition elements.

Table 4. Percentage apparent absorption of minerals in weanling rats fed diets containing cellulose at five different dietary concentrations or 2.5% chitosan

Dietary residue (polymer)	Dietary content (%)	Percentage absorption[a]					
		P	Ca	Mg	Fe[b]	Zn	Cu
Cellulose	2.5	73	74(210)[c]	69	61 †	43	30
	5.0	69	67(200)	70	57 †	35	22
	10.0	74	73(255)	76	66 †	44	34
	20.0	63	62(210)	51	55 †	39	25
	40.0	–	52(220)[d]	–	–	–	–
Chitosan	2.5	56	60	48	16 ‡	28	16

[a]After 12 days, animals were subjected to a 60-hr balance trial. The amount of minerals ingested(dietary intake) minus minerals excreted(fecal and urine) divided by amount of minerals ingested was used to calculate percentage absorption.

[b]Values in the same column not followed by the same symbol(†, ‡) are significantly different($p \leq 0.05$).

[c]Values in parentheses represent milligrams of calcium retained by animals during 60-hr balance period.

[d]Because growth of these animals was significantly lowered because of lower caloric density of diets and lower food intake, calcium data are only reported for comparative purposes.

An important clinical study tends to support our observations. In the Lipid Research Clinic's Coronary Primary Prevention Trial(1984) on cholesterol intervention using cholestyramine, it was observed that the participating subjects had significantly lowered circulating ferritin levels at the end of the study. The lowered serum ferritin concentrations suggested decreased body stores of iron that developed during the 7 years these individuals ingested cholestyramine. Hemoglobin concentrations did not change between the start and end of the experiment. This study has significance for two reasons. First, no other human study has been conducted over such a long period of time, 7 years. Second, the study was accomplished in men who had adequate iron stores. Even though their iron stores were reduced, it was after a 7-year period with a high polymer intake(24g cholestyramine/day). The decrease in ferritin concentrations, although statistically significant, was not felt to be clinically significant.

Our research to date suggests that the chemical charges of conventional food sources of TDF are insufficient to cause mineral binding. Since TDF does not contain positively charged groups, the evidence further suggests that this mechanism is not responsible for decreased mineral absorption.

Phytic Acid

The classification of phytic acid as a component of TDF is an anomaly. Although phytic acid does constitute part of the plant cell wall and is not digested in the alimentary tract of animals and man(Gordon and Lee, 1982), it is not a carbohydrate. Many scientists in the area of TDF research argue that a true TDF must be a carbohydrate. Not all TDF in the human diet may be derived from plant cell walls. Along with phytic acid(or phytin), dietary polymers that may represent the sum total of TDF in the human diet are illustrated in Fig. 3.

It has long been known that phytic acid will

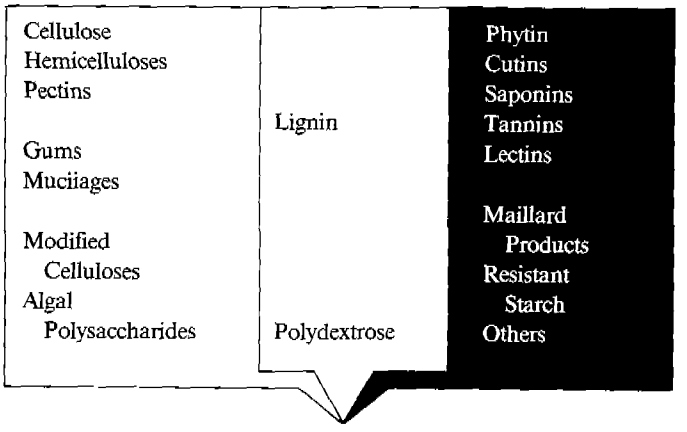

Fig. 3. Dietary components and polymers suggested to contribute to TDF. Plant cell wall carbohydrate polymers and examples of isolated cell wall polymers are indicated on the left. Lignin is a noncarbohydrate plant cell wall polymer, and polydextrose is a synthetic polymer used in foods. There is debate if these polymers should be considered as TDF. Compounds listed on the right are polymers either produced in the manufacture of foods or present as nondigestible compounds. Although these latter compounds are not considered true sources of TDF, they contribute to TDF analytical values and may affect physiological functions in the gut.

impair zinc bioavailability(O'Dell and Savage, 1960 ; Davies, 1982). The discovery that zinc is essential for humans resulted from observations among Egyptian and Iranian populations found to be severely zinc deficient(Prasad, 1983). In addition to consuming diets low in zinc, individuals among these populations were found to be consuming imbalanced diets high in phytic acid. Reinhold et al. (1976) suggested, based on limited data, that TDF and specifically cellulose was the responsible agent for zinc deficiency observed in these populations.

The debate over whether a component of TDF in addition to phytic acid is responsible for impaired zinc nutriture will continue. However, the total action of phytic acid or TDF on other nutrients must be considered. As previously mentioned, extrinsic and intrinsic factors can affect bioavailability(Table 3). In addition to the effects of these two factors, interactions can occur among minerals that can affect their bioavailability(Gordon, 1987).

Recently, it has been shown that phytic acid can enhance the bioavailability of copper(Lee et al., 1988). Phytic acid has also been shown to increase the bioavailability of iron(Gordon and Chao, 1984). We chose to examine further the interactions among phytic acid, zinc, and copper.

Six groups(n=5) of copper-deficient rats were fed AIN-76 diets containing 5 μg copper and 12, 30 or 270μg Zn/g diet with or without 1% phytic acid. After 3 days, the animals were killed, and concentrations of zinc and copper in plasma were determined(Table 5). With increasing amounts of dietary zinc and no dietary phytic acid, plasma copper concentrations decreased($p \leq 0.05$). With 1% phytic acid in the diets containing 12 or 30 μg Zn/g, plasma zinc decreased($p \leq 0.05$). In animals consuming the diet with 270μg Zn/g, this excess zinc overcame the inhibitory effect of the phytic acid on absorption of zinc. Information from my laboratory(Lee et al., 1985) has indicated that phytic acid will impair zinc loading of the intestinal mucosal cell. Without excess Zn, the amount of zinc-binding protein, thionein, synthesized by the cell is lower. The lower concentration of this protein allows for transfer of copper into the body. The entry of zinc into the mucosal cell can be blocked with phytic acid, as illutrated in Fig. 4A. Without phytic acid, or at a high concentration of dietary zinc, the resulting protein metallothionein(thionein plus zinc and/or copper) is increased(Cousins, 1985). Both zinc and copper are bound and held by the protein, retarding the absorption of copper, as illustrated in Fig. 4B.

Table 5. Effect of increasing dietary zinc concentrations and the presence or absence of phytic acid in the diet on serum Cu and Zn concentrations in the Cu-repleted rat[a, b]

Dietary Zn (μg/g)	Dietary phytate (%)	Serum content(μg/dl)	
		Cu	Zn
12	0	43*	100*
12	1	49*	28†
30	0	32†	98*
30	1	46*	37†
270	0	22‡	102*
270	0	23‡	100*

[a]After 3 days of feeding copper-deficient rats diets that contain 5 μg Cu/g in addition to indicated Zn concentrations(Lee et al., 1985).

[b]Values in the same columns not followed by the same superscript symbol are significantly different ($p \leq 0.05$).

Two conclusions can be highlighted from these observations. When phytic acid reduces absorption of zinc, more copper can be made available to the body. The same result can occur if the diet is imbalanced with high zinc concentrations. It is agreed that a diet high in phytic acid would be detrimental to zinc nutrition. However, it is suggested that in moderate amounts, as found in

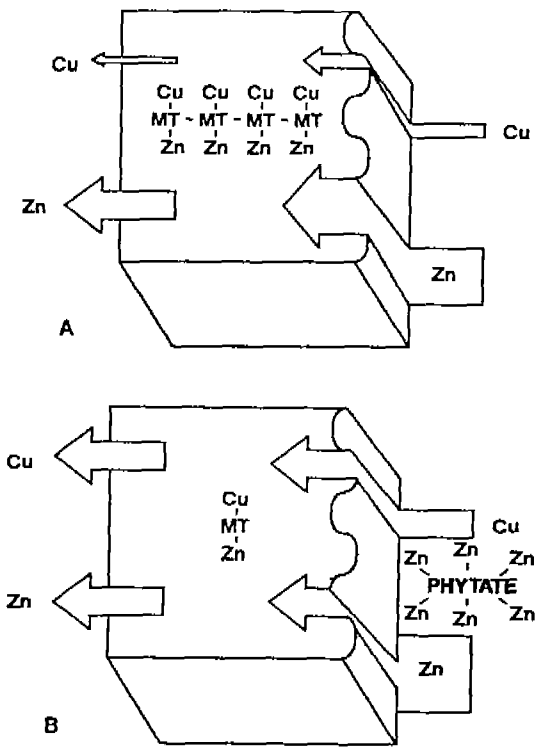

Fig. 4. Interactions among zinc, copper, and phytic acid. Under conditions of high dietary zinc, the amount of metallothionein(MT) protein will increase, binding both zinc and copper. The net result is that less copper can be released from the mucosal cell(A). With phytic acid present to bind zinc in the intestinal lumen, less zinc enters the cell, less metallothionen is produced, and subsequently more copper can pass from the lumen into the circulatory system(B).

a varied diet, these simultaneous series of blockages and enhancements may lead to balanced nutrient absorption.

Soluble Dietary Fiber

With the growing knowledge that SDF is a separate component of TDF that has its own unique physiological function(s) in the intestine, the question arises whether SDF affects mineral absorption. The properties of SDF are such that it dissolves in the stomach and small intestine. It is postulated that SDFs affect nutrient absorption or possibly in some manner regulate plasma nutrient concentrations. To illustrate this point, SDF has been repeatedly reported to be effective in lowering or maintaining blood glucose levels, especially in the diabetic(Jenkins et al., 1986), and in lowering blood cholesterol levels(Chen and Anderson, 1986). Diets to lower blood glucose (Anderson, 1986) in diabetics and cholesterol in individuals with high levels(Van Horn, 1988) appear to include the incorporation of foods containing SDF.

Mechanism of Action

The mechanisms by which the actions of SDF affect nutrient absorption or regulate plasma concentrations are unknown. The actions of SDF may be physical and/or physiological within the gut(Elsenhans, 1983 ; Vahouny and Cassidy, 1985). Two theories are frequently mentioned for the action of SDF on nutrient absorption, and the two actions may be the same or may work synergistically. One theory suggests that the SDF is intermingling with the unstirred water layer along the luminal surface of the intestinal mucosal cells, increasing the thickness of this unstirred layer(Jenkins, 10981). The second theory proposes that the SDF in the unstirred water layer changes the composition of this diffusion barrier and restricts diffusion, thus restricting nutrient absorption(Caspary et al., 1980). With both theories, the water-holding capacity of the SDF can be related to its ability to change viscosity and possibly form gels.

Viscosity changes in the gut produced by SDF and affecting glucose absorption/tolerance have been demonstrated in humans(Gassull et al., 1976 ; Jenkins et al., 1978, 1980 ; Wolever et al.,

1978 ; Crapo et al., 1981 ; Blackburn et al., 1984) animal perfusion studies(Elsenhans et al., 1980 ; Blackburn and Johnson, 1981), and *in vitro* studies (Elsenhans et al., 1980 ; Johnson and Gee, 19 81 ; Edwards et al., 1987). If viscosity in the gut produced by SDF affects the absorption of certain compounds(i.e., glucose and cholesterol), the question arises whether this mechanism of action is common to any nutrient. To examine this latter possibility, the effects of viscosity produced by SDF on the luminal-to-vascular transfer of zinc were measured in the rat using a double-perfusion technique(Kim and Gordon, 1988).

Double-perfusion Technique to Study Zinc Absorption

Details of the double-perfusion technique have been described elsewhere(Smith et al., 1978 ; Steel and Cousins, 1985). Male weanling rats weighing 250~275g were fed a diet containing 50μg Zn/g for 7 days. The animals were anesthetized with phenobarbital solution, the abdominal cavity was opened, and the intestinal tract was exposed. A catheter was inserted into the superior mesenteric artery leading to the small intestine. The vascular perfusate was started through this catheter. All veins along the entire intestinal tract were ligated except those leading from the small intestine to the hepatic vein, from which the vascular perfusate was collected into a fraction collector.

At the beginning of the duodenum and at the end of the small intestine, inflow and outflow catheters were inserted, respectively. Compositions of the luminal and vascular perfusates are presented in Table 6, as are the physical conditions used during each perfusion. The total concentration of zinc in the luminal perfusate was 30mM, consisting of zinc sulfate and 50μCi $^{65}ZnSO_4$. On the basis of the specific activity of the vascular perfusate after it was collected, results were reported as zinc concentrations per unit time. Polymers used in this study were guar gum(Nutriloid TIC pretested guar, high viscosity) and sodium carboxymethylcellulose(Gum Ticalose, TIC pretested 5000, "R" coarse) obtained from TIC Gums, Inc., New York, NY. High methoxy pectin(HMI, Unipectin C) was supplied by Sonofi Bio-Ingredients, Germantown, WI. The B-glucan was provided by the Quaker Oats Company(Barrington, IL). The concentrations of each polymer required to produce luminal perfusates of equal viscosity are reported in Table 7.

With luminal perfusates having a viscosity of 250 cP, it was observed that the transfer of Zn into the vascular system was significantly inhibited by all polymers(Fig. 5) compared to controls with no SDF in the perfusate. Two other polymers were also investigated with similar inhibitory results at high viscosity : sodium alginate(Satialgine S1100, obtained from CECA, Sanofi, Inc., St. Louis, MO) and a second sample of B-glucan.

Table 6. Composition and conditions of luminal and vascular perfusates used in double-perfusion studies in rats

Components	Luminal perfusate	Vascular perfusate
KCL(mM)	3.9	3.9
$MgSO_4 \cdot 7H_2O$(mM)	1.2	1.2
KH_2PO_4(mM)	1.2	1.2
$NaHCO_3$(mM)	2.5	2.5
$CaCl_2 \cdot 2H_2O$(mM)	2.5	2.5
NaCl(mM)	150.0	150.0
L-Glutamine(mM)	6.0	0.6
D-Glucose(mM)	0.56	5.6
Dextran(6% soln)	–	77%
Dexamethasone(μM)	–	0.76
Zinc as $ZnSO_4$(μM)	30.0(+^{65}Zn)	15.0
Horse serum(%)	–	5.0
Flow rate(ml/min)	0.39	2.89
Norepinephrine (μg/min)	–	100
Temp(℃)	37.5	37.5
pH	7.4	7.4
Oxygen	No	Yes

Table 7. Concentration of solube dietary fibers or gums to achieve luminal perfusates of equal viscosity

Viscosity(cps)	0≤10	40	125	250
Shear rate(sec^{-1})	23	23	46	46
Control(no SDF)	0	—	—	—
Guar gum	0.1	0.50	0.55	0.62
Sodium carboxylmethylcellulose	0.1	0.53	0.83	1.00
B-Glucan	0.1	0.46	0.69	0.80
High-methoxy pectin	1.0	1.70	2.50	3.08
Ethylenediaminetetraacetic acid[a]	0.1	—	—	—
Phytic acid[a]	0.1,0.5	—	—	—

[a]Did not change viscosity of luminal perfusate.

Two polymers, pectin and guar gum, were then evaluated at lower viscosities. With a viscosity of 125 cP, zinc transfer was no different compared to a luminal viscosity of 250 cP(Fig. 6). With the pectin concentration reduced to 1%(Table 7), which gave a viscosity equal to or less than 10 cP, zinc transfer was identical to that observed in control animals with no SDF(Fig. 6). Guar gum was then tested at viscosities of 125, 40, or ≤10 cP(Fig. 7). Results indicate that zinc transfer was directly affected by viscosity and was unrelated to type of SDF : zinc transfer increased as viscosity decreased. When viscosity was essentially unchanged with 1% pectin or 0.1% guar gum, zinc transfer was not different from that observed in control animals with no SDF in their luminal perfusate(Fig. 6 and 7, respectively).

Experiments were completed in which all four of the original polymers were evaluated again at viscosities of 125, 40, and ≤10 cP. In addition, effects on zinc transfer of added phytic acid(1% or 0.5%) or 0.1% sodium ethylenediaminetetraacetic acid(EDTA) in the luminal perfusate(without SDF) were determined. Results for these experiments(Fig. 8) were identical to those previously observed and indicated in Fig. 5, 6, and 7. Phytic acid at both concentrations completely inhibited the transfer of zinc into the vascular system as was expected. The transfer of the zinc from the perfusate containing the zinc-EDTA was

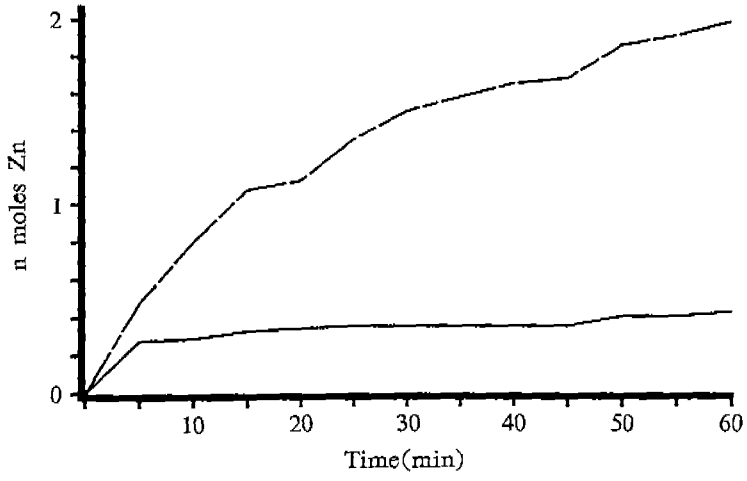

Fig. 5. Zinc transfer from the lumen to the vascular system in rats during a double-perfusion technique over 60 min. In control animals with no SDF in their luminal perfusate(– – – –), zinc transfer increased with time, reaching 2 mol zinc after 60 min. This curve represents the mean data of six measurement(rats). Each of six sources of SDF, 250 cps, was tested in triplicate. The solid line(————) represents the mean data for zinc transfer from 18 animals. Deviation are not illustrated and were less than 70% of mean values.

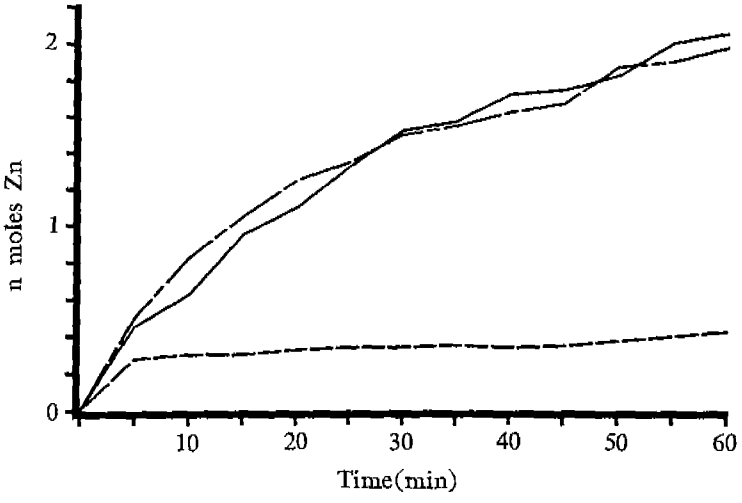

Fig. 6. Zinc transfer from the lumen to the vascular system in rats over a double-perfusion technique for 60 min. Pectin was the source of SDF. At 125 cps(– – – –) zinc transfer was impaired. With 1% pectin(≤10 CP), zinc transfer(– —— – ——) was equal to that observed in control animals with no SDF in their luminal perfusate(———). Each curve represents the mean value obtained from three animals. Deviations are not illustrated and were less than 7% of mean values.

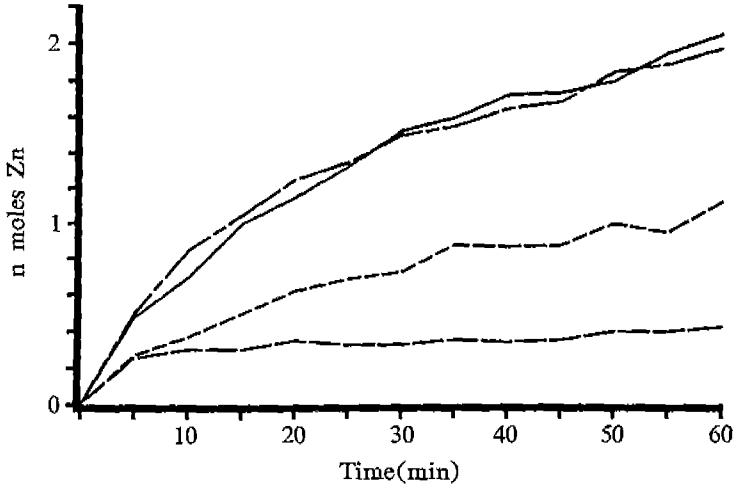

Fig. 7. Zinc transfer from the lumen to the vascular system in rats during a double-perfusion technique over 60 min. Guar gum was the source of SDF. Zinc transfer was measured with luminal viscosities of 125 cps(—— ——), 40 cps(– – – –), ≤10 cps(– —— –), and with no added SDF(control, ———). All curves represent mean values of three animals. Deviations are not illustrated and were less than 7% of the mean values.

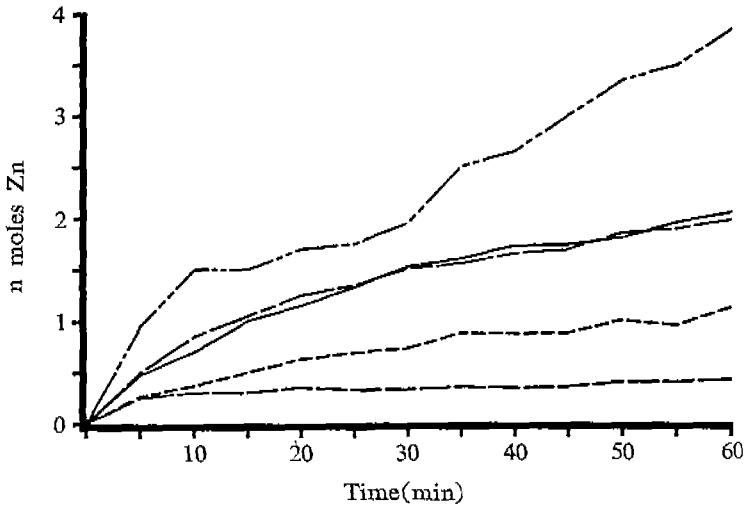

Fig. 8. Zinc transfer from the lumen to the vascular system in rats during a double-perfusion technique over 60 min. Data represent means of analyses of four different sources of SDF evaluated at different viscosities in duplicate. Zinc transfer with luminal viscosities of 125 cps(—— ——), 40 cps(— — — —), ≤10 cps(— —— —), and with no added SDF(————). With 0.1% EDTA in the luminal perfusate(—— — — ——), Zn transfer was higher than in control animals(————). No zinc transfer could be detected when phytic acid(0.5% or 1.0%) was added to the luminal perfusate(not shown). Deviations are not illustrated and were less than 7% of the mean values.

greater than observed in the control animals(Fig. 8). Apparently this complex(zinc-EDTA) is more easily absorbed through the cellular absorption and transport process than is free zinc(Oestreicher and Cousins, 1982).

Summary

The consumption of foods rich in TDF should not be associated with impaired mineral absorption and long-term mineral status. In surveys of populations consuming high amounts of TDF, e.g., Third World populations and vegetarians, gross deficiencies in mineral nutrition have not been noted. If mineral status is low among these groups, it is most likely caused by the inadequacy or imbalance of the diet and not by the TDF. The key word is interaction, which should be interpreted in dietary imbalances that produce nutrient deficiencies.

There are no strong data to support the concept that TDF inhibits mineral absorption through a binding chelation mechanism. Limited data suggest that positively charged groups on polymers such as chitosan and cholestyramine will decrease iron absorption in humans and animals. Because TDF does not contain positively charged groups, future research should be directed at the possible role of protein consumed along with TDF and the combination of effects on mineral nutrition.

Phytic acid is acknowledged as a potent chelator of zinc. However, its association with zinc and its propensity to lower Zn bioavaiability may enhance the absorption of other elements, notably copper and iron. The importance of interactions among nutrients, including TDF, will gain additional attention in the scientific community.

Soluble and insoluble dietary fiber function di-

fferently in the intestine. Insoluble fibers accelerate movement through the intestine. Soluble dietary fibers appear to regulate blood concentrations of glucose and cholesterol, albeit by some unknown mechanism. Increased viscosity produced by the SDF in the intestine may provide an explanation of how this class of polymers affects plasma glucose, cholesterol, and other nutrients.

Employing a double-perfusion technique in the rat, we demonstrated that viscosity produced by SDF will delay transfer of zinc into the circulatory system. This delayed absorption should not be interpreted as decreased utilization. A great deal of additional research is required to prove the importance of luminal viscosity produced by SDF on slowing nutrient absorption or regulating blood nutrient homeostasis.

Increased intake of TDF in the total human diet appears desirable. A dietary intake of 35g/day should not be considered to have a negative effect on mineral absorption. It is important to educate people that an intake of more than 35g TDF/day may cause an imbalance in the diet that can adversely affect mineral utilization.

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