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DIETARY FIBER

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CONTENTS

INTRODUCTION

What we refer to as dietary fiber has been discussed in medical literature from the time of Hippocrates, and probably earlier. The cited quotations from Hippocrates, Galen, English doctors of the sixteenth century and others are related almost exclusively to the laxative properties of whole-grain breads. Burkitt (19) has traced briefly some the early history from Hippocrates, to the Persian physician Hakim (9th century AD), Allinson, Lane, and McCarrison in England, and Graham and the brothers Kellogg in the United States. As a historical aside, it is to be noted that one of the earliest fiber trials is described

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in the Bible (Daniel 1:8–15) and details that Daniel and nine of his cohorts on eating pulses for ten days appeared as healthy as ten others who had partaken of Nebuchadnezzar's feast.

The modern fiber era dates to the writings of Surgeon Captain T. L. Cleave (28); his paper, entitled "The Neglect of Natural Principles in Current Medical Practice" appeared in the *Journal of the Royal Naval Medical Service* in 1956 and sketched the basis for the "fiber hypothesis." His work came to the attention of Denis Burkitt, who popularized it with the collaboration of Hugh Trowell and to considerable extent A. R. P. Walker. There is little question that the scientific work and publications of these four scientists laid the groundwork for the great current interest in fiber. It is equally true that the indefatigable devotion of Burkitt to the cause of fiber has been the stimulus for the interest of both the scientific and lay populations. The American fiber era was born with the paper by Burkitt, Walker & Painter (20) that detailed eight medical conditions prevalent in the United States and missing or rare in Africa and suggested that lack of dietary fiber was the underlying problem. This work caught everyone's imagination and stimulated an immediate flood of popular books on fiber—scientific treatises came a bit later. The public's attraction to fiber may be because for one of the first times in history physicians advised addition of something to the diet rather than deletion.

There are several excellent recent books devoted to dietary fiber (13, 45, 196, 209, 212). These books cover virtually all aspects of fiber research. The enusing discussion does not cover the widely discussed areas of fiber research related to atherosclerosis, diabetes, and colon cancer, but touches on other important facets of fiber research that are accorded less currency.

TERMINOLOGY

The currently accepted term—dietary fiber—was coined by Hipsley in 1953 (82) in an effort to describe the unavailable carbohydrate in plant foods. Dreher (46) has listed over twenty terms applied to fiber. These include crude fiber, plant fiber, roughage, plantix, nonnutritive fiber, and dietary fiber. Only the last of these endures, even if it, too, falls short of precision. Dietary fiber is generally described as plant material that resists digestion by human alimentary enzymes. Dietary fiber is a generic term that includes a number of substances of unique chemical structure, characteristic physical properties, and individual physiological effects. With the exception of lignin, all of the materials that we call dietary fiber are carbohydrate in nature, and with the exception of lignin and wood cellulose, all are broken down to some extent by the enzymes of gastrointestinal bacteria. The products of this digestion are hydrogen, methane, carbon dioxide, and short-chain fatty acids—acetic, propionic, and butyric.

The principal components of dietary fiber are the major structural components of the plant cell wall: cellulose, noncellulosic polysaccharides, mainly hemicellulose and pectic substances, and lignin. Cell walls of immature plants consist of about 25% cellulose, 60% noncellulosic polysaccharides, and a trace of lignin, whereas the mature cell wall contains approximately 38% cellulose, 43% noncellulosic polysaccharide, and 17% lignin (185). The term dietary fiber has now been expanded to include natural or synthetic polysaccharides such as pectin, gums, mucilages, algal polysaccharides, and modified celluloses.

A classification of the chemistry of the substances designated as fiber is presented in Table 1. Selvandran (183) has classified fiber composition as a function of source (Table 2).

Other plant components that are associated with fiber-rich foods and that may themselves assume a physical or physiological role include tannins, waxes (including cutin or suberin), phytic acid, Maillard products, and chitin.

ANALYSIS

Analysis of dietary fiber has become more sophisticated as our knowledge of fiber and its chemistry has developed. Until recently, most compilations of

Table 1 Chemical composition of fiber

Component	Major constituents: Primary chains	Major constituents: Secondary chains	Comments
Cellulose	Glucose	—	Linear polymer with β-(1,4) linkages
Hemicellulose	Mannose, glucose galactose, xylose arabinose	Arabinose galactose glucuronic acid	Mainly β-(1,4) pyranosides
Pectins	Galacturonic acid	Rhamnose, fucose arabinose, xylose	Mainly α-(1,4) galacturans; varying methylation
Mucilages	Galactose-mannose, glucose-mannose, arabinose-xylose, galacturonic acid	Galactose	
Gums	Galactose, glucuronic-mannose, galacturonic acid, glucose	Xylose, fucose, galactose	
Algal polysaccharides	Mannose, xylose, glucuronic acid	Galactose —	Contain sulfate
Lignin	Sinapyl alcohol, coniferyl alcohol, *p*-Coumaryl alcohol	—	Complex, cross-linked, phenylpropane polymer

Table 2 Source and composition of dietary fibers[a]

Food source	Fiber containing tissue	Major components
Cereals	Parenchymatous endosperm; seed coats, partially lignified	Noncellulosic polysaccharides, arabinoxylans, β-D-glucans, glucuronoarabinoxylans, cellulose, lignin
Fruits, vegetables	Parenchymatous flesh; partly lignified vascular tissues; cutinized epidermal tissues	Noncellulosic polysaccharides, pectic substance, xyloglucans, glucuronoxylans, cellulose, lignin, cutin, waxes
Seeds	Parenchymatous cotyledons; thickened endospermal walls	Noncellulosic polysaccharides, pectic substances; xyloglucans, galactomannans; cellulose

[a]After Selvandran (183).

composition of food presented data for crude fiber. Crude fiber values are obtained by a method developed in the early 1800s for analysis of animal feeds. The method consists of treating the test material with hot water, acid, and base. As much as 80% of the hemicellulose, 60% of the lignin, and 50% of the cellulose can be lost during analysis (217). Crude fiber data as related to foodstuffs are of no practical value since they underestimate dietary fiber content from 70 to 370% (174).

Van Soest and his colleagues (66, 216, 218) pioneered methods using neutral or acid detergent that can provide a fairly accurate analysis of dietary fiber. Southgate & Durnin (194, 195) introduced a method involving enzymatic hydrolysis of starch followed by acidic hydrolysis of noncellulose polysaccharides to give the component sugars that are then determined colorimetrically. The cellulose is hydrolyzed in strong sulfuric acid and the glucose determined colorimetrically or by gas-liquid chromatography (GLC) and lignin values are obtained gravimetrically. Other methods make use of enzymes (amylase, proteases) at various stages of analysis. After hydrolysis the component sugars are analyzed by GLC or high performance liquid chromatography (HPLC) and uronic acids are analyzed colorimetrically while lignin is determined as an acid-insoluble residue (55, 130, 155). The various methods are not reproducible in the sense that physical constants such as melting point are, but their results are generally comparable. The enzymatic plus gravimetric methods can measure total fiber or give values for water-soluble and water-insoluble fiber separately. There are several recent reviews of the subject (6, 47, 90).

PHYSIOLOGICAL EFFECTS

The physical properties of dietary fiber determine its subsequent physiological behavior. Eastwood & Mitchell (53) have described fiber as a hydrated sponge passing through the gastrointestinal tract. The physical properties of this sponge (water-holding capacity, cation exchange, adsorption of organic materials) are a function of its origin, age, and mode of preparation. In the colon, bacterial degradation of the fiber will alter its properties. In the cecum, fiber may provide a matrix for adherent bacteria. Stool weight reflects residual fiber and adherent bacteria and is affected by the bacterial degradation products—gases and short-chain fatty acids.

An important property of fiber is hydratability. Hydratability is a function of a fiber's three-dimensional structure as well as of the pH and electrolytes in the solvent (163). Increasing the levels of free polar sugar residues will increase water holding. Since maturity of a plant affects cell wall composition, it also changes hydratability of the fiber derived from that plant. Particle size of wheat bran can alter its water-holding ability and its degradability; thus it can affect stool weight, a physiological response (16, 17). Finely ground wheat bran holds 26% less water than unground bran (53). The range of water-holding capacity (g H_2O/100 g binding substance) goes from a high of 447 and 312 for bran and mango, respectively, down to about 40 for potato and turnip.

Cation Binding

The cation binding and exchange capacity of fiber for calcium (89) and iron and zinc (88) has been demonstrated. There are numerous studies of the effects of fiber-rich foods and isolated fibers on mineral balance in experimental animals and man. The data are, at times, contradictory, but this may be due to duration of individual experiments and to other components of the diet. Wheat bran does not appear to affect calcium, iron or zinc status significantly in rats (7, 22, 61, 142). Other types of fiber (carrageenan, agar, guar gum) interfered with absorption of calcium, iron, zinc, copper, chromium, and cobalt in rats in an experiment lasting eight days (71). Wheat bran fed for more than two years did not affect bone calcium but lowered bone zinc in one study (116); it led to copper, zinc, nickel, and calcium imbalance in another (161). The first study was based on direct tissue mineral analysis, whereas the second used X-ray emission spectrography. Dreher (48) reviews over thirty studies relating to mineral balance in adults. In general, addition of wheat bran or feeding of wheat breads led to negative calcium balance, but levels of fiber and length of study affect results. Thus, van Dokkum et al

(215) found imbalances only when neutral detergent fiber intake increased from 22 to 35 g daily.

Wheat bran added to a high-protein diet affected calcium balance significantly (40) but pectin did not (42). Cellulose added to bread led to negative calcium balance in women (187). Kelsay et al (109, 112) reported that fruit and vegetable fiber led to negative balance for calcium, zinc, copper, magnesium, and silicon. However, the diet contained spinach, whose oxalic acid content affected mineral availability. Repetition of the study and substitution of cauliflower for spinach resulted in no calcium or magnesium imbalance (110). It has been suggested that phytate may be responsible for the mineral imbalances caused by consumption of high-fiber bread (159); however, phytate is not the sole cause of the observed results. Sandstead et al (173) showed that addition of modest (26 g) amounts of wheat or corn bran does not affect copper or zinc in subjects after a three-week period of adaptation. Twenty-six grams of wheat or corn bran represent about 11.5 or 23.9 g of fiber, respectively. Zinc and calcium balances are also not affected after adaptation (172), particularly if dietary protein levels are reduced. These findings reflect those of Cummings et al (40) and emphasize the need for considering all dietary additions in the light of interaction of all dietary components.

Generally, reasonable levels of dietary fiber do not appear to exert a significant influence on mineral balance of adults consuming an adequate diet. However, in the case of populations subsisting on marginal diets or in young children or the elderly in developed countries, the potential for mineral imbalance exists and, where possible, the diets should be augmented with zinc, iron, and calcium.

Binding of Bile Acids

Fibers, fiber-rich foods, and grains all show a capacity to bind bile acids and bile salts. Eastwood & Hamilton (52) demonstrated that grains could bind cholic acid suspended in an appropriate buffer and showed further that the lignin component of the grain was principally responsible for the binding capacity. Studies of binding of bile acids by fractions of alfalfa or bran also show that the presence of lignin in these substances contributes greatly to their binding properties (200). Balmer & Zilversmit (9) found that fiber could bind sodium cholate and cholesterol and Birkner & Kern (14) reported that hemicellulose and residues of apple, celery, lettuce, potato, and string bean could bind sodium glycocholate and sodium chenodeoxycholate. Kritchevsky & Story (118) reported that bran, oat hulls, and cellulose bound sodium taurocholate. A more thorough study examined the binding of cholic, chenodeoxycholic and deoxycholic acids and their glycine and taurine conjugates (199). Each type of fiber exhibited distinct binding properties; generally, lignin and alfalfa bound bile acids and their conjugates more avidly than bran or cellulose. Because of the nature of the experiment, it was not possible to determine bile acid binding to soluble fibers such as pectin, but Story (personal communication) has recently obtained some binding data by using molecular sieve techniques.

More recent studies (213, 214) have shown that fibers can also bind glycerides, fatty acids, and phospholipids. The fiber in cereal products such as maize meal and samp can bind taurocholate, with easily preparable corn meal binding 55% as much taurocholate as a comparable quantity of alfalfa (119). Condiments and spices such as curry powder, paprika, and dried celery all bind taurocholate (198). Curry powder, for instance, binds almost twice as much taurocholate as does alfalfa. The binding of glycocholate and glycochenodeoxycholate by ether-extracted residues of diets ingested by three Seventh Day Adventist populations (vegan, lacto-ovovegetarian, nonvegetarian) and by a non–Seventh Day Adventist population (202) does not reflect either serum cholesterol levels or fiber intakes (120).

Lipidemia

Fiber is related to bile acid metabolism and this may, in turn, influence lipidemia. Portman (152, 153) found that deletion of fiber from the diet of rats increased bile acid turnover time and decreased fecal steroid excretion. The hypocholesterolemic effect of pectin in cholesterol-fed rats was attributed to increased bile acid excretion (126). Dietary pectin is hypocholesterolemic in man (103, 105, 136) and results in significant increases in fecal bile acid content. In rats, substitution of virtually any source of fiber for cellulose increases the concentration of fecal neutral and acidic steroids (117).

The effects of fibers on serum and liver lipids in experimental animals (117) and on serum lipids and lipoproteins in humans (178) have been summarized. In general, soluble fibers such as pectin or guar exert hypolipidemic effects but insoluble fibers such as wheat bran or cellulose do not. In 1980, Kay & Truswell (106) summarized results from 24 studies in which soft white wheat bran was fed to human subjects. The amount of bran fed varied between 14 and 72 g/day and the studies lasted between 2 and 52 weeks. Only two of the studies showed a decrease in plasma cholesterol (reduction of 7 and 10%, respectively). The situation has not changed since then. Considering the data on bile acid binding and excretion by dietary fiber and findings vis-à-vis plasma or serum and liver cholesterol, one must conclude that effects of fiber on bile acid metabolism represent, at best, a small part of the overall mechanism(s) related to hypolipidemia.

Digestion

Dietary fiber exerts its influence along the entire alimentary tract from ingestion to excretion. Heaton (73) has tabulated the action of fiber at the various levels of the digestive tract (Table 3). Fiber-rich foods require a longer chewing time, hence, take longer to ingest (131). Continued chewing results in increased flow of saliva and dilution of the oral contents. It has been suggested (168) that this action helps remove food particles from the teeth and may reduce the buildup of dental plaque.

Chewing enhances the flow of gastric juice and, between the additional gastric juice and saliva, the volume of the gastric contents increases which leads to a feeling of satiety. Ingestion of whole fruit results in a significantly greater feeling of satiety than ingestion of a calorically equivalent amount of fruit juice (72). Whole apples are more satiating than apple puree or apple juice (69). Eating high-fiber bread reduced ad libitum caloric intake (68, 135).

The increase in chewing time when eating fiber-rich foods may also result in reduced food intake. Duncan et al (51) compared subjects eating a diet low in energy but high in fiber (fruits, vegetables, legumes, whole grains) with a group eating a high-energy, low-fiber diet (fats, rich desserts). The daily caloric intakes on the two diets were 1570 and 3000 kcal, respectively. Total eating time on the high-fiber diet was 33% greater (69 vs 62 minutes/day) and chewing time was 42% greater (17 vs 12 minutes/meal). After eating, the satiety scores of subjects ingesting either diet were identical.

Dietary fiber and fiber components influence rates of gastric emptying. Polysaccharides that gel and increase the viscosity of stomach contents delay gastric emptying. Pectin and guar gum slow gastric emptying in normal (83) or overweight (226) subjects, as well as in subjects with bowel problems (123). Some of this effect may be a function of the viscosity of the fiber. Leeds (122) showed that the times required for half emptying of glucose from the stomachs of rats fed guar gum preparations of low, intermediate, or high viscosity were 14, 28, and 41 minutes, respectively. A summary of fourteen studies of gastric emptying in humans (1) reveals that pectin and guar gum generally increase emptying time, but there are studies in which they have no effect. In one experiment, cellulose was found to decrease emptying time.

Table 3 Effects of dietary fiber in the gastrointestinal tract[a]

Site	Activity
Mouth	Stimulates saliva
Stomach	Dilutes contents; prolongs storage
Small intestine	Dilutes contents; delays absorption
Large intestine	Dilutes contents; bacterial substrate; traps water; binds cations
Stool	Softens; enlarges; prevents straining

[a]After Heaton (73).

Fiber-rich foods tend to decrease nitrogen digestibility. Studies carried out with fruits and vegetables, whole-wheat bread and wheat or oat bran all report increased nitrogen excretion (21, 39, 63, 108, 111, 114, 197, 221). When fiber components were used, cellulose (188) and ispaghula husk (156) showed no effect, but pectin (44) did. However, in another experiment (87) cellulose and hemicellulose were active but pectin was not. These contradictory findings reveal the need for more definitive work in this area.

There is, at this writing, no in vivo evidence that fiber can alter protein digestibility or affect amino acid absorption. Guar gum inhibited hydrolysis of a tripeptide by everted segments of rat jejunum but had no effect when intestinal homogenates were used (54).

Fiber affects secretion of gastrointestinal hormones, which in turn increases gastric pH (125) and reduces secretion of glucagon (92) and gastric inhibitory peptide (137). Brans and unrefined grains exhibit greater buffering capacity than polished rice or white flour (206), and wheat bran or guar gum have been shown to modify gastric pH in subjects fed a standard meal (170). Some fibers influence the activity of pancreatic enzymes and in this way they limit the availability of absorbable products of digestion. Schneeman and her colleagues have done much to elucidate the effects of fiber on pancreatic enzyme activity. In vitro studies (50, 177) showed that insoluble fibers reduced activity of amylase, lipase, trypsin, and chymotrypsin, whereas pectin had no effect on trypsin activity but enhanced activity of the other three enzymes.

Studies conducted in rats (62, 149, 166, 184) indicated that pancreatic enzyme activity was unaffected by pectin, guar, or cellulose and was enhanced by wheat bran. In the intestine, activities of amylase, lipase, trypsin, and chymotrypsin were enhanced significantly in rats fed guar or pectin, but cellulose and wheat bran had virtually no effect. These results are not consistent with data obtained by other experimental modalities (70, 87). Pectin has been reported to decrease activity of mucosal alkaline phosphatase (18, 203), and lactase and invertase (142, 203) to have no effect on disaccharidases (204) or to enhance enzymic activity (181). Studies using some type of standardized protocols (fed, re-fed, or fasted animals, preparation of tissue, etc) are needed.

Glycemia

There are many studies demonstrating that dietary fiber can modify plasma glucose and insulin responses after a single test meal. The data have been reviewed extensively (3, 91, 122, 228). Generally, healthy volunteers were given a glucose load (50 g) alone or with 12 g of fiber (guar gum, pectin, methoxycellulose, bran) and in every case there was a flattening of the glucose tolerance curve. The insulin response was not always proportional to the glucose response (96). The reduced glycemic response was correlated with the viscosity of the fiber preparation. Studies using xylose, which is not metabolized, have shown that the lower glycemic response is due to delayed absorption rather than to malabsorption (54).

Another aspect of the relationship between dietary fiber and carbohydrate availability involves the effects of endogenous fibers of foods on bioavailability of carbohydrate from the same food. This effect has been labeled "biological equivalence" by Otto et al (143) and "glycemic index" by Jenkins and his associates (95, 97). Different foods are digested at different rates (98, 141). Jenkins et al (97, 98) subjected different foods to digestion by human enzymes in a dialysis tube, with the rate of digestion being assessed by the rate of release of the digestion products (glucose, maltose, etc) into the dialysate. The glycemic index of a food is calculated by comparing the blood glucose response evoked by that food with the response evoked by bread or glucose. Jenkins & Wolever (93) reported on the glycemic index for a large number of food classes. There were wide variations within each class. The glycemic index is a function of a number of factors, fiber content being only one of them. The concept of glycemic index provides an idea of digestibility of starchy foods and demonstrates that the digestible components of these foods may have a fiber-like effect. Ross et al (166) report that glycemic index of processed wheat products correlates positively with the percentage of starch digested in vitro, which in turn correlates positively with the degree of starch gelatinization. Glycemic indices derived in different laboratories are in relatively good agreement (31, 94, 99, 143, 222), differing by about 10% (222).

Transit Time and Stool Weight

Many sources of fiber reduce mouth-to-anus transit time. Transit time can be measured by administering a dye such as brilliant blue or carmine red or by feeding plastic pellets, polyethylene glycol, chromium, or isotopically labeled capsules and then measuring first appearance (128) and/or time of recovery of a previously specified number (usually 80%) of the markers (81), or kinetically analyzing the excretion curves (229). None of the methods is completely satisfactory (190).

Particle size plays an important role in determining transit time and fecal weight. Coarse bran is more effective than fine bran in reducing transit time and increasing fecal weight (16, 77, 115). The source of the bran is also important. Smith et al (189) fed fine or coarse bran derived from either soft white or hard red spring wheat. With soft white wheat bran the coarse material increased fecal weight by 59% and decreased transit time by 59%; fine bran increased fecal weight by 26% and decreased transit time by 24%. Coarse red spring wheat bran increased fecal weight by 28% and decreased transit time by 66%, and the fine bran increased fecal weight by 15% and decreased transit time by 9%. The results were attributed to water-holding capacity, although Stephen (197) has suggested an inverse relationship between water holding capacity and fecal weight. Wrick et al (229) fed subjects coarse or fine wheat bran, cellulose, and cabbage and found no relationship between total fecal water and frequency of defecation.

Over a half century ago Williams & Olmsted (224, 225) fed volunteers a number of different fibers, including bran, cabbage, agar, and sugar beet pulp. Greatest increments in stool weight were observed in subjects fed agar or cabbage but stool weight did not correlate with the subjects' assessment of laxative effect. They also found no relationship between stool weight and recovered residue. There was some correlation between stool weight and unrecoverable (in stool) cellulose and hemicellulose on one hand, and stool content of volatile fatty acids on the other. This suggests an effect of metabolic products of fiber. Cummings (37) reviewed the effect on stool weight of a number of fiber preparations. Bagasse and bran increased stool weight by 124 and 117%, respectively (based on a fiber intake of 20g), while pectin and guar gum increased stool weight by less than 20%.

Digestible fiber provides substrate for colonic flora that proliferate, and bacterial mass represents a large fraction of fecal mass of subjects fed this type of fiber. Undigestible fiber residue represents most of the fecal bulk of those subjects to whom it is administered, with bacterial mass representing only a small portion of the fecal solids. Cummings et al (41) fed subjects bran (18 g fiber/day), cabbage (18.3 g fiber/day), carrot (20.1 g fiber/day), apple (21.9 g fiber/day), and guar gum (17.2 g fiber/day). Increase in fecal weight per day was as follows: bran, 107%; cabbage, 63%; carrot, 62%; apple, 44%; and guar gum, 16%. The increase in stool weight was correlated significantly with the amount of pentose-containing polysaccharides present in each particular fiber.

Bran is not degraded to any great extent by colonic bacteria; thus its water-holding capacity exerts a significant effect on stool weight. There is some bacterial proliferation in the large intestine of bran-fed individuals, and the excreted bacteria (which are about 80% water) add to the bulk of the stools.

Short-Chain Fatty Acids

When dietary fiber, or starch that escapes intestinal digestion, is degraded by colonic bacteria, the principal products are carbon dioxide, hydrogen, methane, and the short-chain fatty acids (acetic, propionic, and butyric). The amount of acetate produced is about 3–4 times that of either propionate or butyrate (76). Cummings (34–36) has reviewed the literature and discussed at length the implications of short-chain fatty acid metabolism and utilization. The short-chain fatty acids are absorbed from the colonic lumen (134) in a process that is concentration dependent and is associated with a rise in pH and fall in CO2, stimulation of water and sodium uptake, and accumulation of bicarbonate.

Cummings (36) has presented a schematic representation of the integrated processes. The absorbed short-chain fatty acids are metabolized by the colonic epithelium, liver, and peripheral tissues. Cummings & Branch (38) estimate that short-chain fatty acids represent about two thirds of the potential energy available had the carbohydrate been absorbed by the small intestine. The main products of their metabolism in the colonic epithelium are carbon dioxide, water, and ketone bodies. In the rat cecal wall, about 12% butyrate is converted to ketone bodies (160). In human colonocytes, butyrate is metabolized to carbon dioxide and ketone bodies (165). The proximal colon converts more butyrate to ketone bodies than the distal colon. The metabolic fates of acetate and propionate in the colon are unclear. The short-chain fatty acids enter the portal blood and are transported to the liver. Although acetate, propionate, and butyrate are all present in human portal blood (43), only acetate reaches the peripheral tissues (150).

Høverstad & Bjørneklett (85) studied the relations between short-chain fatty acid excretion, transit time, fiber intake, and fecal weight in human volunteers. Short-chain fatty acid levels in the feces (but not their concentration) correlate significantly with mean fecal weight and transit time, and fecal weight and transit times were significantly correlated with each other, but dietary fiber did not correlate with any of the other variables. They concluded that substrates other than fiber were principal contributors to short-chain fatty acid production. The other substrates might well have been various starches that had escaped digestion. They found seven short-chain fatty acids in the feces, namely (% per day) acetate (54.1), propionate (17.1), isobutyrate (1.8), butyrate (20.7), isovalerate (2.7), valerate (2.7), and caproate (1.8).

The interests in the gastrointestinal effects of dietary fiber and of short-chain fatty acids run parallel to one another, and it has been tacitly assumed that fecal short-chain fatty acids arise from dietary fiber. However, a study by Scheppach et al (176) has shown that addition of a fermentable fiber (not specified) to normal diets of healthy subjects did not affect concentration of short-chain fatty acids. Concentrations (μmol/g dry wt feces) of acetate, propionate, and butyrate were 113 ± 10, 45 ± 6, and 30 ± 8 before addition of fiber and 122 ± 31, 50 ± 17, and 22 ± 4 afterwards. (The values presented here have been rounded.) The data also show that addition of fiber increases variability of response. The presence of short-chain fatty acids in feces of patients with short bowel syndrome is noteworthy. The fate and function of these acids in humans are unknown but they offer an important area for future investigation, one that may exert a profound effect on the metabolism of the colon, liver, and other tissues.

Morphology

The jejunal villi in the human fetus are finger-like and regular, as they are in typical adults in most Western societies (26, 30). The intestinal villi of vegetarians (26) or of individuals in developing countries (144) are, contrastingly, broad and leaf-shaped with many ridges and convolutions. Rats maintained on a fiber-free diet exhibit finger-shaped villi; however, when they are fed a commercial, fiber-containing diet or are fed a semipurified diet containing pectin, there is a drop in the number of jejunal villi and they exhibit mucosal ridges (201). These findings suggest that the morphology of the developing small intestine can be affected by diet. Dietary fiber supplementation can also influence intestinal length and weight in adult animals (18, 178, 231). Alterations in intestinal morphology after feeding of various fibers can be correlated roughly with the bile-acid-binding capacities of the fibers (23).

Cassidy et al (24) have studied the effects of diets free of fiber or containing a soluble (guar gum) or insoluble (cellulose) fiber on intestinal morphology in the suckling and weanling rat. Ninety-eight percent of villi in suckling rats are finger shaped. There are no finger shaped villi in rats fed commercial ration and only 5% in those fed a fiber-free diet. In rats fed 10% cellulose the ratio of finger-shaped villi is 80/20 and in rats fed 5% guar gum the ratio is exactly reversed, namely, 20/80. Rats fed a fiber-free diet exhibit fewer jejunal villi and shorter villi; those fed guar gum have more crypt and villus cells.

The intestinal length and mucosal protein content of rats is affected by dietary fiber (211). Intestinal length of rats fed a fiber-free diet is 124 ± 6 cm. Insoluble fibers (alfalfa, cellulose, bran-pectin 3:1) cause a slight shortening to 121 ± 3 cm. Pectin and psyllium increased the length to 127 cm, and guar reduced it to 118 cm. In the proximal intestine, all fibers tested reduce protein content significantly from 58 ± 7 to 32 ± 2 mg (average of six fibers). In the middle intestine the protein content of the control tissue is 65 ± 6 mg; alfalfa feeding leads to significant decrease in protein content to 40 ± 4 mg and guar gum to a significant increase to 87 ± 2 mg. Cellulose, bran-pectin 3:1, pectin, and psyllium have no significant effect. Only guar gum and psyllium increase significantly the protein content of the distal intestine from 41 ± 5 to 70 ± 6 and 64 ± 5 mg, respectively.

It is evident that the level and type of dietary fiber can alter the structure of the intestine and influence many aspects of intestinal metabolism. The relation of these changes to overall metabolic effects has not yet been elucidated.

Gastrointestinal Disorders

Diverticular disease of the colon is rare in African blacks. Painter (146) in discussing the literature on diverticulosis in Africa cites seven studies in which only 20 cases were seen in almost 12,000 subjects. In contrast, necropsies from Western countries report an incidence between 2.6 and 45%, and based on barium enemas the incidence ranges from 4.2 to 40%. Diverticulae are caused by high, localized, intraluminal pressures, which cause so much segmentation that the colon functions as a series of small reservoirs rather than as a tube. Painter et al (147) found that a higher-fiber diet abolished or relieved 90% of the symptoms in 70 subjects. The treatment required administration of bran three times a day. Bran fed as bran, bran tablets, biscuits, or crispbread worked equally well. Painter (146) points out that the optimum amount of bran required is different for each patient and must be arrived at by trial and error and adds that the rest of the diet should also be altered to include more fiber-rich foods.

In 1980, Almy & Howell (2) reviewed the status of diverticular disease. They commented on the fact that the fiber hypothesis had revitalized interest in diverticular disease but pointed out that only one randomized, controlled trial had been carried out (15). They also pointed to the many unresolved problems, including the need to ascertain the role of a high-fiber diet as a means of possible prevention of this disease. A recent review (1) has identified the gaps in the literature regarding the effects of fiber in diverticular disease.

There are a number of gastrointestinal disorders in which dietary fiber or its lack have been implicated. In most cases, the populations that are compared have extremely different life-styles and fiber intake is but one readily discernable difference. In most cases, the evidence is purely epidemiological and it is virtually impossible to carry out clinical trials or comparisons. In almost every case the comparison is made between a developed population ingesting diets high in calories and possibly low in fiber and developing populations whose diets are different as are almost all other aspects of their daily life.

The incidence of gallstones is associated with hyperglycemia, hypertriglyceridemia, obesity, and excessive caloric intake (101). Scragg et al (182) examined the effects of diet in a cohort of newly diagnosed cases of gallstones. The fact that the disease was newly diagnosed suggests the subjects had not yet changed their dietary life-style. Increased risk was associated with increased intake of simple sugars, calories, and fat. Decreased risk was associated with increased alcohol intake and in one logistic regression model (which excluded sugar) with increased intake of fiber. Analysis of the daily fiber intake of 233 patients (176 women, 57 men) and an equal number of controls showed the patients and controls ingested an average of 18.6 and 20.1 g fiber daily, respectively. Comparison of 255 patients with 322 hospital controls showed that the former ingested 18.6 g/day of fiber and the latter 18.7 g/day.

The lithogenic index is a measure of the cholesterol saturation of the bile and is based on the relation of the molar ratios of bile acids, phospholipids, and cholesterol. No clinical trials of fiber effects on gallstone formation have been reported so that the evidence relating to fiber intake and lithogenesis in humans is circumstantial. Increased levels of biliary deoxycholic acid may also be related to risk of gallstone formation. Wheat bran (30–50 g/day) has been shown to reduce the amount of deoxycholic acid in bile and to lower the cholesterol saturation index as well (132, 151, 223). Comparison of the effects of feeding pectin (12 g/day), cellulose (15 g/day), and lignin (12 g/day) for four weeks to normal subjects showed that only pectin lowered the lithogenic index (78). Oat bran (18 g/day) did not affect the lithogenic index in normal subjects (5). Clearly, the possible fiber effect is unique for specific types of fiber, which suggests that a specific mechanism should be sought. In the hamster lithogenesis model, lignin (167), pectin (11, 121), and cellulose (121) inhibit gallstone formation. Pectin appears to promote regression of gallstones but cellulose does not (121).

Effects of fiber on subjects with irritable bowel syndrome are equivocal. A dietary survey of patients and controls showed that the former group ingested less vegetable fiber, but otherwise intake of total fiber, fruit fiber, or cereal fiber was the same in the two groups (79). A diet high in wheat bran was reported to reduce pain in one study (129) but not in another (192). A 24–36-month followup of 14 subjects treated with a high-fiber diet showed that 7 were improved, 2 worsened, and 5 remained unchanged (80). Fielding (64) has suggested that patients whose major problem is constipation will be the ones most benefitted by increasing their bran intake.

Inflammatory bowel disease refers to Crohn's disease and ulcerative colitis, two conditions that have in common the fact that they occur in young adults and are of unknown etiology. The incidence of Crohn's disease is about 1–2 per 100,000 in the United States, England, Scotland, Norway, Denmark and Switzerland and is somewhat higher in Sweden and South Wales; the incidence of ulcerative colitis in the same areas is 4–7 per 100,000 (74).

Since the 1950s the incidence of Crohn's disease (32) has risen remarkably in Western countries (44). The timing of the appearance of the disease, the countries where it is prevalent, and its absence in American and African blacks led to the hypothesis that this disease may be due to a lack of dietary fiber (208). Most case-control studies of Crohn's disease show that cases ingest considerably more sugar than controls (74). Thornton et al (205) studied the diets of thirty newly diagnosed Crohn's patients and found that their sugar intake was nearly twice that of matched controls (122 vs 65 g/day). They also had a very low intake of raw fruit and vegetables. Intakes of cereal and cooked vegetables were similar for cases and controls as were intakes of fat, protein, and starch. Others find little difference in fiber intake between cases and controls (104, 205). Treatment of Crohn's disease with diets high in fiber has yielded inconsistent results. Heaton et al (75) observed some benefit but Jones (100) and Levenstein (127) and their colleagues did not. Considering the unknown etiology of Crohn's disease and its relative rarity, it is not surprising that the literature presents equivocal results. This is an area where many more careful studies are needed. Although Crohn's disease and ulcerative colitis are often considered together, there have been no suggestions that dietary fiber could play a role in the latter syndrome.

The definition of constipation is subjective. The majority of the Western populations are said to have a single bowel movement daily with an average weight of 120–130 g (162), but a wide variation is observed (230) and there seems to be an effect of personality, so that on the same diets extroverts excrete more stool than introverts (210). Connell et al (29) suggested that constipation be defined as fewer than three bowel movements a week. However, many people who fit this description do not consider themselves to be constipated. Other suggestions have been to base the definition on stool weight, transit time, and stool consistency, but none of these parameters is completely acceptable.

Clark & Scott (27) found 5–25 g of coarse bran daily decreased constipation in elderly men but not in elderly women. Coarse wheat bran (10–20 g/day) or ispaghula were found to relieve constipation in elderly patients and to be superior to laxatives (4, 191). A one-year study in a nursing home found that 25 g/day of fiber eliminated the need for laxatives (84). Both corn and wheat bran (20 g/day) increased frequency of defecation and fecal weight and decreased transit time in a group of ten women (67). The data suggest the fiber, especially wheat bran, is effective in the treatment of constipation.

Anti-Toxic Effects

Dietary fiber possesses anti-toxic effects that are seldom recognized. Wilson & De Eds (227) found that rats fed 6% fiber were more protected against toxic effects of cadmium than those fed 3% fiber. Ershoff and his colleagues (56–60) carried out a number of studies in which the addition of fiber to rat diets protected them against the toxic effects of surface-active agents, food colorings, and other agents. The studies were designed to test weight gain and survival and did not include pathology. When Tween 20® (15%) was added to a basal, fiber-free diet, survival over a 21-day period was reduced by 67% and weight gain by 65%, compared to the basal diet. Addition of 10% alfalfa meal to the Tween-containing diet led to 100% survival and 16% higher weight gain than the control. When 10% cellulose was added to the diet survival was 100% but weight gain was 43% below the control (56). When 5% amaranth (FD&C Red No. 2) was added to a basal, fiber-free diet fed to rats, they did not gain weight and only one of six survived for 14 days. Addition of 10% pectin, cellulose, or alfalfa to the diet gave 100% survival and optimum

weight gain (6
Yellow No. 5) or Sunset Yellow (FD&C Yellow No. 6) (58).

Ershoff tested the effects of basal and stock diets on toxicity of graded levels of sodium cyclamate in immature Sprague-Dawley or Long Evans rats (57). When the basal diet was used, Sprague-Dawley rats showed, after 21 days, 31% less weight gain on 2.5% sodium cyclamate and 71% less weight gain on 5% sodium cyclamate. The weight gain of Long Evans rats was unaffected by 2.5% sodium cyclamate and was reduced by 38% on 5% cyclamate. These results illustrate a strain difference in response. When added to stock diet, neither 2.5 or 5.0% sodium cyclamate affected weight gain in either strain. Table 4 summarizes the effects of a variety of fibers on weight gain of rats fed 5% sodium cyclamate. While there is a range of effect on weight gain, ranging from 47% of control on wheat bran to 107% of control on psyllium seed, there was 100% survival compared with 21% when the sodium cyclamate was added to the fiber-free regimen (59).

Adverse Effects

There are possible adverse effects of excess fiber ingestion. There are physical effects due to obstruction or excess gas formation. Pectins, gums, and hydrophillic colloids (which can be extensively hydrated) can swell and cause bolus obstruction of the esophagus or intestine (12, 102, 140, 193). Stomach

Table 4 Protective effect of dietary fiber in immature rats fed 5% sodium cyclamate[a]

		Average body weight gain (g)	
Dietary group	No.	7 days	14 days
Basal (B)	12	34 ± 2	78 ± 5
B + 5% sodium cyclamate (BC)	24	6 ± 1[b]	19 ± 4[c]
BC + supplements (10%)			
Apple powder	6	8 ± 2	25 ± 3
Wheat bran	12	8 ± 2	36 ± 4
Locust bean gum	6	13 ± 2	38 ± 5
Guar gum	6	17 ± 1	53 ± 3
Gum tragacanth	6	28 ± 2	65 ± 3
Gum karaya	6	30 ± 2	71 ± 3
Blond psyllium seed	6	39 ± 3	83 ± 4
Cabbage powder	6	20 ± 2	58 ± 3
Alfalfa meal	12	17 ± 3	55 ± 5

[a]After Ershoff & Marshall (59) basal diet: 66% sucrose; 24% casein; 5% cottonseed oil; 5% salt mix.
[b]75% survival.
[c]21% survival. All other groups 100% survival.

obstruction (phytobezoar) has been described in a subject who ingested a large amount of orange pith (133). Volvulus is a form of intestinal obstruction caused by twisting of the sigmoid colon. This condition is not common even in the people of developing countries who subsist on very high-fiber diets; it is very rare in Western societies. However, small bowel volvulus and sigmoid volvulus have been reported (8, 49, 65, 171). Persorption, passage of particles from the intestine into the circulation, has been reported with microcrystalline cellulose (145). Carrageenans have been shown to be persorbed in the rat (139). Volkheimer et al (219, 220) reported on persorption of raw starch granules in humans. Four to six days after the subjects were fed corn stained with fuchsin, dyed plant fibers of up to 500 μm in length were found in the blood (179). This is an area requiring more experiments to establish how widespread the process is and what its toxicological implications might be.

Adverse metabolic effects due to fiber ingestion include slowed absorption of digoxin (17) and penicillin (86). More work is needed to understand fully the influence of dietary fiber on drug disposition. In humans, dietary fiber has no effect on absorption of ascorbic acid (113), riboflavin (164), pyridoxine (124, 180), folate (169), or pantothenate (207). Rats fed pectin or cellulose excrete more vitamin B_{12} than rats maintained on fiber-free diets (33).

Since gelling fibers can interfere with absorption of lipids, effects of fiber on absorption of fat-soluble vitamins is of particular interest. In humans, wheat bran, cellulose, pectin, guar gum, carrageenan, or lignin had no effect on postprandial serum levels of vitamin A (10, 103, 157) nor are vitamin A levels low in vegetarians (157). Kelsay (107) found more vitamin A excreted in subjects on a diet rich in vegetables and fruit than on a low-fiber diet. Neither pectin nor cellulose alter vitamin A excretion in rats (148, 186). High (6–8%) levels of dietary pectin decrease vitamin E bioavailability in rats, but low (3%) levels do not (175); levels of wheat bran as high as 20% have no effect (138). There are suggestions that high levels of dietary fiber may interfere with vitamin D metabolism (158, 232).

Diets high in fiber are associated with fecal energy loss (63, 108, 195). This may be viewed as an adverse effect and was discussed above. The loss may be as high as 300 kcal/day depending on the type and amount of fiber. The loss of energy is in the form of protein and fat, but to what extent these represent bacterial residues is not known. The extent of energy loss is relatively small and may be important only in subjects subsisting on marginal caloric intake.

The influence of dietary fiber on mineral balance has been discussed. In general, there is no real problem in populations subsisting on adequate diets. However, deficiencies can develop in countries where the diet is marginal in calories and micronutrients. Zinc deficiency is seen in the Middle East in populations subsisting primarily on unleavened whole-grain bread (25, 88, 154).

Determining fiber effects on micronutrient availability involves the question of adaptation to diet, a question that has not been resolved. In general, problems arise in subjects whose fiber intake is high in relation to other nutrients. The subjects most at risk are children and the elderly, whose diets are likely to be low in micronutrients but high in fiber. The possibility of augmenting diets with some trace minerals—calcium, iron, zinc—should be considered.

EPILOGUE

The subject of dietary fiber is broad, and every facet of this area of nutrition has been discussed at numerous conferences and in many publications. The foregoing discussion has attempted to touch on the less-publicized, but still important, research. One question still remaining is how much dietary fiber do we need and which kind. After a review of available data, an expert panel (1), addressing itself to the United States population, concluded our daily intake of fiber should be derived from the everyday diet, i.e. whole grains, vegetables, fruits, rather than from specific supplements. The dietary intake would ideally provide a ratio of insoluble to soluble fiber of about 3:1. The optimum intake, based on considerations of desirable fecal weight and transit time, would be about 20–35 g/day or about 10–13 g per 1000 kcal. This level of intake was suggested for the normal healthy adult. Additional factors must be taken into account when prescribing for the young, the elderly, or persons with special dietary requirements.

Dietary fiber is a necessary component of a normal diet and not a nutritional panacea. There is a massive research effort in the fiber field. It should provide answers to some of the questions raised in the foregoing discussion as well as in other important health-related areas, principally colon cancer. In the last dozen years there have been great advances in our understanding of fiber analysis and mechanisms of physiological action. It is realistic to suppose that equally large strides will be taken within the next few years.

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