# Dietary Fiber and Health [a]

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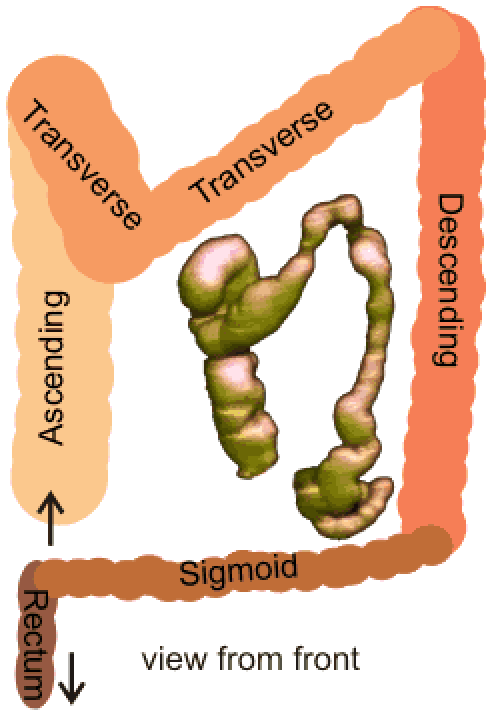
## Dietary fiber

Dietary fiber [257] is generally accepted as having protective effects[b] against a range of diseases predominant in Western developed countries [1608] including colorectal cancer[d], coronary heart disease [1360], diabetes, obesity, and diverticular disease[i]. They also may help control obesity by increasing satiety and reducing appetite within weight-loss programs [1528]. Some have particularly beneficial effects in treating related conditions such as hypertension in the overweight [1258]. The term 'dietary fiber' is commonly defined as plant material that resists digestion by the secreted enzymes of the human alimentary tract but which may be fermented by microflora in the colon. As such, it includes most hydrocolloids. After much debate, there is now an acceptable legal definition of 'dietary fibre' that include carbohydrate polymers with one or more beneficial physiological effects [1678].[e] Increased fiber consumption has been associated with lowering total serum cholesterol and LDL cholesterol, modifying the glycemic and insulinemic response and protecting the large intestine from disease. While the physiological properties of a polysaccharide are difficult to predict on the basis of structure alone, they are partly predictable on the basis of physicochemical properties such as fermentation, water-holding capacity, viscosity, and bile acid binding. The main components of dietary fiber are non-starch polysaccharides including cellulose, hemicellulose (composed of a variety of heteropolysaccharides including arabinoxylans), β-glucan, and pectins. Another, and often major, component of plant foods that escape absorption and digestion in the small intestine and behaves, at least physiologically, as dietary fiber is resistant starch. Non-digestible oligosaccharides have aroused significant interest in recent years due to their ability to stimulate growth of potentially beneficial bacteria such as *Bifidobacteria* in the gut as well as other potential health benefits including inhibition of intestinal infection and reduction in cancer risk [1192].

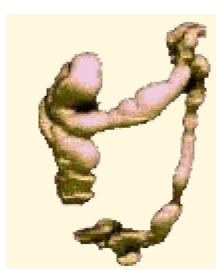
The physiological properties of hydrocolloids [1622] are dependent on the site, rate and extent to which they are absorbed or fermented in the intestine. Consumption of hydrocolloids has been found to, increase stool weight, alter gut transit time, alter activity of the colonic microflora, influence appetite, absorb toxins and modify the absorption of fats, sugars, minerals and bile acids. The extent to which specific hydrocolloids exert their physiological effects will be dependent on a complex mixture of structural, chemical and physical properties (summarized below).

| Dietary fiber comparison | | |
|---|---|---|
| **Physicochemical property** | **Major Dietary Sources** | **Physiological effect** |
| **Fermentation** | Resistant starch, β-Glucans, Pectin, Guar | Energy source · increase in biomass<br>Short chain fatty acid production · reduction in pH of colon (inhibition of 7-α-dehydroxylase),<br>anti-neoplastic activity of butyrate |
| **Water Holding Capacity** | Non-fermentable portion of hydrocolloids for example, Cellulose, Arabinoxylans, Algal hydrocolloids | Increased stool bulk· shorter gut transit times |
| **Viscosity** | Pectin, Guar | Delayed gastric emptying and slower transit time through small bowel |
| **Gel Formation** | Guar, Locust bean gum, Alginate [c] | Reduced rate of nutrient absorption (for example, glucose, bile acids) |
| **Binding of Organic Molecules** | Hydrocolloids with large hydrophobic surface area for example, β-Glucans, Arabinoxylans, Methyl cellulose | Binding of bile acids, carcinogens and mutagens |

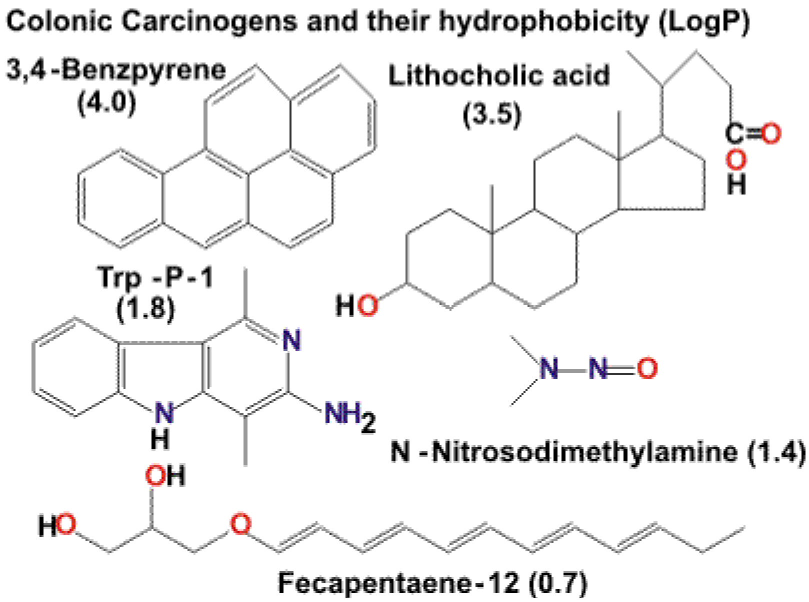



## The Colon

The colon is a very important part of our digestive tract and consists of several distinct areas (see right)[f] . It is responsible for the recovery of ingested and secreted water and electrolytes plus the salvage of energy from undigested food by fermentation. The colon has a 'skin' about a mm thick with a high surface area of invaginations ('crypts') but covered with a thick layer highly hydrophilic mucus (~2% w/v of mainly MUC2[g]) used as a lubricant and protective layer and associated with high density water. Every day about 60 g solids and 1600 ml water is injested with a further about 7 liters of water secreted in the upper digestive tract. The size of the human colon is not well known with its volume (variable but ~1 L, ~20% gas) much smaller than commonly quoted. Digested food from the small intestine, containing the excess secreted water, enters the ascending colon at the lower right-hand side of the body (on left in the diagram). The ascending colon squeezes in pulses (with the contained material rising and falling) when most of this excess water is being recovered.



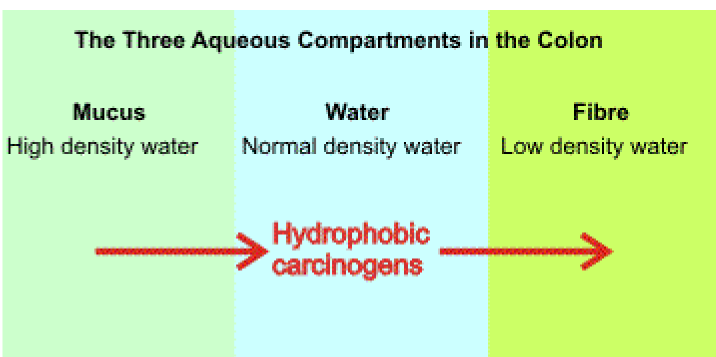
As the material becomes more solid and less liquid its viscosity increases and eventually it passes over the top into the transverse colon. Water continues to be removed along with fermentation products (see below) in the transverse colon and into the descending colon where faecal matter gathers. The sigmoid colon is surrounded by muscle that contracts to expel this matter through the rectum.The food takes about 2 days to travel through the digestive tract with this time spent mostly in the colon. The faecal output (~130 ml, ~19 g bacteria dry weight.) contains only ~11 ml of free water along with ~18 g non-bacterial solids; the remainder being bound water.




As the material travels through the colon, the organisms present extract energy by rearranging their atoms, generally by removing the more hydrophilic parts such as carbon dioxide and short chain fatty acids. Such an environment tends to keep carcinogenic hydrophobic materials( from the diet or formed by fermentation) away from the live cells of the colon wall, so reducing any cancer risks. Consequently the molecules that remain are either non-fermentable (e.g. 3,4-benzpyrene and other polycyclic aromatic hydrocarbon from smoked foods and the natural bile acid lithocholic acid) or fermentation products (e.g.
heterocyclic aromatic hydrocarbons particularly tryptophan metabolites, as Trp-P-1, from cooked red meat and other high quality protein, fecapentaene-12: from anaerobic organisms and N-nitrosodimethylamine from protein and nitrates). Many of these are quite hydrophobic (see right with their relative hydrophobicities[h]) and associated with cancer. As the fermentation is progressive through the colon, it is not surprising that the highest concentration of such molecules is at the distal end of the colon and this is associated with the higher risk of cancer here, even with the progressively thicker mucus layer (see table below).

**Colon compartments**

| Colon (typical) | Right (up) | Transverse | Left (down) | Sigmoid (storage) | Rectum (ou |
|---|---|---|---|---|---|
| **Volume, $cm^3$** | 350 | 300 | 200 | 80 | 20 |
| **Mucus surface, $cm^2$** | 380 | 420 | 320 | 200 | 60 |
| **Mucus depth, µm** | 430 | 460 | 540 | 580 | 620 |
| **Relative cancer risk** | 6 | 8 | 6 | 26 | 42 |




Within the colon there are a number of aqueous environments. SThe two most important of these are formed by the mucus and dietary fibre. These form separated aqueous compartments (i.e. phases), whether they are completely dissolved or not. The properties of these aqueous phases depends on the structure of the macromolecules and consist of low density water around the fermented dietary fibre residue and higher density water throughout the mucus. These conditions will encourage the partition of carcinogens and potential carcinogens and protective agents between the phases in such a way as to be potentially either protective or harmful. Further, as material passes through the colon, the action of microorganisms is likely to change the properties of the phases in a way that may be either beneficial or harmful, depending on the structure. The concentration of the carcinogens within the mucus towards the rectum coincides with increased cancer prevalence. The presence of dietary fibre generally tends to partition hydrophobic carcinogens away from this mucus and within the partially fermented dietary fibre, so reducing cancer risk. When more unfermented fiber is present, a low density water environment with greater aqueous volume is produced which will further extract the hydrophobic molecules so causing a further reduction in their concentration within the mucus and hence in contact with the live cells beneath [1806]; the fiber and mucus environments behaving as a 'typical' partitioning aqueous biphasic system. High stool weight and throughput with a high-fiber diet is associated with low colon cancer occurrence whereas low fiber diets and constipation are more associated with increased cancer risk, due to the longer contact time and low water content with consequent lower partioning within the faecal material.

## Colonic Fermentation

The rate, site and extent of hydrocolloid fermentation in the gut is dependent on a number of factors including solubility, chemical structure, availability of other more readily fermentable substrates and the composition of the colonic microflora [1927]. Hydrocolloids, generally being relatively pure additives, are more available than typical dietary fiber, which is complexed with plant material and normally consumed as whole grains. Water-soluble hydrocolloids are more readily available and will be fermented earlier in the colon, than insoluble hydrocolloids, so long as suitable microbial enzymes are available. Terminal residues are fermented first, and hydrocolloids containing α-L-arabinofuranose or α-D-galacturonic acidresidues are generally more susceptible to fermentation. Of the major components of dietary fiber, xylans, pectins and gums are significantly fermented in the gut, cellulose is only partly broken down and lignin is essentially an inert material.Resistant starch, which forms a major part of the substrate available for colonic fermentation, is completely degraded in the large bowel and probably has a significant role in the protection systems associated with carbohydrate fermentation. Insoluble fibers are difficult to digest because a two-phase reaction is involved, but insoluble particles (for example, resistant starch) may provide a surface for the growth of bacterial microcolonies in fermentative processes. Exactly where and how quickly fermentation takes place is important. Some soluble fibers become partially insoluble as a result of hydrolysis by gut enzymes, but conformational 'persistence' may prevent the fiber from precipitating while in the colon. There is a time lag before precipitation and, if there is insufficient time for the fiber to precipitate, it persists in solution. The main end products of colonic fermentation are the short chain fatty acids (SCFA) acetic, propionic and butyric and the gases carbon dioxide, hydrogen and methane. SCFA are an important energy source for anaerobic bacteria and may play a role in the prevention of colorectal cancer. They also represent a significant salvage of energy for the body, recovering about half the energy that would have been available had the hydrocolloid been digested and absorbed in the small intestine. Production of SCFAlowers the intestinal pH resulting in enzymatic inhibition of the 7-α-dehydroxylase, that catalyses secondary bile acid formation, and the further reduction of secondary bile acid concentrations due to precipitation. Lower colonic pH may also change the composition of the gut flora to one less prone to produce carcinogens. Butyrate has been proposed to have a direct role in colorectal cancer prevention, due to its ability to inhibit colon carcinoma cell growth *in vivo*. Specific hydrocolloids may vary in both the composition and total concentration of SCFA produced during colonic fermentation. In a recent study hydrolyzed guar gum produced the highest levels of total SCFA compared with other dietary fiber sources when incubated with human fecal microflora, while cellulose produced significantly higher levels of propionate. Arabinoxylanoligosaccharides have been proposed to alter the bacterial composition of the colon in a beneficial way by stimulating growth of bacteria from the genera *Bifidobacteria* in preference to the potentially more harmful anaerobic bacteria such as*Clostridium spp*. Similarly, galactomannans are readily fermented by the beneficial organisms *Bifidobacteria* and *Lactobacilli*.Resistant starch, however, has been reported to stimulate growth of the more anaerobic *Clostridia* species.

There are connections between a person's (healthy) gut flora, and that of their mothers when in the womb, and aspects of their general and mental health [1864], but the details of this still have to be established.

## Water-holding capacity (WHC)

As the primary function of hydrocolloids is to retain water, they have an important effect on stool bulking, and consequently on gut transit times as a high water-holding capacity forces the material through the gut faster. Increased stool weight can cause dilution of the intraluminal contents limiting the exposure of the gut to secondary bile acids and other toxins and potential carcinogens. The water holding capacity (WHC) of a hydrocolloid is related to the primary chemical structure, the hydrophobic/hydrophilic balance and the particle size. Watter-insoluble fibers, such as cellulose, although having relatively low water content, retain water in pores and energy is required to remove it. WHC increases with particle size, due to the greater number of pores and voids in the sponge-like matrix. Conversely pectins and guar gum are almost completely fermented in the gut and, despite high initial WHC, have little effect on transit time. The stiffness of a hydrocolloid network may be important in delaying the escape of gas (by preventing gas bubbles coalescing), which will reduce stool density and increase stool bulking.

## Viscosity and gel formation

Hydrocolloids may be categorized as either water-soluble (for example, pectins and guar) or water-insoluble (cellulose), though this labeling is not always helpful in predicting their physiological effects. Soluble hydrocolloids are noted for their effect on the stomach and the small intestine whereas insoluble fibers are noted for their effect on the large intestine, though some hydrocolloids (for example, arabinoxylans) have an effect on both. The extent of pre-processing, including cooking, affects the rate of solubilization in the intestine, as does particle size (smaller particles have larger exposed surface areas for their weight). Also the type and regularity of branching present affects both solubility and the extent of the exposed hydrophobic surface. These factors contribute to the hydrodynamic volume of a polysaccharide and hence itsviscosity. The entanglement of polymer chains increases viscosity, which depends on about the fifth power of concentration. Above the critical concentration (C*, see rheology), even if fermentation reduces the size of a polysaccharide molecule fourfold, the viscosity will increase eight-fold when half the water is removed in the ascending colon. The high viscosity associated with hydrocolloids is often given as the cause of their effect on glucose and lipid metabolism (that is, reducing hyperglycemia); the consequent high viscosity of the intestinal contents reducing the rate of absorption of fat, glucose, and nutrients so allowing their absorption along a greater length of the small intestine and flattening the absorption profile.

## Binding to bile acids

*In vitro* binding of bile acids by certain components of dietary fiber has been well documented. Bile acids are a group of related amphiphilic steroids, possessing both a hydrophilic and a hydrophobic face. The primary bile acids, cholic acid and chenodeoxycholic acid, are synthesized from cholesterol in the liver and released into the bile conjugated to glycine or taurine in order to solubilize fats and cholesterol for uptake in the small intestine. In the colon, bile acids that are not absorbed and recycled by the enterohepatic circulation are mostly deconjugated and 7-dehydroxylated to give the secondary bile acids, deoxycholic and lithocholic acid. Conjugation and the presence of hydroxyl groups gives the primary bile acids more hydrophilic character whereas deoxycholic acid and lithocholic acid are more lipophilic in nature. The effects of pH, available surface area and hydrophobicity of the sterol on the adsorption of bile acids to certain hydrocolloids has been shown. The adsorption capacity of bile acids to wheat, corn, oat, barley and rice fibers was favored by an acidic pH environment, large hydrophobic surface area and greater hydrophobicity of the bile acid. Adsorption of bile acids by dietary fiber is one of the proposed mechanisms for the hypocholesteremic effect of dietary fiber. Increased fecal excretion of bile acids leads to the increased metabolism of cholesterol in the liver, thus lowering serum cholesterol levels. Evidence in human subjects suggests that soluble fibers such as pectin, psyllium, guar and oat bran are effective serum cholesterol-lowering agents [1360]. Bile acids have been implicated in the etiology of colon cancer [229]. A number of studies have shown that colorectal cancer patients have higher levels of secondary bile acids both entering and leaving the colon. There is a strong relationship between cereal fiber consumption and the prevention of colorectal cancer. Many of the most effective dietary fibers contain arabinoxylans. Cereal fibers are particularly effective at binding or partitioning putative co-carcinogens such as fecapentaenes, heterocyclic amines and secondary bile acids into the matrix of the fiber, thus reducing their cytotoxic effect. These carcinogens/promoters are then carried out of the body by undigested insoluble fiber thus lowering their effective concentrations in the intestinal tract. The exact nature of the interaction between bile acids and dietary fiber is unclear but likely to be hydrophobic in nature.

Several properties allow a polysaccharide to bind bile acids. A high degree of order on the surface affects binding as bile acids are stiff molecules and require an ordered static surface with which to bind. A large hydrophobic surface also promotes binding. In addition, the presence of soluble fiber may influence how much bile acid binds to the insoluble fiber that is present. Low-density water near the surface of a polysaccharide increases the likelihood of bile acids binding to hydrophobic areas, and low-density water is created mainly by stiff-type molecules. There, may be aqueous biphasiceffects, and the presence of lignin and other hydrophobic molecules is also important. Lithocholic acid (a major secondary bile acid) exists in chains when it is crystalline; it persists in solution and may 'sit' on ordered arabinoxylan structures. The length of bile acids is equivalent to that of three carbohydrate residues, and consequently, molecules with three carbohydrates in an ordered structure should bind more readily.

## Footnotes

[a] This page mostly originated from reference [228] which contains many original references. [Back]

[b] It should not be forgotten that health-promoting vitamins, minerals and antioxidants are also present in the plant materials that form natural dietary fiber but are not covered by the definition of dietary fiber [257]. They may well be responsible for some of the beneficial effects of fiber noted in clinical trials [300]. [Back]

[c] Alginate has been shown to possess a range of useful cardiovascular and gastrointestinal properties [885]. [Back]

[d] Colorectal cancer is a major cause of cancer death in the developed world. Although it is clear that hereditary factors, lifestyle and diet all contribute to the disease, there is currently a dispute over whether dietary fiber is beneficial or not. Fiber from grain, cereals and fruit have been shown to reduce the risk of colorectal adenoma (benign tumors that are known to be associated with the development of cancerous tumors) [923]. A major European study of 519,978 individuals showed that in populations with low dietary fiber intake, doubling the total fiber substantially reduces the risk of cancer [924]. However, although a pooled analysis of 725,628 individuals from 13 studies did show this association, it failed to show the association when other risk factors were taken into account except at very low dietary fiber intake [925]. High dietary fiber intake is still recommended for its (additional) beneficial effects on heart disease and diabetes. [Back]

[e] Dietary fibre is now defined (in the European Community) as carbohydrate polymers with three or more monomeric units, which are neither digested nor absorbed in the human small intestine and belong to the following categories: (1) edible carbohydrate polymers naturally occurring in the food as consumed; (2) edible carbohydrate polymers which have been obtained from food raw material by physical, enzymatic or chemical means and which have a beneficial physiological effect demonstrated by generally accepted scientific evidence; (3) edible synthetic carbohydrate polymers which have a beneficial physiological effect demonstrated by generally accepted scientific evidence.' [1678]. [Back]

[f] The central part of the figure is of the actual colon from the 'Visible man'; Joseph Paul Jernigan, a 5' 11'' 199 pound, slightly overweight American, executed by lethal injection of KCl for murder on August 5 1993. His last meal was 2 cheeseburgers, French fries, tossed garden salad and thousand Island dressing plus iced tea. His body was frozen and sliced into 1 mm slices, imaged, and put on the WEB. [Back]

[g] MUC2 is a long thin charged polyanionic molecule (700 × 10 nm radius) that is 78 % glycosylated. It is further sulfated, particularly when found towards the distal end of the colon. (Allen A., Hutton D. A. and Pearson J. P. The Muc2 gene product: a human intestinal mucin. *Int. J. Biochem. Cell Biol.* **30** (1998) 797-780). [Back]

[h] Hydrophobicities are calculated by the method of: Leo A. J. Calculating Log P(oct) from structures. Chem. Rev. 93 (1993) 1281-1306. [Back]

[i] Although many physicians and patients believe that a high-fiber diet and frequent bowel movements prevent the development of diverticulosis, recent work indicates that these are associated with greater, rather than lower, prevalence of diverticulosis [1863]. [Back]

Source：http://www1.lsbu.ac.uk/water/hyhealth.html