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A Review of Physiological Effects of Soluble and Insoluble Dietary Fibers

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Abstract

This paper seeks to characterize the effects of Total Dietary Fibers (TDFs), Soluble Dietary Fibers (SDFs), and Insoluble Dietary Fibers (IDFs) with regard to the rates of digestion, enzymatic activity, the metabolic syndrome, diabetes and glucose absorption, glycemic index, and weight gain. This review intends to narrow pertinent data from the vast body of research, including both in vivo and in vitro experiments. SDF and IDF share a number of the theorized beneficial properties in the diet including weight loss, increased satiety, effects on inflammatory markers, and intestinal microbiota. The benefits of SDF, including the prevention of macronutrient absorption, the slowing of gastric emptying, and the reduction of postprandial glucose responses as well as hypocholesterolemic effects, and colonic fermentation, are believed to be a result of its viscous nature. Increased insulin sensitivity could be a promising factor contributing to the beneficial effects of IDF. Another issue exists in the need for the strengthening of collaborative efforts between the food science and nutritionist disciplines. The goal between these fields should be to increase the likelihood that DF is added to foods at effective quantities without deleterious effects on the sensory appeal of the food.

Keywords: Soluble dietary fiber; Insoluble dietary fiber; Total dietary fiber; Physiological effect

Introduction

The consumption of healthy, low-calorie, and nutritionally balanced foods containing dietary fiber (DFs) has become a growing focus among consumers. For some time, DFs have been distinguished for their beneficial contribution to overall health. A broad array of food applications are being enriched and advertised based on their DF content. DFs have been targeted for their positive effects regarding the treatment and prevention of constipation, the control of serum cholesterol levels, the reduction of the risk of diabetes and intestinal cancer, and the stimulation of beneficial microorganisms [1]. The ability to utilize different DFs for food applications is correlated with their differing functional properties including the fiber source, type, as well as the degree to which the fiber has been processed [2]. DFs have been divided into two primary classes: soluble dietary fiber (SDF) and insoluble dietary fiber (IDF) [3]. Simply stated, they are classified based on their ability to dissolve in water. However, solubility of DF structure cannot be fully described in this way [4]. This paper seeks to characterize the effects of Total Dietary Fibers (TDFs), SDFs, and IDFs with regard to the rates of digestion, enzymatic activity, the metabolic syndrome, diabetes and glucose absorption, glycemic index, and weight gain. The investigation of the interrelated nature of each of these factors requires a detailed examination of a plethora of previously conducted research. This review intends to narrow pertinent data from the vast body of research, including both in vivo and in vitro experiments.

Definitions and Types: SDF, IDF and TDF

Definitions of dietary fiber

DFs are often simply described as any non-digestible carbohydrates that are not broken down in the intestinal tract [5]. However, scientific and regulatory bodies around the world define fiber differently. In 2009, the Codex Committee on Nutrition and Foods for Special Dietary Uses (CCNFSDU) [6] established an internationally accepted legal definition of DF. The definition states, "Dietary fiber means carbohydrate polymers with ten or more monomeric units, which are not hydrolyzed by the endogenous enzymes in the small intestine of humans and belong to the following three categories: (1) Edible carbohydrate polymers naturally occurring in the food as consumed. (2) Carbohydrate polymers, which have been obtained from food raw material by physical, enzymatic or chemical means and which have been shown to have a physiological effect of benefit to health as demonstrated by generally accepted scientific evidence to competent authorities. (3) Synthetic carbohydrate polymers which have been shown to have a physiological effect of benefit to health as demonstrated by generally accepted scientific evidence to competent authorities".

Defining characteristics of DF

Fiber has been defined in the scientific community based on at least one of four characteristics: (1) source, (2) chemical characteristics, (3) resistance to digestion, and (4) beneficial physiological effects [4]. Biological definitions describing the origins of fiber have traditionally referred to non-starch polysaccharides obtained from plant cell walls. One of the earliest definitions offers an example: "DF is the proportion of food which is derived from the cellular walls of plants, which is digested very poorly in human beings" [7].

Fiber can be characterized chemically based on chain length and the types of linkages between each monomeric unit. However, one challenge with this method has been the determination of the appropriate chain length [4]. The Codex definition for fiber indicates that fibers have a degree of polymerization (DP) ≥ 10. Despite these precisely defined criteria, the definition also includes a footnote that the decision on whether to include carbohydrates with a DP > 2 (i.e., oligosaccharides) is up to national authorities [6]. The chemical bonds between the monomeric units provide another means of chemical characterization. Non-starch polysaccharides are linked by β-linkages in most cases but characterization on this basis would exclude resistant starches, which contain α-1,4 linkages [4].

SDF and IDF exhibit unique structural components and, consequently, varying physiological effects [8]. SDFs have been linked to the lowering of cholesterol in the blood and the decrease in the intestinal absorption of glucose while IDFs have been associated with the absorption of water and regulatory intestinal affects [9]. These differing physiological effects depend primarily on the structural and physical properties of a respective type of DF. These differences cause DFs to exhibit various *in vivo* behaviors including hydration, swelling, and enzymatic attack [2]. Cui et al. [10,11] have discussed thoroughly about relationship between chemical structure, molecular weight and their corresponding physiological properties of DFs. DFs also may play a role in digestive regulation due to their influence on the rate of starch degradation thus preventing excessive glucose absorption [12]. In vitro digestion models have been used to report the impact of DFs on the degree of starch digestion and the predicted glycemic index (pGI) for a variety of food items such as pasta, biscuits, and bread among many others [3,13-15]. When incorporated into starch-based foods, DFs can entrap granules of starch while restricting the availability of water. This results in a limiting effect on the accessibility of digestive enzymes to starch granules and, consequently, a lowering of the pGI [3].

Indigestibility and a lack of absorption by the small intestine alone may not be responsible for all of DFs favourable physiological effects [4]. DFs possess a number of other notable physical properties considered by some to be more physiologically relevant such as viscosity, the ability to form gels, and the rate they are fermented by intestinal microbes [16]. These effects in the gastrointestinal tract may not only improve laxation and increase stool bulking, but also have metabolic consequences including improvements in serum lipids and postprandial glycemia as well as the promotion of satiety [4].

Soluble dietary fiber (SDF)

SDF is specifically defined as DF capable of being dissolved in a buffer and enzyme solution modeled after the aqueous enzyme solutions present in the human system [4]. SDFs increase total transit time by delaying gastric emptying and also slowing glucose absorption while non-viscous soluble fibers primarily act as a substrate for microbial fermentation in the colon [4]. SDFs include oligosaccharides, including fructooligosaccharide (FOS), pectins, β-glucans (oat and barley grains), galactomannan gums, alginate, and psyllium. Fructooligosaccharides (FOS), also known as oligofructose and inulin are known collectively as fructans [17]. They are found in plants including agave, artichokes, asparagus, leeks, garlic, onions, yacon, jícama, and wheat [18]. Pectin is present in most primary cell walls and is particularly abundant in the non-woody parts of terrestrial plants. It is primarily found in the fruit skin but also in small amounts of fruit: apples, pears, apricots, cherries, oranges as well as some vegetables such as carrots. Pectin is a linear polysaccharide mainly comprised of about 300 to 1000 D - galacturonic acid monosaccharide units [18]. Fruits are the major source, but pectins also represent 15% - 20% of the fiber in vegetables, legumes and nuts [19]. The β-glucans are polysaccharides of D-glucose monomers linked by β-glycosidic bonds. They occur most commonly as cellulose in plants, the bran of cereal grains, the cell wall of baker's yeast, certain fungi, mushrooms and bacteria [18]. Galactomannans (GMs) are polysaccharides consisting of a mannose backbone with galactose side groups and are commonly used in foods as stabilizers due to their high water binding capacity and their emulsification and viscosity increasing properties [20]. GM gums vary by their ratios of mannose and galactose and include fenugreek gum (mannose:galactose; 1:1), guar gum (mannose:galactose; 2:1), tara gum (mannose:galactose; 3:1), and locust bean gum, (mannose:galactose; 4:1) [20]. Roberts et al. [15] succeeded at preparations of bread with 5 and 10% substitutions of fenugreek gum for wheat flower that matched texture and volumes of control bread, demonstrating the potential for the manufacture of high fiber enriched breads. Alginates are unbranched polysaccharides that are composed of 1 - 4 linked β-D-annuronic acid and α - guluronic acid [21]. Alginate is distributed widely in the cell walls of algae, and is also an exopolysaccharide of bacteria including Pseudomonas aeruginosa though commercially available alginates currently come only from algae [21]. Through binding with water they form viscous hydrogels useful as thickening agents and are also useful in numerous biomedical applications [21]. Psyllium is the common name used for several members of the plant genus Plantago whose seeds are used commercially for the production of mucilage [18]. The term psyllium is used interchangeably for the seed husk, the seed, and the entire plant. Psyllium is cultivated, because the seed husk is a rich source of SDF, known as psyllium hydrophilic mucilloid, psyllium hydrocolloid, and psyllium seed gum [18]. Some studies [22] stated that SDF is responsible for prevention of type II diabetes due to the viscosity of the soluble fibers.

Insoluble dietary fiber (IDF)

IDFs primarily consist of cellulose and some hemicelluloses, resistant starch, and lignin. Cellulose is a polysaccharide consisting of a linear chain of several hundred to over ten thousand β; 1 - 4 linked D - glucose units and is the most abundant organic polymer on earth [23]. It is the principal component of the cell walls of most plants and forms about 25% of the fiber in grains and fruit and about a third in vegetables and nuts [19]. Much of the fiber in cereal bran is cellulose. Hemicelluloses are polysaccharides containing sugars other than glucose. They are associated with cellulose in cell walls and present in both water soluble and insoluble forms. About a third of the fiber in vegetables, fruits, legumes and nuts is made up of hemicellulose [19]. The main dietary sources of hemicellulose are cereal grains [19]. Resistant starch (RS) is the fraction of starch that is not hydrolyzed by amylase to D-glucose in the small intestine within 120 min of consumption, but is fermented in the colon [19]. Sources of resistant starch include whole grains, legumes, cooked and chilled pasta, potatoes, rice and unripe bananas [19]. RS has been classified into four general subtypes, RS1, RS2, RS3 and RS4. RS1 is physically inaccessible starch, which is entrapped within whole or partly milled grains or seeds; RS2 is a type of raw starch granules (such as banana and potato) and high-amylose (high-amylose corn) starches; RS3 is retrograded starch (either processed from unmodified starch or resulting from food processing applications); RS4 chemically modified starch to obtain resistance to enzymatic digestion (such as some starch ethers, starch esters, and cross-linked starches) [19]. Factors that determine whether starch is resistant to digestion include the physical form of grains or seeds, the size and type of starch granules, associations between starch and other dietary components, and cooking and food processing [19]. Lignin is a complex polymer of aromatic alcohols and is most commonly derived from wood. It is an integral part of the secondary cell walls of plants filling the spaces in the cell wall between cellulose, hemicellulose, and pectin components [19]. Foods with a woody component are good sources of lignin such as celery and the outer layers of cereal grains. In general, IDFs increase fecal bulk and the excretion of bile acids and decrease intestinal transit time (laxative effect).

Total dietary fiber (TDF)

Nearly all naturally available high-fiber foods contain varying amounts of both soluble and insoluble DF [24]. Whole grain and bran products are the main sources of cereal DF while the primary sources of SDF are fruits, vegetables and products from oat and barley (soluble β-glucans) [3]. Whole grain food products contain approximately 12% TDF, and there is a strong relationship between whole grain and cereal DF intake [16]. Whole grains are cereal grains that contain cereal germ, endosperm, and bran, in contrast to refined grains, which retain only the endosperm. Common whole grains include wheat, oat, and barley [16]. Some bran (the hard outer layers of cereal grain) derived food products, such as many breads and cereals, contain up to 25% TDF [16].

DF and Metabolic Syndrome / Diabetes Prevention and Risk Reduction

Metabolic syndrome describes a group of metabolic irregularities that occur together in an individual. It is well documented as independent risk factors for cardiovascular disease [25]. When grouped together in this syndrome, the risk of developing cardiovascular disease, as well as type 2 diabetes, is increased [26]. A large number of randomized studies in humans and experimental models have demonstrated evidence of the effectiveness of foods rich in DF positively regulating body weight, appetite, gluconeogenesis, sensitivity to insulin and cardiovascular disease risk factors such as low-density lipoprotein (LDL) and hypertension [27]. More recently, studies of DF refer specifically to the beneficial effects on most of the homeostatic abnormalities present in individuals affected by the metabolic syndrome [28,29].

High fiber diets are commonly described as a daily fiber intake greater than 25 grams in women and greater than 38 grams in men [30]. The benefits of high fiber diets are primarily linked to the viscous and / or gel-forming properties of soluble DF [31]. Several studies have demonstrated positive physiological effects of both SDF and IDF despite the expectation that only SDF would provide physiological benefit in the diet, primarily by the lowering of cholesterol in the blood and the decrease in the intestinal absorption of glucose [16]. A high intake of cereal IDF was strongly associated with remarkably decreased diabetes risk in several studies [32]. Data pooled from six studies including some 290,000 subjects indicate that two servings per day of whole grains might reduce diabetes risk by a remarkable 21% [33]. A cause and effect relationship cannot be definitely stated because of the known limitations of estimation of food intake from quantitative food frequency questionnaires (FFQs) [32]. However, these results do repetitively indicate that the consumption of IDF could definitely play an important role in the prevention of diabetes [32].

DF consumption might alter diabetes risk as a consequence of its effect on appetite and, consequently, body weight [3]. A large number of studies show increased satiety after eating or decreased hunger when subjects consumed high DF diets, both under conditions of controlled energy intake and when energy intake was consumed without restriction [30]. Conversely, no clear conclusion can be drawn that low versus high glycemic index meals are a key factor promoting satiety [16,34,35].

DF and reduced predicted glycaemic index

The glycemic index is a means by which foods can be ranked on the basis of the glycemic impact in relation to the available carbohydrate within those foods [3]. The GI of a food is a tool useful in determining the rate at which the carbohydrates in a food are digested and absorbed as glucose. A number of studies designed to determine the quantity of residual starch following digestion indicate that SDF additions to pasta significantly reduce the amount of starch digested over a 300 min period [36]. This reduction in reducing sugar release following digestion, and the extent of starch degradation results in a reduction in the predicted glycemic index (PGI) of such foods [3]. A range of DFs (SDF and IDF) has been used in the production of pasta and bread products. In vitro starch breakdown of these foods have shown that the addition of DF has an important physiological effect by reducing the amount of glucose produced following digestion with alpha amylase [36-38].

Colonic fermentation and intestinal bacteria

Fermentation occurs to almost all DFs to some degree but the rate of fermentation varies widely. With regard to intestinal physiology, DF should not be considered from a singular standpoint but rather as a term that encompasses a variety of moieties with varying physiochemical properties [39]. SDF, insoluble resistant starch and oligosaccharides tend to be fermented more readily than cereal DFs into gases and physiologically active byproducts [40].

Short-chain fatty acids (SCFAs) such as acetate, propionate, and aforementioned butyrate are produced by bacterial fermentation of DF in the intestines [31]. The concentrations of different SCFAs vary and depend on the substrate as well as the intestinal microbiota present. Increased production of SCFAs is believed to be beneficial because this reduces glucose output from the liver and improves lipid homeostasis [26]. It is not certain for patients consuming high soluble DF diets that the fermentability of DF is the primary factor contributing to reduction in diabetes risk. Studies have revealed that low fermentable cereal DF (corn and wheat) consumption indicate stronger associations with a reduction in diabetes risk than more readily fermentable soluble DF from fruit and vegetables [32,33].

DF consumption may also affect additional factors correlating the intestinal microbiota with obesity and insulin resistance. One study using mice as subjects found that obese individuals have a different makeup of various intestinal microbiotas than do lean individuals, and once the heavier individuals lose weight a transition toward the "lean microbiota" is observed [41]. Interestingly, when transplanting the intestinal microbiota from obese mice or from lean mice to gnotobiotic mice (no intestinal microbiota present) the recipients of the "obese microbiota" showed increased fat gain, despite comparable energy intake [41]. Another study, this time in humans, indicates that a diet high in SDF (oligofructose) results in a reduction of gram-negative bacteria and body weight while a diet high in fat increases the ratio of gram-negative bacterial lipopolysaccharides (LPS) containing microbiota [42]. Four weeks of continuous subcutaneous infusion of LPS increased weight gain, liver fat, inflammatory markers, and markers of insulin resistance to an extent similar to that of a diet high in fat [42]. These studies indicate that the consumption of SDF may consequentially positively influence the ratios of specific types of "lean" intestinal microbiota.

DF consumption and body weight

A number of mechanisms have been suggested for how DF positively impacts weight management, including promoting satiation, decreasing absorption of macronutrients, and altering secretion of gut hormones [43]. A large number of observational studies show an inverse, and often dose-dependent, [44] correlation between DF intake and body weight [16]. Effects were found with individuals in the highest vs. lowest percentile of DF consumption gaining 3.6 kg less over a period of ten years [44]. Several short-term interventional studies conducted with whole foods high in DF and with supplemental fiber further demonstrate that notable losses of body weight can be achieved with high DF diets. Howarth et al. [45] concluded that increased DF intakes have been associated with a body weight loss of 1.9 kg over 3.8 months with greater weight loss in more obese subjects.

Studies have also been conducted to determine differences in the effects of fermentable and non-fermentable DFs with regard to weight loss and satiety. Surprisingly, no clear difference regarding weight gain or loss has been shown between SDF and IDF and fermentable and non-fermentable DF, or between foods naturally high in DF and fiber supplements in human studies [30]. Nevertheless, reductions in the body weight of subjects consuming high DF diets most surely contributes to a reduced risk of the development of metabolic syndrome as well as type 2 diabetes [16]. One of the reasons that weight loss programs mandating a diet high in fiber are consistently more successful is that DF has been found to reduce hunger, especially in low fat diets. The fibers expand creating a bulking effect while promoting a feeling of "fullness" [46] making it easier for the dieter to adhere to their program.

DF and insulin sensitivity

Several studies indicate that an increased intake of total DF is inversely associated with insulin resistance [47]. Investigation of different types of soluble and insoluble DF in randomized controlled interventional studies returned assorted results. Consumption of wheat bran for three months had no effect on fasting glucose and glycated hemoglobin levels in diabetic subjects [31]. High DF rye bread did enhance insulin secretion but did not appear to improve insulin sensitivity in postmenopausal women, estimated with the frequently sampled intravenous glucose tolerance test [48]. Conversely, improved markers of insulin resistance have been reported after consumption of various other sorts of insoluble DF when using a second meal test design [16].

A randomized controlled crossover study in healthy women investigating the effects of weakly fermentable insoluble cereal DF and highly fermentable resistant starch found markers of insulin sensitivity in a second meal test were improved to a similar extent with all DF, independent of the rate of colonic fermentation [17]. A dose-dependent correlation between fermentability of DF and improved markers of insulin sensitivity was unlikely, and the available methods to estimate colonic fermentation rates in humans have limited accuracy [5].

Diets high in IDF have been found to improve insulin sensitivity in studies utilizing the euglycemic clamp to measure insulin action on glucose utilization. Incorporation of radioactive-labeled glucose during euglycemic clamps makes it possible to measure glucose metabolism in individual organs [49]. In both short-term and more prolonged studies measuring insulin sensitivity in this way, consumption of IDF increased whole body glucose disposal independent of changes in body weight [16,50,51]. Insulin resistant subjects are more likely to eventually develop diabetes. Therefore, improved insulin sensitivity as a result of a diet high in IDF could definitely be a very important factor contributing to reduced diabetes risk.

DF and inflammation

"In the cross-sectional National Health and Nutrition Examination Survey study, Grooms et al. [52] found that high fiber intake was related to the reduction in systemic inflammation. Some studies show that a diet high in total DF coupled with the consumption of a SDF supplement significantly decreased levels of the inflammatory marker CRP [53]. DFs including fructans, galactooligosaccharides, β-glucans, pectins, and resistant starch have been found to bind to C-type lectin receptors (CLRs) on immune cells, suggesting a direct immune modulatory effect [40]. Fermentation of SDF by colonic bacteria may also play a role as a consequence of the anti-inflammatory properties of butyrate, a short-chain fatty acid, they generate [26]. Reductions in inflammatory markers have been found to be similar with IDF, as well as more readily fermentable, SDF. Ma et al. [54] carried out a longitudinal study with 524 subjects designed to examine associations between DF intake and CRP. They found that the elevated CRP concentration was significantly lower in participants with the higher TDF intake. Krishnamurthy et al. [55] also concluded that high DF intake was associated with decreased inflammation, and the association was stronger in magnitude in patients with kidney disease.

Conclusion

SDF and IDF share a number of the theorized beneficial properties in the diet including weight loss, increased satiety, effects on inflammatory markers, and intestinal microbiota. Many of the benefits are likely to be a result of the viscous nature of SDF consumption including the prevention of macronutrient absorption, the slowing of gastric emptying, and the reduction of postprandial glucose responses as well as hypocholesterolemic effects, and colonic fermentation. Increased insulin sensitivity could be a promising factor contributing to the beneficial effects of IDF. Considering the body of research, there is a good deal of evidence that DFs play an important role regarding the structure of food, the availability of carbohydrates, the breakdown of starch, and, consequently, the GI of foods. Therefore, the management of weight and methods to structure diets as well as the prevention and management of diabetes and the metabolic syndrome can all be linked to DF consumption. This idea is further supported by the findings of numerous studies linking diets containing foods of high GI values with increased risks of weight gain, obesity, and diabetes [56]. Additionally, DF has been linked to the manipulation of enzyme expression involved in lipid synthesis, modification of hormonal responses, and the stimulation of gluconeogenesis [3]. One area of research focus could be to further study the mechanisms behind the role of low-GI foods in managing obesity and diabetes at the molecular level. Additionally, a large body of work has been performed to reveal much regarding the way individual food items impact human physiology but research involving more complicated food systems with multiple foods mimicking the reality of the human diet would elucidate much about the interactions between food ingredients and food structure, the impacts of DF, and the availability of carbohydrates to digestion. Another issue exists in the need for the strengthening of collaborative efforts between the food science and nutritionist disciplines. The goal between these fields should be to increase the likelihood that DF is added to foods at effective quantities without deleterious effects on the sensory appeal of the food. This collaborative effort would allow for the creation of many additional fiber-rich food products with heightened potential to positively impact consumer health by combatting obesity, cardiovascular disease and type II diabetes.

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