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Metabolic effects of dietary carbohydrates: The importance of food digestion

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ABSTRACT

High blood glucose and insulin concentrations, even if within the normal range, are associated with an increased risk to develop type 2 diabetes and cardiovascular diseases. Dietary carbohydrates are the main determinants of blood glucose levels in the postprandial period; therefore, the effects of dietary carbohydrates on human health are strongly related to their rate of digestion in the small intestine. This has raised much interest on food properties able to retard carbohydrate digestion and absorption. This review is focused to examine food properties which influence carbohydrate digestion in order to predict their potential influence on health markers. Among them, it is worth to underline the role of viscosity, the physical form of the food, cooking methods and processing, the type of starch (amylose or amylopectin), the presence of anti-nutrients and the amount of fiber, fat, and proteins. In this respect particularly relevant is the type of starch present in the food, since amylose is slowly digested by intestinal α-amylases while the digestion of amylopectin is faster. However, the food component that has the strongest impact on digestion and absorption of dietary carbohydrates is dietary fiber that modulates the postprandial glucose rise by multiple mechanisms. In fact, dietary fibers may increase ingesta viscosity, thus delaying the gastric emptying time and slowing both carbohydrate digestion and the rate of glucose transport to enterocytes. In addition, they can influence the composition of the gut microbiota and induce the production of short-chain fatty acids that beneficially affect glucose and lipid metabolism. In short, the knowledge of food characteristics able to retard carbohydrate digestion and absorption in the intestine can help modify food properties with the aim of improving their functionality.

1. Introduction

Dietary carbohydrates are the main source of energy in the human diet; in addition, they are the main determinant of postprandial blood glucose levels. In the last decades, the potential effects of carbohydrate-rich diets on human health have been debated, due to some possible untoward effects on glycemic control and plasma lipid concentrations. In particular, a high intake of refined carbohydrate foods has been associated to increased plasma glucose and insulin levels in the postprandial period, an elevation of fasting and postprandial plasma triglycerides and a reduction of HDL-cholesterol levels (Katan, Grundy, & Willett, 1997; Rivellese, Giacco, Genovese, et al., 1990; Riccardi & Rivellese, 1991; Sacks & Katan, 2002). A large body of evidence indicates that blood glucose concentrations are an important and independent risk factor for cardiovascular diseases (CVD) not only in diabetic patients but also in individuals with normal fasting glucose values. The results of a meta-analysis of prospective observational studies show that both fasting and post-challenge glucose levels are associated with the cardiovascular disease (CVD) risk (Kodama, Saito, Tanaka, et al., 2012). In particular, plasma glucose levels after an oral glucose load are a better predictor of CVD risk than the fasting glucose values. In fact, in the fasting condition plasma glucose concentrations are rather steady while in the postprandial period glucose fluctuations occur and last a few hours, particularly in subjects with abnormalities of glucose metabolism, even if asymptomatic. A higher postprandial glucose response, although within the normal range, is associated with increased plasma insulin and lipid levels that contribute to the development of endothelial dysfunction; this, in turn, represents an early step of the vascular damage preceding the formation of atherosclerotic plaques (Fig. 1) (Nitenberg, Cosson, & Pham, 2006; Mah & Bruno, 2012). Since human beings consume at least three meals per day, they spend a significant length of time in the absorptive state. Therefore, in order to reduce the risk of CVD it seems reasonable to try to limit blood glucose fluctuations in the postprandial period.

Results of several studies, both in vitro and in vivo (animals and humans), have provided important insights into the mechanisms by which increased blood glucose levels may contribute to accelerate the atherosclerotic process and increase CVD. Indeed, post-prandial increments of blood glucose levels, even in the normal range, can influence not only plasma lipoprotein concentrations, but also their composition

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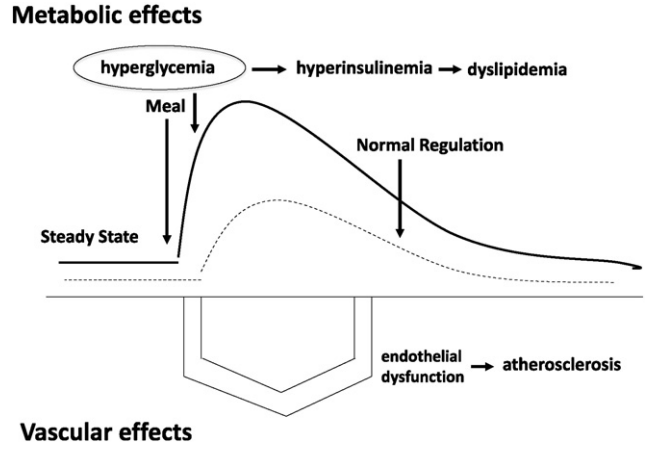

Fig. 1. Metabolic and vascular effects induced by increased postprandial blood glucose levels. The dash line indicates normal fasting and postprandial blood glucose levels, the solid line a disproportionally high blood glucose response to the meal. High postprandial glucose and insulin levels induce an endothelial dysfunction that can eventually lead to the disruption of the anatomical integrity of the arterial wall (atherosclerosis).

and metabolism; in addition, they increase the oxidative stress and the production of advanced glycation end-products (AGE-proteins), all involved in atherogenesis. Modified lipoproteins and glycation end-products may be up taken by monocytes within the arterial wall triggering the atherosclerotic process (Fig. 2). High blood glucose levels can also impair insulin secretion and sensitivity, thus contributing to a further deterioration of plasma glucose levels and to the development of type 2 diabetes. Moreover, they can induce subclinical inflammation that contributes to insulin resistance and worsens the vessel wall injury (Mazzone, Chait, & Plutzky, 2008).

However, it has to be underlined that carbohydrates are a heterogeneous class of nutrients and their metabolic effects are often different in relation to their digestion and absorption. Therefore, the aim of this review is to examine food properties which influence carbohydrate digestion in order to predict their potential influence on health markers. Moreover, knowledge of factors able to retard carbohydrate digestion and absorption in the intestine can help modify food properties with the aim of improving their functionality.

2. Nutritional classification of dietary carbohydrates

Carbohydrates are traditionally classified as mono-, oligo-, and polysaccharides on the basis of their chemical structure. However, a classification based purely on chemistry is not adequate to predict their different effects on health. Hence, a classification based on their ability to be digested and absorbed in the small intestine, thus contributing directly or indirectly to the body carbohydrate pool (glycemic carbohydrates) is more appropriate. In this classification, carbohydrates that are not digested and absorbed in the small intestine, namely dietary fiber, are kept separate from glycemic carbohydrates (Englyst, Liu, & Englyst, 2007).

Furthermore, glycemic carbohydrate intake is associated with an increase of post-prandial blood glucose levels in a dose–response manner. However, the majority of foods contain a mixture of glycemic and non glycemic carbohydrates in different proportion; therefore, the size of their hyperglycemic effect can be different according to the carbohydrate composition (both quantity and quality) of each specific food. In fact, Jenkins et al., in 1981 showed that the consumption of three different carbohydrate-rich foods – glucose, white bread and lentils – containing the same amount of available carbohydrates, induced different postprandial blood glucose responses in healthy volunteers, with the lowest response for lentils, the highest for glucose and intermediate for bread (Jenkins, Wolever, Taylor, et al., 1981). Based on the available evidence, carbohydrate-rich foods have been classified based on their effects on postprandial glycemia, as indicated by their glycemic index (GI). This is calculated by dividing the incremental area under the curve of blood glucose concentrations measured after the ingestion of a 50 g carbohydrate portion of the test food by the incremental blood glucose area achieved with a portion of a reference food (glucose or white bread) containing the same amount (50 g) of carbohydrate; GI is expressed as percentage (Jenkins et al., 1981).

Generally, fiber-rich foods have a low GI, even though not all foods with a low GI necessarily have a high fiber content (Atkinson, Foster-Powell, & Brand-Miller, 2008). The postprandial blood glucose response is influenced not only by the GI of the food but also by the amount of ingested carbohydrates. So the concept of glycemic load (GL = the GI of a specific food multiplied by the amount of carbohydrate contained in an average portion of the food consumed) has been developed to better represent both the quantity and the quality of carbohydrate intake (Venn & Green, 2007). Each unit of dietary GL represents the equivalent glycemic effect of 1 g carbohydrate from white bread that is used as the reference food (Willett, Manson, & Liu, 2002).

3. Food characteristics and postprandial glucose rise

Delayed dietary carbohydrate digestion and absorption may have significant beneficial implications for prevention and treatment of metabolic disorders. Many factors may influence the digestion of carbohydrates in the small intestine, including viscosity, the physical form of the food, cooking methods and processing, the type of starch (amylose or amylopectin), the presence of anti-nutrients and the amount of fiber, fat, and proteins (Table 1).

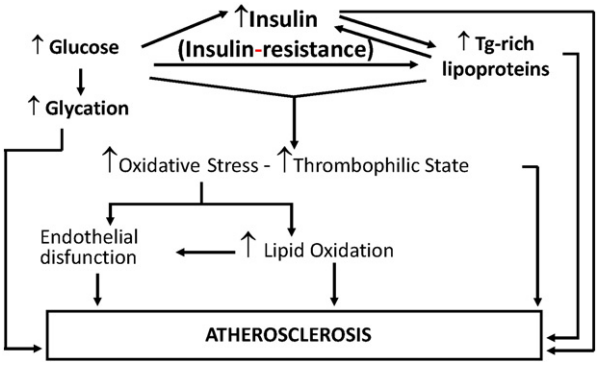

Fig. 2. Potential mechanisms linking postprandial metabolic abnormalities to atherosclerosis.

Table 1
Food characteristics which may influence carbohydrate digestion and postprandial glucose response.

Food characteristics	Mechanisms
Viscosity (viscous fiber)	Delayed gastric transit time
Physical form of the food	Reduced accessibility of starch to digestive enzymes
Amylose/amylopectin ratio	Amylose is digested lower than amylopectin
Cooking processes (drying/boiled cooking, time and temperature)	Accessibility of starch
Antinutrients (amylase and sucrose inhibitors)	Inhibition of digestive enzymes
Fiber	Microbiota modification and SCFAs* production
Protein content	Stimulation of insulin release
Fat content	Delayed gastric transit time/amylolysis reduction

*SCFAs = Short Chain Fatty Acids.

Viscosity plays a very important role in reducing postprandial plasma glucose concentrations. Soluble fibers – when hydrated (i.e., gel-forming) – increase the viscosity of digesta, thus reducing the postprandial glycemic response (Dikeman & Fahey, 2006; Jenkins, Kacinik, Lyon, & Wolever, 2010). The reduction in postprandial blood glucose correlates with the viscosity of the meal and the gastric transit time (Juvonen, Purhonen, Salmenkallio-Marttila, et al., 2009; Yu, Ke, Li, Zhang, & Fang, 2014). In fact, beta-glucan from two sources of oat concentrates affects postprandial glycemia in relation to its viscosity (Panahi, Ezatagha, Temelli, Vasanthan, & Vuksan, 2007): the higher is its viscosity, the greater is the magnitude of the effect. Moreover, a high viscosity of oat bran-enriched beverages stimulates postprandial satiety in healthy humans by increasing postprandial levels of glucagon-like peptide 1 (GLP-1) and peptide YY (PYY) (two gastrointestinal hormones related with satiety), decreasing postprandial ghrelin levels (the hormone that stimulates hunger) and by delaying the gastric emptying rate (Juvonen et al., 2009). In short, the beneficial effects of viscous fibers on postprandial glucose levels are related to their ability to delay both digestion and absorption of carbohydrates in the small intestine.

The importance of the physical form of the food in modulating carbohydrate digestibility has been investigated in several studies. The mastication of foods represents the first step in the process of carbohydrate digestion; in fact, chewing enhances salivation and mixes food particles with salivary enzymes, thus initiating the hydrolysis of carbohydrates in the mouth. Moreover, reduction of the particle size increases the delivery of food from the stomach to the small intestine and the rate of digestion: the larger surface area of masticated food facilitates the access of carbohydrates to pancreatic enzymes. This mechanism underlines the importance of the physical form in which the food is delivered to the small intestine in modulating the glycemic response (Read, Welch, Austen, et al., 1986). In fact, Golay et al. (1986) evaluated the effect of processed beans consumption (containing 50 g of carbohydrate) on glucose response in type 2 diabetic subjects. Beans were processed by two different cooking methods: one maintained the integrity of the starch granules while the other one disrupted their structure. The results showed that blood glucose and insulin responses were significantly lower after the ingestion of beans with the intact granular structure than those with ruptured starch cells. This study suggests that the benefits of fiber-rich foods on postprandial glucose response depend not only on their viscosity but also on their ability to reduce the accessibility of starch to digestive enzymes. In fact, in natural fiber-rich foods starch granules are often surrounded by fiber and this reduces their interaction with alfa-amylases, thus slowing carbohydrate digestion. However, fibers, although important, are not essential in relation to the modulation of starch accessibility. We have investigated this aspect in a study in which we evaluated the postprandial glucose response of four starchy foods based on wheat: white bread, toasted bread, pizza and potato dumplings, consumed in portion containing the same amount of available carbohydrates and similar for their nutrient composition (Giacco, Brighenti, Parillo, et al., 2001). Plasma glucose response was 30% lower after potato dumplings than after white bread and other leavened products. Scanning electron microscopy of potato dumplings showed a compact structure with starch granules surrounded by a matrix of heat-denatured wheat protein and dispersed starch, resembling that of pasta, another wheat food with a low GI; this structure is compatible with impaired accessibility of starch to digestive enzymes. In comparison, the structures of leavened products (white bread, hard toasted bread and pizza) were much less compact, presenting high porosity and smaller and more dispersed starch granules.

The nature of starch also influences its digestibility and the postprandial glucose response. Starches high in amylopectin have been shown to be digested more quickly than those high in amylose (Behall, Scholfield, Yuhaniak, & Canary, 1989; Björck, Granfeldt, Liljeberg, Tovar, & Asp, 1994), likely because amylopectin has many more non-reducing chain ends than amylose where digestive enzymes can grab hold of it (BeMiller & Whistler, 2009).

Studies in vitro and in vivo have shown that cooking processes may also influence starch digestibility (Wang & Copeland, 2013). Jenkins et al. found that drying cooked red lentils in a warm oven for 12 h resulted in a significantly enhanced glycemic response and rate of in vitro starch digestion compared with lentils boiled for 20 min and consumed without any further processing (Jenkins, Thorne, Camelon, et al., 1982). Therefore, the type and time of cooking may influence the in vivo and in vitro digestibility of carbohydrate foods. In the cereal kernel starch molecules are aggregated in semi-crystalline granules; starch becomes soluble in water when heated. The granules swell and burst, the semi-crystalline structure is lost and molecules start leaching out of the granule, forming a network that holds water and increases the mixture's viscosity. This process is called starch gelatinization and makes the starch more easily digestible. During cooking, the starch becomes a paste and increases further its viscosity. During cooling of gelatinized starch, starch molecules recrystallize, or retrograde. Retrograded amylose is poorly digested by human amylases and concurs to the formation of the so-called “resistant starch” (RS). Consumption of RS enriched foods is associated with lower postprandial glycemic and insulinemic responses (Li et al., 2010). Low processing temperature, low moisture content, or inclusion of other ingredients in the intact product can block the hydration of food starch, thus promoting RS formation. In addition, amylose is also prone to react with other food components (Hoover, 2010): its coupling with lipids has been shown to reduce the rate of amylolysis, both in vitro and in vivo (Buddrick, Jones, Hughes, Kong, & Small, 2015) (Larsen, Rasmussen, Rasmussen, et al., 2000). In fact lipids mechanically cover part of the starch granules, thus reducing the ability of carbohydrate molecules to absorb water. This inhibits the swelling of starch granules and their subsequent collapse or rupture, and hence facilitates the formation of RS (recrystallization of the amylose fraction) which appears to take place within hours of the gelatinization of starch.

The application of new biotechnologies for manufacturing foods can help retarding the digestibility of starch. This is the case of sourdough fermentation with selected lactobacilli for production of bread. This type of bread contains higher concentrations of resistant starch than bread leavened with baker's yeasts alone; therefore its consumption could contribute to reduce postprandial glucose levels (De Angelis, Rizzello, Alfonsi, et al., 2007).

Another food component that may affect starch digestibility and glycemic response is represented by anti-nutrients. It is well known that amylase inhibitors decrease glucose absorption in rats and humans. Indeed, amylase and sucrose inhibitors (α-glucosidase inhibitor and α-glucosidase-hydrolase inhibitor) have shown to reduce the rate of carbohydrate digestion and absorption and therefore they have been used for the treatment of diabetes (Lee, Kaneko, Jutabha, et al., 2015). Antinutrients are naturally present in vegetable foods and their concentration may contribute to modulate the postprandial glucose rise.

Macronutrient composition of foods may also influence postprandial glucose levels. Protein and fat reduce the glycemic response in a linear, dose-dependent manner, with proteins having about 3-times the effect of fat (Moghaddam, Vogt, & Wolever, 2006). This effect is likely due to the ability of protein to stimulate insulin release, conversely, fat delays the gastric emptying (Frid, Nilsson, Holst, & Björck, 2005; Gentilcore, Chaikomin, Jones, et al., 2006; Lodefalk, Aman, & Bang, 2008). These mechanisms are mediated by gut hormones such as gastric inhibitory polypeptide (GIP) and GLP-1 that stimulate insulin secretion; in this respect an important role is also played by fatty acids and amino acids that can influence insulin secretion directly or through the stimulation of hormones of the entero-insulin axis (Moghaddam et al., 2006).

Finally, blood glucose response after a meal is modulated by the amount and type of dietary fiber. As reported above, many studies have shown that dietary fiber, particularly of the soluble type, significantly reduces postprandial glucose levels and the average daily blood glucose profile (Chandalia et al., 2000; Giacco, Parillo, Rivellese, et al., 2000; Tosh, 2013). Moreover, they have beneficial effects also on fasting

glucose metabolism; these effects are mediated by their fermentation by gut microbiota and by their ability to influence the gut microbiota composition.

4. Impact of dietary fiber on gut microbiota

Scientific evidence in animals and humans support the concept that modification of the intestinal microbiota and changes in intestinal permeability are potential triggers of inflammation in obesity and represent a risk factor for the development of type 2 diabetes (Hartstra, Bouter, Bäckhed, & Nieuwdorp, 2015).

In genetically obese ob/ob mice caecal microbiota contain more Firmicutes and fewer Bacteroidetes than lean wild-type strains, even when mice are fed the same low-fat, polysaccharide-rich diet. Similar changes have also been observed in humans comparing fecal microbiota of obese and lean subjects (Ley, Turnbaugh, Klein, & Gordon, 2006). Bacteroidetes levels increase when body weight is reduced, independently from the diet composition, suggesting that Bacteroidetes may be responsive to the energy intake. A similar effect has also been observed in people who loose weight after bariatric surgery. In these patients, levels of Bacteroides and Prevotella were inversely correlated with energy intake and adiposity. However these results have not been confirmed in all studies (Schwiertz et al., 2010).

Several cross-sectional studies in different populations suggest that diet significantly impacts on the composition of the intestinal microbiota. The landmark study by De Filippo, Cavalieri, Di Paola, et al. (2010) demonstrated that children living in Burkina Faso, who consumed high amounts of plant polysaccharides, had low levels of Firmicutes and increased levels of Bacteroidetes — mainly Prevotella and Xylanibacter — in their fecal microbiota compared with age matched Italian children consuming a Western diet. Prevotella and Xylanibacter degrade cellulose and xylans and are associated with increased fecal short chain fatty acids (SCFAs) that have been linked with a beneficial impact on glucose and lipid metabolism in many studies. High colonic SCFA levels could also inhibit the growth of potentially pathogenic Enterobacteriaceae, such as Shigella spp. and Escherichia spp., that were significantly under-represented in fecal samples of the Burkina Faso children. Other studies comparing people from rural societies with individuals living in Western countries have confirmed a different microbiota patterns and higher fecal levels of SCFAs in populations on vegetarian diets as compared to people eating a western type of diet (Wu, Chen, Hoffmann, et al., 2011). In addition, intervention studies in humans have clearly shown that supplementation of diet with oligosaccharides, inulin and oligofructose confer benefits to the host intestinal health by selectively stimulating growth of indigenous bacteria, particularly Bifidobacterium and/or Lactobacillus spp., reducing clostridia and by increasing the concentrations of total SCFAs, (Roberfroid, Gibson, Hoyles, et al., 2010; Whelan et al., 2005).

SCFAs may induce beneficial metabolic effects through the enhancement of mitochondrial activity, prevention of metabolic endotoxemia, and modulation of liver gluconeogenesis and lipogenesis via different routes of gene expression and hormone regulation (den Besten, Havinga, Bleeker, et al., 2014; Cani, Amar, Iglesias, et al., 2007; Davie, 2003; Moreira, Texeira, & Ferreira, 2012). SCFAs, particularly acetate and propionate, can modulate lipid and glucose metabolism and reduce the appetite by hypothalamic satiety signals (De Vadder, Kovatcheva-Datchary, Goncalves, et al., 2014). Most of the absorbed acetate and propionate reaches the liver (where it is largely oxidized) via the portal vein, (Tremaroli & Bäckhed, 2012). Liver metabolic clearance of SCFA is very high and so concentrations in the blood are about 100-fold lower than those in colonic digest and feces (Topping & Clifton, 2001). Looking at possible dietary approaches able to stimulate SCFA production, we evaluated whether a 12-week consumption of a diet rich in whole-grain products (mainly based on wheat) may influence the production of SCFAs in subjects with the metabolic syndrome. In addition, we hypothesized a potential role of SCFAs in the modulation of postprandial glucose and lipid metabolism. Our results show that after 12-week fasting propionate was increased in people who consumed the diet rich in whole-grain as compared with the control group with a clear significant correlation between cereal fiber intake and plasma propionate levels. When the study population was stratified according to the median value of fasting plasma propionate values, a reduction of postprandial insulin levels was observed in subjects with high propionate (values above the median value) as compared to subjects below the median. These results suggest that cereal fiber may induce a relatively fast modification of colonic microbiota that, in turn, increases fiber fermentation and SCFA production (data unpublished). SCFA and, in particular, propionate may contribute to the reduction of insulin concentrations (indicative of an improved insulin sensitivity) observed when the whole-grain diet is consumed (Giacco, Costabile, Della Pepa, et al., 2014).

In summary, the influence of dietary carbohydrate on glucose and lipid metabolism is modulated by multiple dietary features (macro/micronutrient composition, amount and properties of fiber and food structure) that act at different levels of the gastrointestinal tract: at the stomach level, delaying gastric emptying, in the small intestine, slowing starch digestion and nutrient absorption, and in the colon by changing the bacterial flora in favor of bacteria able to ferment fibers and produce SCFAs. These in turn reach the liver via the portal vein where they modulate glucose and lipid metabolism.

5. Clinical relevance of carbohydrate digestion in relation to glucose and lipid metabolism

Epidemiological studies have shown that a diet based on carbohydrate-rich foods with a high fiber content, particularly whole grain products, and with low GI/GL may contribute to prevent the metabolic syndrome, type 2 diabetes and CVD (Rizkalla, 2014; Ye, Chacko, Chou, Kugizaki, & Liu, 2012.). The Nurses' Health Study during a follow-up of 6 years, reported an increased incidence of type 2 diabetes by 2.5 in women who consumed a diet with a higher GL and a lower cereal fiber content (Salmerón, Ascherio, Rimm, et al., 1997a). These results were confirmed in a cohort of men of the Professional' Follow-up Study (Salmerón et al., 1997b). However, up to now no intervention studies have evaluated the potential of low-GI, high-fiber diets to reduce the risk of diabetes, although in studies aimed at diabetes prevention by lifestyle modifications, an increase in fiber consumption was often part of the intervention.

In relation to prevention of CVD, intervention studies evaluating the effects of a low-GI diet on clinical events are not available; moreover, the results of the few available intervention studies evaluating the effects of GI on the cardiovascular risk factor profile are not always concordant. However, a meta-analysis of clinical trials including healthy participants and individuals with CVD, provides consistent evidence that low GI diets reduce total and LDL-cholesterol levels (Goff, Cowland, Hooper, & Frost, 2013). Furthermore, lipid improvements appear greatest and most reliable when the low GI intervention is paralleled by an increase in dietary fiber.

The best evidence of the clinical usefulness of GI is available in diabetic patients in whom low-GI foods, particularly those rich in fibers, have consistently shown beneficial effects on blood glucose control in both the short and the long-term (Riccardi, Rivellese, & Giacco, 2008; Rivellese, Giacco, & Costabile, 2012).

As reported above, the benefits of regular consumption of dietary fiber, particularly from cereal sources, on type 2 diabetes and CVD risk are mediated by multiple mechanisms including reduction of atherogenic lipoproteins, body weight reduction, improved glucose metabolism, blood pressure control, and reduction of chronic inflammation (Cho, Qi, Fahey, & Klurfeld, 2013; Giacco et al., 2014; Satija & Hu, 2012; Streppel, Arends, van 't Veer, Grobbee, & Geleijnse, 2005; Vitaglione, Mennella, Ferracane, et al., 2015; Ye et al., 2012). The beneficial effects of diets rich in carbohydrate and fiber and with low GL

are more evident in persons with diabetes because they have an impaired regulation of glucose metabolism, particularly in the postprandial period and, therefore, are more sensitive to dietary carbohydrates. As a matter of fact, an intervention comparing the effects of a diet rich in carbohydrate and fiber (carbohydrate 53%, fiber 54 g) versus one rich in carbohydrate but low in fiber (carbohydrate 53%, fiber 16 g) showed that the presence of fiber improved blood glucose control (both 2 h post-prandial glucose and mean daily glucose levels were significantly reduced) and decreased the concentrations of atherogenic lipoproteins (total and LDL cholesterol, total and VLDL triglyceride levels) in patients with type 2 diabetes (Rivellese, Riccardi, Giacco, et al., 1980).

Further benefits of a high-carbohydrate/high-fiber diet have been observed on postprandial lipid metabolism that is a well known risk marker for CVD (Nordestgaard, Benn, Schnohr, & Tybjaerg-Hansen, 2007). Patients with type 2 diabetes have more pronounced postprandial dyslipidemia, and this may account, at least in part, for their higher rate of CVD, not completely explained by hyperglycemia and the classic risk factors alone (Pastromas, Terzi, Tousoulis, & Koulouris, 2008). A diet rich in carbohydrate and fiber, mostly based on legumes, vegetables, fruits, and whole grain cereals, may be particularly useful for the treatment of diabetic patients, because of its multiple effects on different cardiovascular risk factors, including postprandial lipid abnormalities. Beneficial effects on glucose metabolism of an increased consumption of foods naturally rich in fiber with low GI were confirmed also in type 1 diabetic patients by a long term (6-month) dietary intervention. In this study the high-carbohydrate/high-fiber diet with low GI decreased significantly mean daily blood glucose levels, glycated hemoglobin and the rate of hypoglycemic events compared with a diet similar for nutrient composition but low in fiber and with a high GI (Giacco et al., 2000) (Fig. 3).

6. Conclusions

Postprandial glycemic and lipid responses are linked to the risk of chronic diseases. The rate of digestion of dietary carbohydrates in the intestine plays a clinically relevant role in the regulation of post-prandial metabolism. After a meal, glucose levels are modulated by the rate of carbohydrate digestion in the small intestine and by fermentation of undigested carbohydrates in the colon. In fact, once carbohydrates reach the colon, they have a beneficial impact on microbiota composition and on SCFAs production, that contribute to the improvement of glucose and lipid metabolism. This explains why a diet based on legumes, vegetables, fruits, and whole grain cereals can induce a significant improvement of the cardiovascular risk factor profile, particularly in type 2 diabetic patients, and is able to reduce substantially the overall risk of cardio-metabolic diseases.

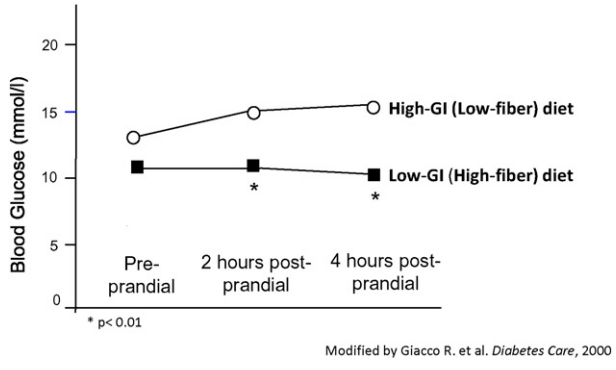

Fig. 3. Average postprandial glycemic responses in type 1 diabetic patients after two diets similar for their nutrient composition and differing exclusively for their fiber content and for their Glycemic Index. (A long-term randomized controlled study: 24 weeks, n = 63 patients) (modified from Giacco et al., 2000).

Knowledge of the mechanisms underlining digestion of carbohydrate-rich foods is relevant in order to predict their influence on post-prandial metabolism and, therefore, their impact on health; moreover, it can help modify food properties with the aim of improving their functionality.

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