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Dietary fibre, glycaemic response, and diabetes

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The much publicised global trend in rising levels of obesity and diabetes has refuelled interest in the dietary intake of the macronutrients (fat, protein, and carbohydrates) necessary to maintain the state of normalcy (good health) of an individual. Both scientific and public attention have focused on the dietary mediation of chronic health syndromes, either through use of dietary supplements, or a review of the whole diet situation. Dietary supplements have been used extensively both as pharmacological supplements, food ingredients, in processed foods to aid weight control, and the regulation of glucose control for diabetic patients. Particular interest has focused on the use of dietary fibres, especially soluble dietary fibres (such as guar gum, locust bean gum, and psyllium fibres), resistant starch, and slowly digestible carbohydrates. These have been shown to alter food structure, texture, and viscosity, and hence the rate of starch degradation during digestion. Research has also illustrated an association between the rate of carbohydrate degradation during digestion, and the regulation of postprandial blood sugar and insulin levels. The current paper explores the potential use of dietary fibres in the treatment of obesity and diabetes.

Keywords: Diabetes / Dietary fibre / Glycaemic index / Obesity / Resistant starch

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1 Prelude: obesity and diabetes, global problems

Diabetes mellitus affects around 30 million people in the Pacific Basin alone, with insulin resistance currently estimated to be present in 1 in 4 people in developed countries. The USA provides a good case study when examining trends in the rising prevalence of obesity, a key risk factor for diabetes development. During the period between 1984–1998 the number of individuals with a body mass index (BMI) above 30 kg/m^2 was around 23%, by 1999–2000 the incidence of obesity had risen to 30.5% [1]. Figures for the UK show that 23% of the population are defined as obese, and 4.8% men and 3.6% of women suffer from diabetes [2], whereas in New Zealand approximately 35% of the population can be considered overweight and 17% obese. This serves to indicate the global nature of the problem the food and health industries face.

Although the fact that more than one in three adults in the USA can be regarded as obese is worrying in itself, even more alarming is that the number of overweight children in the USA has risen by 50% in the last 10 years [3]. Estimates suggest that approximately 9 million children over 6 years of age are considered obese in the USA. This dramatic rise in childhood obesity has led to a predicted risk of between 30–40% for children born in 2000 being diagnosed with noninsulin-dependent diabetes mellitus (NIDDM or Type 2 diabetes) during their lifetime [4]. The problem appears to be global, and estimates for Australasia indicate that there has been a 3- to 4-fold increase in obesity within children during 1985–1995, with currently 5% of children considered as obese. This emergence of Type 2 diabetes in children represents an ominous development in view of diseases such as macrovascular (heart disease, stroke) and microvascular (kidney failure, blindness, blood clotting) sequelae [5]. Such increases in obesity levels can be associated with increases in diabetes, and it is this effect which clearly illustrates the potential problem society is going to be faced with in future years. Reports suggest that Type 2 diabetes accounts for over 90% of all diagnosed cases of diabetes mellitus, and that worldwide approximately 250 million people will suffer from diabetes mellitus by the year 2010.

Increasing levels of diabetes will have a huge financial impact on society. For instance, if we return to the USA situation, the national health care expenditure in the USA related to diabetes, obesity, and related health problems has been estimated at $180 billion (NZ $) for 2004 [4]. Simi-

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Abbreviations: DF, dietary fibre; **GI**, glycaemic index; **GL**, glycaemic load; **RS**, resistant starch; **SEM**, scanning electron microscope larly, direct costs to the UK national health service has been estimated as \$1 billion (NZ \$) [6]. Recent estimates for New Zealand show that the estimated 106000 diabetic patients cost current diabetic services \$247 million for 2001/2, and that if health services are maintained at current levels, the cost of diabetes health care will reach over \$1 billion in New Zealand by 2021.

These financial costs of obesity, diabetes, and the metabolic syndrome can not be ignored. Indeed, the cost of treatment of such a pandemic of associated conditions by conventional medical means is likely to be prohibitive. There is therefore an urgent need for broader strategies that influence the nutritive value of generally available foods without changing their popular appeal. Dietary regulation of hyperglycaemia and hyperinsulinaemia will undoubtedly be more economically viable in the long-term than pharmacological intervention, and thus are likely to feature as important methods to control diabetes. Such diets have been shown to reduce the possibility of developing obesity and its related diseases [7].

2 Factors responsible for increases in obesity and diabetes

There is little doubt that the main reason for increased obesity and diabetes levels is lifestyle. For instance, it has been argued that because the human population has a relatively stable genetic background, the rapid increases in obesity are almost certainly to be related to environmental factors, such as changes in diet and lack of physical activity [8]. The increase in lack of physical activity amongst populations remains a concern with regards to obesity. Research from Mexico has indicated that the risk of becoming obese decreased by 10% for each hour per day of moderate-to-vigorous exercise, whereas it increased by 12% for each hour per day of television watching [9]. Indeed, television viewing has been shown to affect obesity levels by both decreasing the amount of physical activity of an individual, and also increasing the energy intake through the consumption of snacks and energy-dense (potentially high glycaemic) foods [10].

Although the role of physical activity can not be disregarded as a factor which has compounded the prevalence of obesity, other diet-related factors must be explored, such as the consumption of foods with a high energy content (these may include fast foods, convenience/snack foods, and some confectionary and soft drink products), intake of high glycaemic index foods, portion size, and processing of foods. The increase in potentially energy-dense food intake during the last 15–20 years was illustrated by Guthrie *et al.* [11] who specifically examined the trends in the consumption of convenience food. The researchers estimated that whereas fast food consumption accounted for only 2% of a children's energy intake in the late 1970s, this had risen to 10% by the mid 1990s, a fivefold increase in the space of less than 20 years. Many of these convenience food meals can be considered as energy-dense with high glycaemic indexes or fat levels. Consumption of these readily available meals (often associated with relatively large portion size of both the food and possibly an energy-dense soft drink) can create a positive energy balance when consumed in association with a normal diet [5].

More recently, research by Pereira *et al.* [8] illustrated the potential negative effects of convenience food intake with regards to the nutritional status of an individual. The authors conducted a study recording the convenience food habits of around 3000 people (differentiated by sex and age), and related these habits with weight gain and insulin resistance over a 15 year period (1985–2000). Their results show that convenience food intake was higher in men than women, more prevalent in younger individuals, and there were inverse correlations noted for convenience food intake and intake of whole-grains, dietary fibre, reduced-fat dairy products, and physical activity. Not surprisingly, the authors concluded that, even after taking into account lifestyle factors, convenience food intake was directly related to weight gain and insulin resistance. Binge eating has also been related to body weight status [12], with many individuals suffering from binge eating disorder (BED) also being obese [13].

Socio-economic factors are likely to affect an individual's consumption of fast/snack/convenience foods and food intake in general. Sensible dietary intake and regulation of physical activity still remain the most attractive approach to controlling the incidence of obesity and Type 2 diabetes. Although public awareness of the associations between food intake and obesity is high, there is a general lack of momentum for self-regulation of food intake. For instance, in a recent study investigating public perceptions of childhood obesity, 85% of people questioned were in favour of increasing the marketing of healthy foods and drinks, and 75% of respondents were in favour of restricting the amount of fast food and less healthy food marketed during children's television programmes, however, the majority (59%) of respondents were opposed to increasing the costs of fast food marketed to children [14].

It appears that we, as consumers, may be aware of the dietary implications of our food choices, and support the concept of regulating dietary intake. However, many people still consume unbalanced diets, including diets low in dietary fibre. The food industry and dieticians have the challenge therefore, to produce foods with the same, if improved, sensory appeal, and which facilitate the consumption of a health-balanced diet situated to the needs of the individual consumer. The consumption of more dietary fibre may be a beneficial step towards a balanced nutritional diet.

3 Carbohydrate metabolism

It is perhaps too simplistic to say that carbohydrates are an essential source of energy for the body, however, the role of carbohydrate metabolism in nutrition is the cornerstone of our regulation of energy intake and body weight maintenance. Complex carbohydrates (for instance starches) are metabolised by the body into their monosaccharide constituents. Although many of the monosaccharides have roles in nutrition, glucose metabolism and absorption receives the majority of attention in relation to obesity and diabetes. Postprandially available glucose is absorbed and transported *via* the portal vein to the liver. The liver maintains blood glucose levels by converting glucose into glucose-6-phosphate and glycogen. The exact utilisation of glucose by the body depends on whether there is an abundance or shortage of available glucose. For instance, at times of glucose abundance, the glucose may be converted into glycogen. When blood glucose levels are low, or begin to fall, the liver can increase the supply of glucose to the body by utilising these stores. Insulin and glucagons act as regulators of blood glucose levels, with insulin increasing the active transport of glucose into fat and muscle cells.

4 Dietary fibre and glucose metabolism

Many of the diets recommended for balanced nutrition include a large proportion of dietary fibre (DF). Current recommendations suggest an intake of 20–40 g dietary fibre per day [15]. Fibre intake has been shown to improve glucose/insulin metabolism in Type 2 diabetes patients [16–22]. Thus, dietary fibre can have an impact on food by reducing the rate of glucose breakdown and absorption, hence avoiding an excess of glucose in the body and facilitating the steady breakdown of carbohydrates and release of glucose. It is also clear that we as consumers have knowledge of the use of fibre in diets. For instance, a survey investigating public opinion of DF consumption found that when asked to define source of DF, 42% of respondents mentioned vegetables, 33% cereals, 27% fruit, 25% bread, and 19% porridge. When asked about the function DF has in human nutrition, 35% said it was related to bowel function, 24% related to stomach function, 23% related to digestion, and 12% commented that DF makes you feel full and decreases appetite [23].

5 Carbohydrate utilisation, glycaemic index, and the diet

Diet has long been the cornerstone of diabetes treatments. The Ebers Papyrus (1550 BC) details a diet rich in wheat-germ to aid nutrition. Wheat-germ has subsequently been shown to exert a glucose-lowering efficacy. Although the concept of the glycaemic index (GI) is marketed in some quarters as a "revolutionary new way to self-manage your diet", much of the initial work was conducted in the last three decades and before. The glycaemic index of foods is a method by which foods can be ranked on the basis of the glycaemic impact in relation to the available carbohydrate within those foods. The work of Jenkins *et al.* [17–22] helped to develop this concept. Values for the glycaemic index are based on postprandial (blood) glucose response over a 2 h period, and are related back to the curves produced after intake of a white bread meal, or consumption of a standard quantity of glucose. Hence, the GI of a food can be determined as:

$$\mathrm{GI} = \frac{\text{Incremental area under blood glucose response curve}}{\text{Corresponding area of blood glucose curve from consumption of a glucose standard}} \times 100$$

Thus, the GI of a food is a useful tool in determining the speed at which the carbohydrates in the food are digested and absorbed as glucose. Generally speaking, the food which has an effect similar to or greater than the test meal (a GI of between 70–100+) is considered as being a high-GI food, food which has a GI of between 55–70 is considered as medium-GI food, whereas those with a GI below 55 is ranked as being low-GI food (Table 1).

Low-GI foods are potentially useful for consumers wishing to reduce the part of their dietary carbohydrate fraction which is rapidly digested into glucose, and hence regulating rise in the level of blood glucose immediately after ingestion. However, certain individuals requiring a high level of blood glucose may be better suited to foods with a high GI. The combination of low- and medium-GI foods, together with a nutritionally balanced diet, could be a goal for people wishing to maintain or reduce weight.

More recently, attention has focused on the concept of glycaemic loading (GL), partly derived from the paper of Salmeron *et al.* [24]. The concept of GL differs from that of the GI, in that the GL refers to impact of the total food has on glucose production. Hence, the GL of a food can be determined as:

$$\mathrm{GL} = \text{GI of food product} \times \text{carbohydrate content}$$

This value may be of particular use when trying to evaluate the glycaemic response of foods within a meal setting, as it takes into account the relative amount of carbohydrate

Table 1. Glycaemic index and glycaemic loading values of some common foods

Food product	Glycaemic index (glucose = 100%)	Glycaemic load (per serving)
Rice (jasmine)	109	46
White bread	95	15
Lucozade	95	40
Cornflakes	92	24
Rice krispies	82	21
Gluten-free bread	79	10
White bread (with resistant starch fibre white)	77	11
Doughnut	76	17
Rice (long-grain, quick cook)	72	20
Weet-bix	69	12
Rice (boiled, white)	69	30
Fanta	68	23
Rice (Basmati)	58	22
Milo	55	9
Kiwi fruit	53	7
Coca cola	53	14
Banana	53	13
Orange juice	50	13
Ice cream	50	6
Baked beans	48	7
Sponge cake	46	17
Oat bran bread	44	8
Muffin	44	13
Barley bread	43	9
Porridge (oats)	42	9
Rye bread	41	5
Apple juice	40	12
Rice (high amylose)	37	15
Yoghurt	34	5
Chickpea	33	10
Lentils	30	5
Apple	30	4
All-bran	30	4
Kidney beans	29	8

Adapted from Foster-Powell *et al.* (2002)

within the food. As with the GI, the GL can be split into three bandings, high GL of 20 +, medium GL of 11–19, low GL of 10 or below. A selection of typical GI and GL values are given in Table 1 for comparison.

The ideas of GI and GL have been taken a step further by Monro and his researchers [25] with their discussions on the use of glycaemic glucose equivalents (GCEs) as a replacement for GI and GL. The authors determine GCEs using the following equation:

$$\text{GCE} = \text{weight of food} \times (\text{\% available carbohydrate}/100) \times (\text{GI of food}/\text{GI of glucose})$$

However, the use of different terminologies to describe the glycaemic response of individuals to food ingestion may be counterproductive when trying to inform the consumer, and care needs to be taken to avoid any unnecessary confusion over terminology.

Although the GIs of numerous foods have been investigated intensively during the last decade, most of the investigations have focused on the measurement of glucose responses, simply comparing the effects of low- and high-carbohydrate diets in healthy and diabetic subjects. Whilst GI has been found to vary with food type, a number of these studies have failed to consider the effect of the physical properties of the diets on glucose uptake, including the effects of food structures. Several hypotheses have been formulated to try to explain the variation of the glycaemic response with food type. A selection of these include resistance to mastication [26], alterations to the microstructure of food particles and degree of starch gelatinisation [27], and variations in the type of starch present (high amylose *vs.* low amylose content) [28]. Some of these hypotheses include parameters that influence digesta viscosity, and thus ease of mixing, digestion, and absorption.

6 Carbohydrate availability in the control of obesity and diabetes

The GI values recorded in Table 1 serve to illustrate that the source of carbohydrate plays a role in the overall glycaemic impact of the food. This observation is by no means new, research by Conn and Newburgh [29] illustrated that different food sources could elucidate different glycaemic responses. However, recent consumer attention has focused on the impact that carbohydrate-dense foods have on the glycaemic response of individuals, with cereal-based foods, such as bread, rice, and biscuits, often targeted as having high GI values and being linked to weight gain. As such, some consumers have decided to avoid carbohydrate intake and replace this food component with protein or fat.

A case in example is the much publicised “Atkins diet”. It has to be said that the “Atkins diet” does work as a weight loss programme. Research has indicated that weight loss from the “Atkins diet” is greater than that from “conventional” low-fat diets for the initial 6 months. However, research has indicated that after this 6 month period, both the “Atkins diet” and low-fat diets are not significantly different [30]. Certainly weight control is an important factor in the treatment of obesity and diabetes, with weight loss from low-calorie diets being shown to improve atherosclerosis risk factors during the early years of diabetes treatment [31]. The regulation of carbohydrate digestion is important in relation to weight control.

7 Carbohydrate digestibility

When considering the digestibility of carbohydrates, it is possible to classify them into two broad groups, namely, rapidly digestible carbohydrates (for instance, freshly

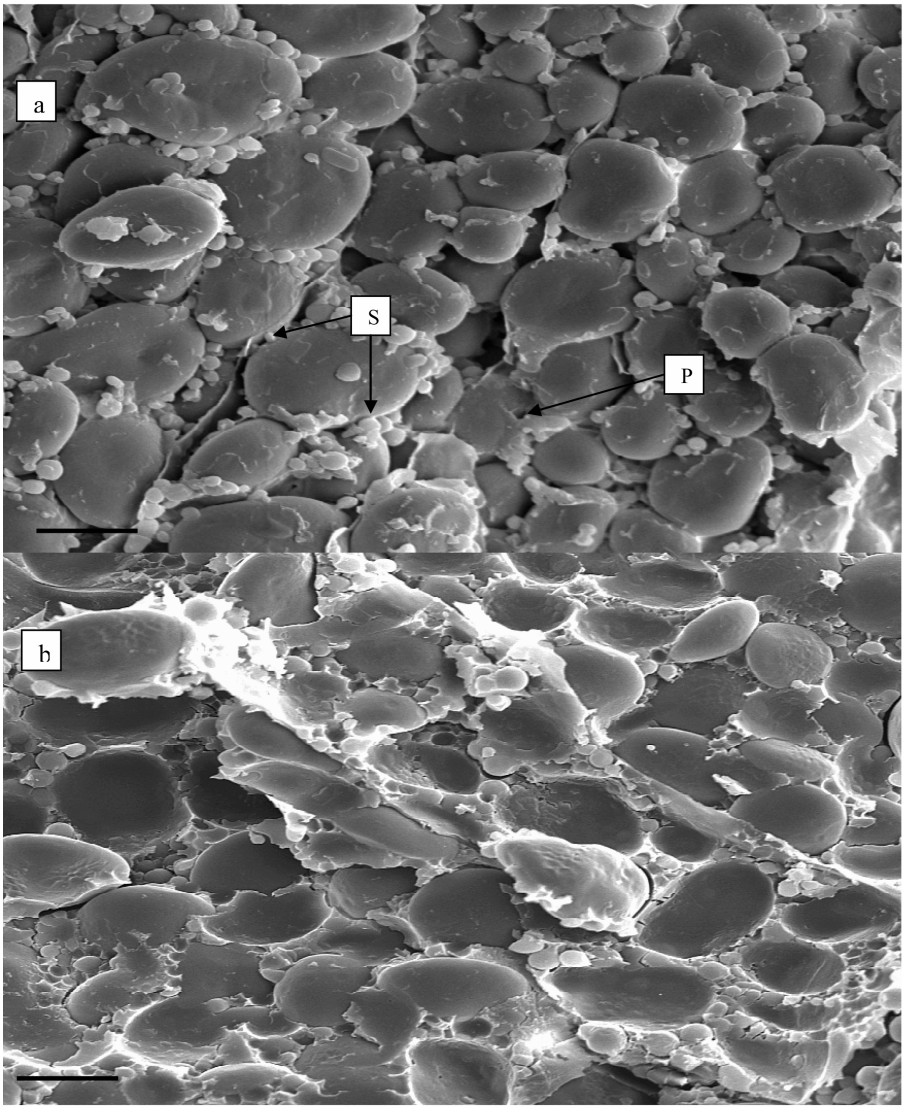


Figure 1. SEM images of (a) soft and (b) hard barley cultivars

S= starch; P= protein matrix. Scale bar represents 10µm.

cooked starch-rich carbohydrate food material), or slowly digestible carbohydrates (for instance, starch present in raw potato or unripe banana are resistant to amylase activity and are relatively slow to digest). Similarly starch from peas, beans, and yams are relatively resistant. Starch which resists amylase activity, has been described as resistant starch (RS). The grouping of RS falls into four main categories:

(i) RS1 – physically inaccessible starch granules such as those embedded in a dense protein matrix. An example of this could be the difference between hard and soft cereal grains (Fig. 1). It is well known from the malting and brewing industry that the degree of starch modification during malting is controlled by the breaking down of the cell wall components, and also the porosity of the grain [32]. Thus, grains which malt quickest (where the starch is converted to sugar rapidly) tend to have less cell wall deposition, and display a grain structure where the protein and starch do not form a cohesive matrix, as is the case in soft endosperm textured barley varieties (Fig. 1 a). In contrast, in the case of hard endosperm textured barley varieties the association between the protein and other cellular components (including starch) is much stronger (Fig. 1 b), hence restricting the accessibility of starch degrading enzymes to the starch during malting [32, 33].

Similarly the effect of partial or complete milling (*i. e.*, particle size of the flour) has an impact on starch availability for degradation. Starch from broken grains can be hydrolysed more rapidly than whole intact grain, whereas the starch in fine flour (with a particle size of less than 75 µm can be more rapidly degraded than the starch from course semolina (500 µm). Thus the intactness of the cellular material of food has an influence on the accessibility of starch to amylolytic enzymes and hence the GI value of foods.

(ii) RS2 – resistant starch granules (*i. e.*, raw potato, green banana, high-amylose maize starch). As mentioned before, unripe banana starch is less rapidly digested than ripe banana starch. The research of Akerberg *et al.* [34] illustrated that bread made from high amylose barley was less readily digested and hence reduced the incremental blood glucose response in healthy subjects. More recently, Hu *et al.* [28] studied the effect of different amylose contents of rice on the digestibility and predicted glycaemic response. Rice samples with amylose contents ranging from 0% to 27% were analysed for pasting performance, degree of starch gelatinisation, and starch digestibility. Predicted GIs for the rice samples with amylose contents of 0–1% were 101–106, whereas values for rice samples with amylose contents greater than 26% were significantly reduced (predicted GI value of 62).

The contribution of amylose to decreasing starch digestibility is partly linked to the compactness of the amylose molecule (straight chained) compared to that of the amylopectin molecule (which forms multibranched molecules). This in turn affects the degree of starch swelling during gelatinisation, and the subsequent accessibility of the starch grain to hydrolysing enzymes. Hence, the structure and composition of starch has a marked affect on the digestibility of the starch.

(iii) RS3 – retrograded starch (*i. e.*, cooked and cooled starchy foods). Cooling of cooked starch results in the products of starch gelatinisation reorganise themselves to form a complex structure. The amylose molecules tend to aggregate during cooling and further reassociations and reorganisations of amylose and amylopectin components occur so that starch crystallization occurs [35, 36].

This crystallization effect after cooking has the notable effect of bread staling, where the crumb of the bread steadily increases in firmness after baking due to the transition of the starch to a partially crystallized polymer. The work of Hu *et al.* [28] on rice starches (mentioned previously) not only investigated the effect of amylose contents of starches on the GI of the grain, but also the effect of cooling and retrogradation. The authors showed that the retrogradation process of rice starch could reduce the predicted GI of the rice by up to 10% [28]. This effect is similar to that of porridge which is left to stand, cool, and thicken.

(iv) RS4 – chemically modified starch (*i. e.*, starch esters and cross-bonded starches). Recent attention has focused on the possibility of modifying the structure of the starch grain to confer differing gelatinisation and processing characteristics. These modified starches could include starches altered through heat or chemical processing, and include cross-linking of starch polymer chains, starch depolymerisation, and pre-gelatinisation of starch. Incorporation of resistant starches into foods reduces the overall available carbohydrate content of that food, and hence can serve to reduce the GL and hence glycaemic impact of foods. These resistant and slowly digestible carbohydrates (SDCs) have been linked to greater glucose control of an individual [37, 38]. SDCs also include the diverse group of polysaccharides classed as non-starch polysaccharides (NSPs). These would include compounds such as galacto-oligosaccharides, malto-oligosaccharides, and fructo-oligosaccharides (such as inulin). Polydextrose (a randomly bound polymer of glucose containing small amounts of sorbitol and citric acid) is another common NSP which resists the hydrolysis by human digestive enzymes. Both inulin and polydextrose have been used as sugar and fat replacers in confectionary and low-calorie foods [39, 40].

8 Dietary fibre

There has been an apparent resurgence in interest recently on the role of DF in regulating weight control and the glycaemic response of individuals. Dietary fibre refers to the fraction of the edible part of plants or their extracts, or synthetic analogues that (i) are resistant to the digestion and absorption in the small intestine, usually with complete or partial fermentation in the large intestine; and (ii) promote one or more of the following beneficial physiological effects, namely, laxation, reduction in blood cholesterol, and modulation of blood glucose.

The work of Burkitt, Painter, Trowell, and Walker, during the 1960s and 1970s pioneered our appreciation of the relationship between increased DF consumption and the role DF could have on the manipulation of diabetes, obesity, heart diseases, large bowel disease, and colon cancer.

DFs are mainly derived from plant material, including cell wall material (although RS is also a category of DF). Their common characteristic is that they escape digestion in the small intestine and reach large intestine where they undergo fermentation; hence their effects on metabolism and disease regulation are intrinsically linked to their physicochemical properties as they pass through the gastrointestinal tract. The physicochemical properties of DFs are dominated by the conformation of the individual polysaccharide chains (ordered, disordered, 'random coil' chain geometry), and the way the polysaccharide chains of different DFs interact with one another and other food components. It is these conformations which affect their hydration characteristics, and hence their solubility.

Traditionally DFs have been classified on the basis of their solubility in water. Thus, they have been defined into soluble and insoluble fibres. In many cases, the physiological activity of DFs are largely determined on the basis of their solubility. Soluble DFs are commonly used in the food industry to modify or control the viscous properties of

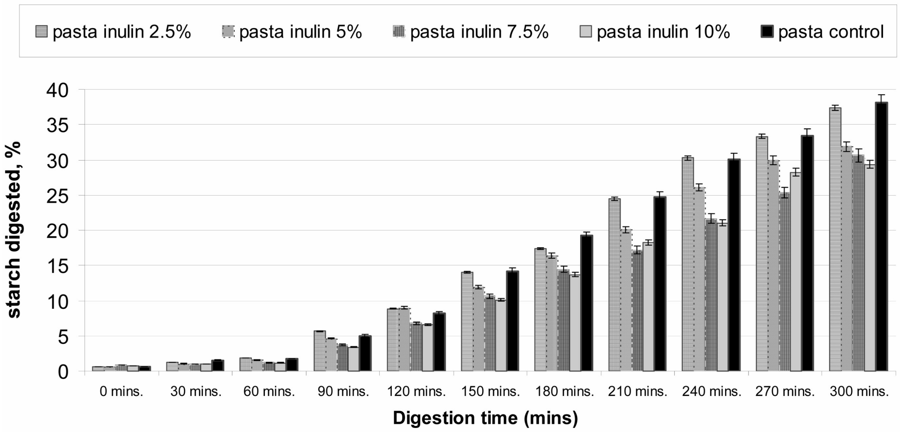


Figure 2. Effect of locust bean gum (lbg) addition on the digestion of starch in pasta following a 300 min *in vitro* degradation

liquid and semi-liquid food products, and alter their textural characteristics. The majority of soluble DFs have an ability to form gels and alter the viscosity of products. This effect has led to them being known as "gums" or "hydrocolloids" within the food ingredient sector. The ability to form gels and viscous networks is not only important in the processing properties of food products, but also their nutritional characteristics. For instance, numerous studies have illustrated the potential of these components to increase the viscosity of digesta when ingested. This in turn may explain the effects observed on carbohydrate metabolism [41].

Research has shown that insoluble DFs (not readily soluble in water) may reduce the transit time within the small intestine [42]. When in the small intestine, DFs are thought to increase digesta viscosity, to strengthen the so-called unstirred water layer in the gut, which potentially leads to a higher diffusion barrier, and also to binding of enzymes nonspecifically, hence reducing their activity. This in itself has a direct influence on the rate of digestion and effectiveness of nutrient absorption [43]. Such effects include moderation of postprandial glucose and insulin response, reduction in total and low-density lipoprotein (LDL) cholesterol and regulation of appetite [44].

The small intestine is the principal site of nutrient digestion and absorption, with hydrolysis of the digestible polymers in food occurring within the first two meters of duodenum [45]. Thus, the manipulation of the small intestine environment is likely to affect food digestibility and stool composition. DF has long been attributed to increasing stool weight and acting as a bulking agent in relation to water absorption. Although this may be valid, there is some evidence that increased consumption of DF does not necessarily alter the moisture content of human stool, which fluctuates between 70 to 75% [46]. Water retention is therefore not the sole determinant of stool consistency.

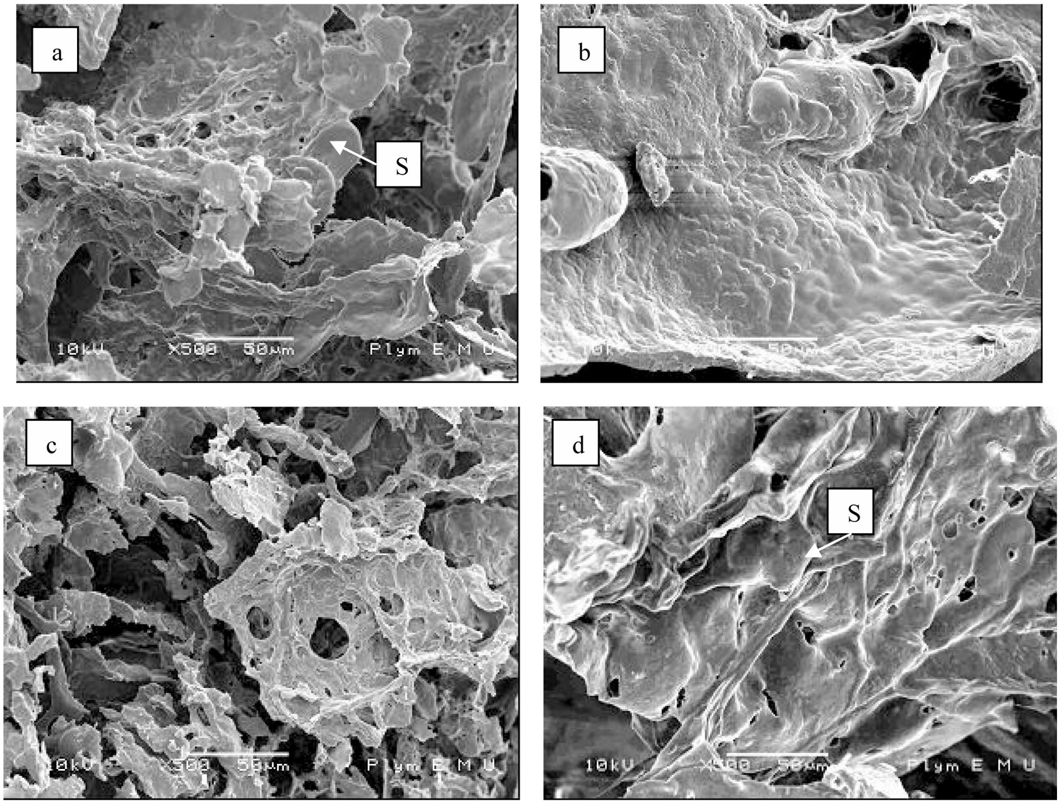
The categorisation of DF into soluble and insoluble fractions can cause problems when trying to determine the functional ingredient in meals (which by their nature are a complex mixture of plant and animal components). It must be borne in mind that many of the so-called DF components are themselves a mixture of polysaccharides in varying states of solubility.

9 The physiological role of dietary fibre: effect on the carbohydrate metabolism

DF has been shown to affect the rate and extent of starch degradation. In particular, soluble DF has been shown to reduce the rate of starch digestion and alter the rate of glucose absorption [8, 47]. Research has concentrated on the use of guar gum in food systems as a postprandial glucose modifying ingredient [27]. Similarly cellular components of cereal grains, such as oat β-glucan gum, have been shown to have nutritional benefits [48–50].

The viscosity-altering behaviour of these soluble DFs within the small intestine must account for some of these effects, however, the DFs also appear to alter the structure of the foods and hence the accessibility of the starch granules to the amylase enzymes [27, 51]. For instance, a range of DFs (insoluble and soluble) have been used in the production of pasta and bread. *In vitro* starch degradation of these products has shown that the addition of DF has an effect in reducing the amount of glucose produced following digestion with amylase [51–53]. This reduction in glucose can not be explained just on the basis of the DF exerting a dilution factor on the starch component of the food. Determination of residual starch following digestion indicates that soluble fiber (such as inulin) additions to pasta (Fig. 2) significantly reduces the amount of starch digested over a 300 min period. In many cases the magnitude of this response is a direct function of dose.

This reduction in reducing sugar release following digestion, and the extent of starch degradation results in a reduc-



S= starch granule

Figure 3. SEM images of a control bread (a) before and (c) after digestion, and a bread containing 10% added guar gum (b) before and (d) after digestion

Table 2. Predicted GI values of cereal foods following addition of soluble and insoluble DFs

Type	Dietary fibre added		
	Level	Bread PGI value	Pasta PGI value
Control	0.0	94.4 ± 1.6	45.2 ± 3.6
Guar Gum	2.5	90.5 ± 1.7	28.3 ± 5.6
	5.0	82.5 ± 6.3	25.6 ± 1.3
Locust bean gum	2.5	81.9 ± 6.9	36.1 ± 0.1
	5	85.4 ± 8.2	34.3 ± 0.7
Pea fibre	2.5	92.0 ± 3.2	44.5 ± 2.5
	5	88.5 ± 1.4	40.3 ± 2.4

tion in the predicted glycaemic index (PGI) of such foods. Table 2 illustrates the potential use of DF ingredients in manipulating the PGI of common foods. As can be seen from these values, the soluble DFs (guar and locust bean gum) appear to decrease the PGI value of these carbohydrate-rich foods to a larger extent than the insoluble DF (pea fibre). What is of interest is the difference in the degree of PGI reduction between food products using the same DF source. Thus, a 2.5 and 5% addition of guar gum to bread reduces the PGI value by 4 and 13%, respectively, whereas a 2.5 and 5% addition of guar gum to pasta elicits a 37 and 43% reduction in PGI, respectively. This indicates that the response of DFs in reducing the GI of foods may be process/product dependent.

Scanning electron microscopy (SEM) images of pasta and bread samples before and after digestion clearly illustrate the possible influence DF additions have in altering food structure, and subsequently the influence that food structure has on the digestibility of starch. For instance, Fig. 3 illustrates the effect of a 10% guar inclusion on bread structure before (Fig. 3 b) and after (Fig. 3 d) a 300 min *in vitro* digestion process. Note that the control bread sample before digestion (Fig. 3 a) shows a porous structure in which individual starch granules are embedded in a glutinous protein matrix, whereas the sample with added guar (Fig. 3 b) is less defined, with protein, DF, and starch in a dense continuous network. This may be a result of the gelation characteristics of the soluble fibre used in this experiment. It is interesting to observe that this dense continuous network is still retained in the added fibre bread sample, even after 300 min ingestion (Fig. 3 d), with starch granules seemingly engulfed in a gelatinous matrix. However, the control bread sample (Fig. 3c) shows evidence of enzymic digestion, with the majority of its structure degraded.

The striking effect of the DF on food structure and starch digestibility may in part be related to the theory on 'thermodynamic incompatibility' of biopolymers as proposed by Tolstoguzov [54, 55]. The thermodynamic incompatibility theory describes the basis by which biopolymers show a preference to be surrounded by their own type in mixed solutions. For instance, Tolstoguzov [54, 55] notes that amylopectin is incompatible with guar gum. Thus, if guar gum is added to a starch-rich matrix, it can lead to phase separation, and an encapsulation of the starchy phase by the guar gum-enriched phase. This encapsulation may then lead to impaired starch gelatinisation and hence degradation (as observed in Fig. 2 and 3).

The *in vitro* results shown above are in agreement with those of other *in vitro* [36] and *in vivo* experiments on the GI of foods. Furthermore, epidemiological data strongly correlates low-GI diets to reduced insulin resistance [36]. The potential consequences of a reduced insulin resistance are the control of diabetes and reduction of the possibility of developing risk factors for degenerative diseases, such as obesity, hyperlipidaemia, and hypertension.

Recently, there has been a renewal of interest in the potential use of β-glucan material in the regulation of diabetes. Studies such as that of Jenkins *et al.* [22] have shown that the use of β-glucan (a soluble cereal DF) can significantly reduce the GI of foods (compared to control samples) without negatively affecting the palatability of the food product. This reduction was in the region of 4 GI units per gram of β-glucan used. Similarly Cavallero *et al.* [56] illustrated that the inclusion of 6 g of β-glucan could reduce the GI by 28 GI units (equivalent to a reduction of over 4 GI units per gram of β-glucan). The research of Symons and Brennan [52, 53] further illustrates the use of extracted β-glucans in the manipulation of starch gelatinisation and hydrolysis events.

Additionally, there is evidence that glucose control in both Type 1 and 2 diabetes can be improved after a 3 month dietary regime of low-GI foods [57, 58]. Conversely, research by Salmeron *et al.* [24] demonstrated that the regular consumption of high-GI foods could lead to doubling of the potential risk of developing Type 2 diabetes. It must be emphasised, however, that low-GI foods *per se* are not the miracle cure with regards to obesity and weight loss, and that the combination of increased physical activity, balanced nutritional planning, incorporation of low-GI foods with slowly digestible carbohydrates, and increased consumption of DFs will help both in weight control (obesity) and the reduction of susceptibility to diabetes.

10 Potential use of the glycaemic index in obesity and diabetes management

The evidence for the benefits of low-GI foods in helping to maintain and regulate the glucose and insulin levels of individuals underlines the potential importance of the GI concept in the management of both obesity and diabetes. Knowledge of the GI of a food, combined with the details of the carbohydrate content of that food, can facilitate the prediction of GI values of even complex meal combinations, and hence aid the manipulation of glucose response of an individual. Frost and Dornhorst [38] used the equation below to determine the GI value of a meal.

$$\text{GI of mixed meal} = (GI_1)(PCF_1) + (GI_2)(PCF_2) + (GI_3)(PCF_3) + \ldots$$

where three or more carbohydrate containing foods are assessed and $GI_{1,2,3}$ represent the GI of foods 1, 2, 3, respectively, and $PCF_{1,2,3}$ represents the proportion of carbohydrate derived from each of the foods 1, 2, 3, respectively.

Although there are a number of tables which detail the GI content of single food items [59, 60], it remains difficult for the consumer to utilise this information to its best potential. The majority of work investigating the effects of DFs or low-GI foods have been conducted on single food products, and not in mixed meal situations where interactions between different food components (most notably proteins and fats) may compound, or reduce the effect of GI foods on glucose and insulin responses [61]. The task for the food industry is to try to remove the complexities behind the GI strategy, and help educate the individual into a better understanding of how to use GI tables and slowly digestible carbohydrates in the form of a balanced diet. Vermeulen and Turnbull [62] evidenced that the GI concept can be used to raise awareness as to the suitability of foods for diabetic and nondiabetic individuals.

11 Conclusions

There is compelling evidence that DF ingredients can have an impact on food structure, carbohydrate availability, starch degradation, and hence the GI of foods. This in turn, has been linked to the regulation of weight control and the manipulation of diet to aid the management of diabetes. The research of Brand-Miller's group in Australia has extended the work of earlier work of David Jenkins's group, and has clearly shown the potential benefits of using GI tables and values in aiding the regulation of glycaemic response of individuals. As such, this group has been successful in increasing the awareness of the public and the food industry to the potential benefits of low-GI foods.

The evidence presented linking diets containing foods of high GI values with increased risks with weight gain, obesity, and diabetes [63], has been linked to the manipulation of enzyme expression involved in lipid synthesis, modification of hormonal responses, and the stimulation of gluconeogenesis. However, more work is needed to investigate the molecular mechanisms behind the role of low-GI foods in regulating obesity and diabetes. Additionally, despite the well-documented effects that individual food components and simple model food systems exhibit on blood glucose and insulin levels, there is still scope for more research to investigate the synergistic behaviour of food components in complex food systems. The interactions between food ingredients and food structure would play a crucial role in this. Furthermore, research should focus on novel processing methodologies in order to lower the availability of carbohydrates to digestion, and hence increase the amount of resistant starch and DF in the diet.

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