Parameters controlling the glycaemic response to breads

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Bread is one of the most widely consumed staple foods worldwide. White-wheat bread, largely consumed in France, is made from highly refined flour, which leads to a low nutrient density. Due to a highly porous structure and gelatinised starch, it is easily broken down during digestion, leading to a rapid increase of glucose released into the bloodstream. Low glycaemic responses are considered favourable to health, especially against a background of diabetes. Literature reports show that selection of raw material is an essential factor in decreasing the glycaemic index (GI) of white bread. There are two means of decreasing the rate of starch degradation: either (i) slowing gastric emptying rate and/or glucose diffusion–absorption through the intestinal mucosa, which can be achieved by incorporating soluble fibre or organic acid in bread, or (ii) limiting starch accessibility to α-amylase by using high-amylose cereal varieties and/or incorporating intact cereal grains. Studies on cereal products show that preservation of the food structure during digestion seems to be a more important GI-reducing factor than the degree of starch crystallinity or the presence of soluble fibre. Thus, we should look to produce bread with a more compact food structure or higher density, which is the case in leavened wholewheat bread or bread with intact cereal grains. The baking process should also be improved to achieve this goal, by using, for example, a reduced kneading time or less yeast than usual.

Breads: Glycaemic index: Food structure

Introduction

Bread is consumed in various forms (white-wheat bread, brown bread, whole bread, bran-enriched bread, and multi-cereal bread, among others). In France, only 15 % of energy intake is derived from bread. An increase in bread consumption in low-bread-consuming countries would be a good way to readjust the carbohydrate:lipid ratio from 45:40 to 55:30 (% of energy), as is generally recommended. Not only the quantity consumed but also the nutritional quality of bread should be improved. Quality varies widely according to the raw materials and baking processes used.

For example, white-wheat bread is made of refined flour (type 55) impoverished in micronutrients (minerals, vitamins, trace elements, phytomicronutrients, fibre) and therefore having a low nutrient density. Moreover, white-wheat bread elicits a high glycaemic response (increase in plasma glucose concentrations after food intake), thereby increasing the risk of metabolic diseases such as type 2 diabetes, CVD and obesity.

However, the glycaemic response to bread varies widely according to the type of bread studied. The glycaemic index (GI; defined as the area under the blood glucose curve following ingestion of a test food, expressed as a percentage of the corresponding area following an equivalent load of a reference carbohydrate, either glucose or white-wheat bread) given in the Foster-Powell table for ninety-five types of bread (Foster-Powell *et al.* 2002) varies from 27 (barley bread with 75 % whole grains) to 95 (extremely porous French baguette). This extreme variability reflects very different rates of starch digestion; starch from a French baguette is rapidly digested, leading to a glycaemic response close to that of glucose (GI 100), whereas starch from bread containing intact cereal grains is digested more slowly. Both raw materials and baking processes can therefore influence glycaemic response.

Low to moderate GI (<70) are considered favourable to health, especially for the prevention of CVD, obesity and type 1 or 2 diabetes (Food and Agriculture Organization & World Health Organization, 1997). Hence, an understanding of the mechanisms underlying such high variability in glycaemic responses for bread appears to be of prime interest. However, in the *in vivo* studies published, the test foods are rarely well characterised, be it at molecular level (degree of starch gelatinisation and retrogradation, percentage of amylose), at microscopic level (starch interactions with

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Abbreviation: GI, glycaemic index.

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other food components: proteins, lipids, and fibres; food matrix porosity) or the macroscopic level (food particle size, in particular its changes during the digestive process), which obviously sets a limitation to the interpretations of the observed differences in glycaemic response. However, it is true that collecting food samples during digestion is a difficult process, in particular in human subjects.

The objective of the present review is therefore to discuss each of the main parameters controlling the variability of the glycaemic responses observed for bread products. The first part will briefly document the way high-GI bread is digested during gastrointestinal transit; then, we will discuss the parameters affecting GI in bread and explore how they can be modified to improve GI.

Digestion of high-glycaemic-index breads during gastrointestinal transit

Due to its porous physical structure (generated by the baking process, mechanical kneading and the respiration of the baking yeasts), bread is easily destructured in the mouth and the stomach (Fig. 1). In pigs, 31 % of starch granules are released from the food matrix during chewing. After 4 h of stomach digestion, the starch granules are no longer embedded in the protein network (Karinthi, 1995). Finally, bread particle size is drastically reduced after bucco-gastric digestion, which favours the subsequent accessibility of starch to pancreatic α-amylases in the small intestine (Karinthi, 1995). In contrast, pasta has a lower glycaemic response (and thus a lower GI, about 60), the particles released from the stomach having a more compact physical structure, with starch less accessible to the pancreatic α-amylases (Karinthi, 1995). Most of the starch granules in pasta remain embedded in the protein network during bucco-gastric digestion.

The second reason why white-wheat breads have a relatively high GI is the fact that starch is highly gelatinised during the baking process (at a temperature of 250°C),

making it particularly accessible to salivary and pancreatic α-amylases. This is compounded by the fact that bread has a porous texture, that the protein fraction (gluten) surrounding the starch is degraded, especially in the stomach where it was estimated in pigs that more than half of proteins are degraded, and that all starch granules are released from the food matrix (Karinthi, 1995).

The interactions between starch and proteins play a role in the glycaemic response of white bread since a gluten-free bread shows a significantly higher glycaemic response than normal white bread (Jenkins et al. 1987; Berti et al. 2004). Adding gluten to gluten-free flour does not restore the initial glycaemic response of the bread (Jenkins et al. 1987). This underlines the importance of the natural interactions between starch and proteins as a parameter controlling the glycaemic response of white bread. Microscopic observations effectively show that the gelatinised starch granules of white bread are embedded in a relatively thin protein network (about 1 μm) (Karinthi, 1995; Juntunen et al. 2002).

White v. wholemeal breads

It is interesting to note that in most of the studies performed with breads made from a less refined flour (what is called wholemeal flour, which in fact corresponds to white flour with added bran fraction), the glycaemic response is similar to that of white bread, suggesting a similar digestive process despite a higher percentage of fibre (for whole and brown flours). This is a reflection of the fact that, for these breads, it is the food's physical structure (a porous texture with highly gelatinised starch) that governs glycaemic response rather than the nature of the raw materials. Therefore, the baking process and above all the intensity of kneading play an essential role in the physical structure, and then the texture of the food. Furthermore, in the case of wholemeal bread, bran, which is rich in insoluble fibres, constitutes inclusions which could disrupt the gluten network and favour the digestive
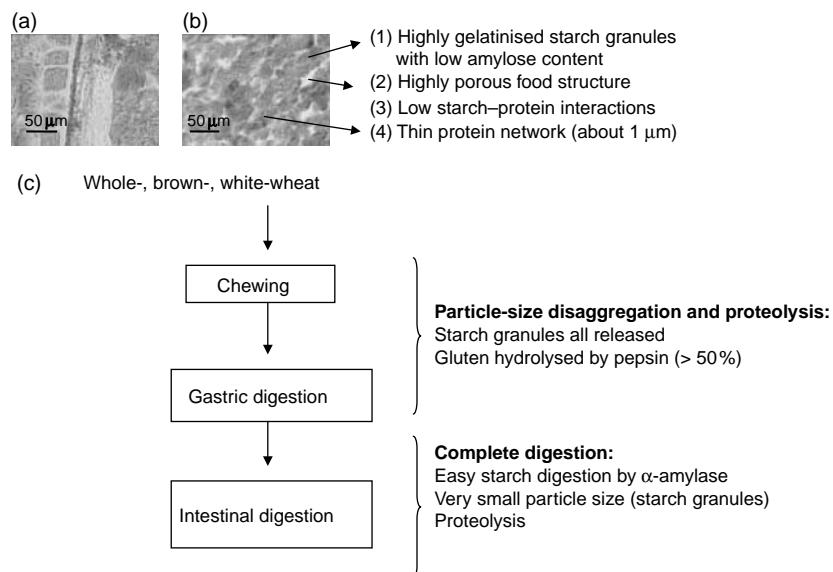
Fig. 1. The different steps in bread digestion. (a) Microscopic structure of whole or brown bread showing bran inclusion, (b) Microscopic structure of white bread, (c) process of bread digestion.

process. Instead of making whole flour by adding bran to white flour always using the same drastic technological process (for example, intense kneading to compensate for the presence of fibre), it would be preferable to directly use wholegrain flour with the totality of wheat fractions (bran, germ and endosperm). Wholegrain flour contains particles with a more intact structure favourable to a slow starch digestion, and therefore to a lower GI (see values in Table 1 for coarse cereal-kernel breads).

It must be noted that even white bread contains dietary fibre, but in a quantity too small (2–3 %) to have an effect on the glycaemic response. To our knowledge, no studies have dealt with the impact of fibre from white bread on its glycaemic response. However, the presence of soluble fibres and other microbial exopolysaccharides in white bread (in addition to starch–protein interactions) may partly contribute to its lower GI in comparison with that of pure glucose.

French v. Anglo-Saxon breads

On the other hand, white or wholemeal bread may have a more moderate glycaemic response depending on the way it is made. For example, most white and wholemeal breads mentioned in the literature are made with white refined flour, with multiple additives, including monoacylglycerols to prevent staling. Monoacylglycerols tend to complex with amylose, leading to a slower rate of starch degradation. In most French white-wheat breads, no monoacylglycerols are added. Moreover there are few determinations of their GI values, and must be considered cautiously as can be seen from values of the Foster-Powell table (Foster-Powell *et al.* 2002); for example, French baguette was shown to have a GI of 95, but this value was obtained from only three diabetic subjects (Bornet *et al.* 1987), and the presence of a gluten network and of soluble fibre (about 2–3 %) is unlikely to lead to a GI close to that of glucose (GI 100). More recent GI values obtained for French breads (Adam *et al.* 2003; Rizkalla *et al.* 2004) are given in Table 1; they range in the GI interval 57–89. Again, the GI value for the traditional French baguette (57 (SEM 9)) must be considered cautiously since it is not significantly different from that of French wholegrain bread (GI 85 (SEM 27)) (Rizkalla *et al.* 2004).

Different ways to reduce the glycaemic index of breads

In order to obtain a lower GI for bread, means to reduce starch accessibility need to be identified. This point is particularly relevant for diabetics, who have a limited range of low-GI foods available, especially in terms of cereal products (Björck & Elmstahl, 2003). Thus, within the hundred cereal products consumed in Western countries, only sixteen have a GI < 70 and could therefore be considered as low-GI foods. These mainly include pasta products, parboiled rice, intact cereal grains (alone or incorporated in bread), bulgur, couscous and cereal products rich in viscous soluble fibre. Data from the Foster-Powell table (Foster-Powell *et al.* 2002) indicate that it is possible to reduce the GI of bread (Table 1). There are two ways of reducing starch accessibility to α-amylases: modifying the digestive physiology (slowing down of gastrointestinal transit or the speed of glucose diffusion–absorption through the intestinal mucosa);

limiting starch accessibility into food particles (Table 2). This can be achieved through the choice of raw materials and technological processes.

Amylose:amylopectin ratio and glycaemic response

Starch is composed of amylose and amylopectin. Due to its linear (and thus more compact) structure, amylose is hydrolysed more slowly than amylopectin, whose branched structure is more accessible to α-amylases.

In wheat flour, amylose is 30 % of the total starch. It has been shown that it is possible to use other cereals that are richer in amylose to complement wheat, such as maize (which can contain up to 70 % amylose), rice (high-amylose varieties) or some barley genotypes (up to 44 % amylose). By mixing wheat flour with other types of flours, it is thus possible to increase the amylose content and significantly reduce the GI of bread (Akerberg *et al.* 1998). Hoebler *et al.* (1999) have shown that adding a high-amylose maize to wheat flour led to a significant GI reduction of 40 units in comparison with white-wheat bread. The percentage of resistant starch in the bread enriched with high-amylose maize flour was estimated to be 14 %. During digestion, a starch fraction (incompletely gelatinised native amylose) resists enzymic degradation. Muir *et al.* (1995) have also used scanning electron microscopy to demonstrate the presence of intact starch granules at the end of the small intestine in ileostomised patients who had consumed a meal rich in resistant starch (high-amylose maize bread). Granfeldt *et al.* (1995*a*) also achieved a considerable reduction of bread GI (GI < 50) by using bread (arepas) composed of high-amylose maize flour (about 70–75 % starch). In addition to maize, barley or rice, another research direction could therefore be the selection of wheat varieties that are richer in amylose. However, this research has not yet been conducted.

Starch–protein and starch–fibre interactions and glycaemic response

Another way to reduce GI is to limit starch accessibility to α-amylases by total or partial starch encapsulation with other components such as fibres and/or proteins. Hard wheat is characterised by stronger starch–protein interactions than soft wheat. This property is thus used in the manufacturing of pasta where the presence of a structured protein network around the starch granules (associated with a very compact food structure) leads to slow and progressive starch hydrolysis, and therefore to a relatively low GI (< 70). We attempted to add wheat semolina in bread to improve GI, but effects were contradictory (Granfeldt *et al.* 1991; Adam, 2002). In the study of Adam (2002), GI was 74 (Table 1) in comparison with French white bread (used as reference), and in the study of Granfeldt *et al.* (1991), there was no difference in the GI of white-flour and semolina breads. This may be attributed to the presence of monoacylglycerols usually added into white-flour bread dough leading to a slower rate of starch digestion (complexation of lipids with amylose), which was not the case in the study of Adam (2002). As a result, GI difference between semolina and white-flour breads were attenuated. Other studies are therefore required to confirm the hypoglycaemic potential

Table 1. Glycaemic indices (GI) of different breads in healthy volunteers*
(Mean values with their standard errors)

Breads	GI (glucose = 100)		GI (bread = 100)	
	Mean	SEM	Mean	SEM
French wheat breads				
Pain au lait (Pasquier, France)	63	10	90	
Traditional baguette†	57	9	82	
Wholegrain bread (loaf)†	85	27	122	
Whole bread‡	55		76	12
Semolina bread§	52		74	13
Leavened whole bread‡	46		67	7
Brown bread§	52		74	5
Brown bread with bran added§	62		89	7
Brown bread with boiled bran added§	43		61	6
Coarse barley-kernel bread				
80 % intact kernels (20 % white-wheat flour)	40		57	10
80 % scalded intact kernels (20 % white-wheat flour)	34		48	10
Barley-kernel bread (50 % kibbled barley) (Australia)	48		69	7
Barley-flour breads				
Wholemeal barley-flour bread	70		100	
Wholemeal barley-flour (80 %) bread (20 % white-wheat flour)	67		95	15
Wholemeal barley-flour (70 %) bread (30 % white-wheat flour) baked 20 h at 120°C (pumpernickel-baking conditions)‖	50		71	9
Wholemeal barley bread, flat, thin, soft (50 % regular barley flour, 50 % high-fibre barley flour) (Sweden)	50		71	11
Wholemeal barley bread, flat, thin, soft (20 % regular barley flour, 80 % high-fibre barley flour) (Sweden)	43		61	7
Wholemeal barley-flour (80 %) and white-wheat flour (20 %) bread fermented or with added organic acids or salts				
Wholemeal barley-flour bread with sourdough (lactic acid)	53		76	
Wholemeal barley-flour bread with lactic acid	66		94	
Wholemeal barley-flour bread with calcium lactate	59		84	
Wholemeal barley-flour bread with sodium propionate	65		93	
Gluten-free multigrain bread (Country Life Bakeries, Dandenong, Australia)	79	13	113	
Oat breads				
Coarse oat-kernel bread, 80 % intact oat kernels and 20 % white-wheat flour	65		93	11
Oat-bran bread (50 % oat bran) (Australia)	44		63	10
Oat-bran bread (45 % oat bran and 50 % wheat flour) (Sweden)	50		72	10
Rye breads				
Coarse rye-kernel bread, 80 % intact kernels and 20 % white-wheat flour (Sweden)	41		58	8
Sourdough rye	48		69	
Wheat bread				
Coarse wheat-kernel bread, 80 % intact kernels and 20 % white-wheat flour (Sweden)	52		74	7
White resistant starch-enriched bread				
Fibre white (Nature's Fresh, Auckland, New Zealand)	77	10	110	
Wholemeal (wholewheat) wheat-flour bread (Canada)	72	6	103	
Wholemeal (wholewheat) wheat-flour bread (South Africa)	75	9	107	
Wholemeal (wholewheat) wheat-flour bread (Tip Top Bakeries, Australia)	77	9	110	
Specialty wheat breads				
9-Grain Multi-Grain (Tip Top Bakeries, Australia)	43	5	61	
Multigrain loaf, spelt wheat flour (Australia)	54	10	77	
Multigrain (50 % kibbled wheat grain)	43		61	
Sourdough wheat (Australia)	54		77	
White-wheat-flour flatbread (Sweden)	79		113	13
Unleavened bread				
Lebanese bread, white (Seda Bakery, Sydney, Australia)	75	9	107	
Middle Eastern flatbread	97	29	139	
Spelt wheat bread				
Spelt multigrain bread (Pav's bakery, Australia)	54	10	77	14
White-wheat-flour bread (Canada)	69	5	99	
White-wheat-flour bread (Sunblest; Tip Top Bakeries, Australia)	70		100	

* Values are from the Foster-Powell table (Foster-Powell *et al.* 2002) unless otherwise indicated, and were obtained with at least eight healthy volunteers. When bread was the reference food used in the original study, the GI value for the food was multiplied by 0·7 to obtain the GI with glucose as the reference food (and by 1·43 when glucose was the initial reference food). When the food reference is bread, GI values should be considered cautiously since white wheat bread has various origins and may therefore have different GI; besides, values above 100 in the right-hand column have no real physiological relevance compared with the GI of 100 for reference white wheat bread.
† From Rizkalla *et al.* (2004).
‡ From Adam *et al.* (2003).
§ From Adam (2002).
‖ From Akerberg *et al.* (1998).

Table 2. Different means to reduce the glycaemic index of bread

Modifications realised	Effect obtained

On the raw materials
  Amylose:amylopectin ratio
  Starch encapsulation by protein or fibre
  Incorporation of intact cereal kernels
	Limitation of the starch accessibility to α-amylase within the food matrix

On the raw materials
  Adding soluble fibre (β-glucans, arabinoxylans)
  Adding organic acids
	Modification of digestive physiology
	  Increased viscosity of the digestive medium
	  Slowing of gastric emptying rate

On the technological process
  Use of leaven (organic acids) instead of regular yeast
  Short kneading and/or long fermentation time
	More compact structure and slowing of gastric emptying rate

of semolina. If the GI reduction of bread semolina was confirmed, such a raw material could be incorporated into the baking mix, especially since semolina is richer in proteins and minerals than soft wheat flour. On the other hand, in most of the studies performed, the use of whole flour (wheat-, barley- or rye-based) richer in fibre did not modify the GI of the breads (Jenkins *et al.* 1981, 1983, 1986; Liljeberg *et al.* 1992; Leinonen *et al.* 1999). As discussed previously, in these studies, the process remained drastic enough to alter the physical structure of the raw materials. However, in the studies of Adam (2002) and Adam *et al.* (2003), brown and whole breads exhibit a lower GI (74 and 76, respectively) than white-wheat bread. Again, these contradictory results could be attributed to the presence of monoacylglycerols in the white bread recipes used in most studies, unlike the French white bread recipe used in the study of Adam *et al.* (2003) which led to a higher GI.

Use of intact cereal grains in bread and glycaemic response

To preserve the physical structure of the food matrix, breads may be made by incorporating into the flour intact cereal grains in which a fibrous network (insoluble fibre) surrounds the starch, limiting the degree of starch gelatinisation and forming a physical barrier to α-amylases. The GI of a bread baked from 40 % intact parboiled barley grains and 60 % white flour is 68. The GI was 33 when the percentage of barley grains was 80 % (Liljeberg & Bjorck, 1994). The same authors (Liljeberg *et al.* 1992), as well as Jenkins *et al.* (1986) and Holm & Björck (1992), obtained similar results with rye (GI 46) and wheat grains (GI 68), respectively, but no effect was observed with oat grains (see also Table 1). In this last case, the absence of effect on GI was attributed to the fact that oat grains are more easily destructured during the thermal process than grains of other cereals. Another positive benefit of using intact cereal grains is the preservation of food particles in the gastrointestinal tract, especially at the gastric level; solid foods are indeed emptied more slowly than liquid foods from the stomach. The glycaemic response is thus slowed down. The use of whole grains in bread may therefore result in low GI values associated with the unmilled and unrefined cereals.

Use of viscous soluble fibre in breads and glycaemic response

Other authors have also shown a positive effect on GI reduction of adding viscous fibre (soluble fibre) (Jenkins *et al.* 1978; Würsch & Pi-Sunyer, 1997). The objective was not to form a physical barrier between starch and α-amylases, but to increase the viscosity of the digestive medium, especially the thickness of the unstirred layer at the level of the intestinal mucosa, limiting the diffusion and thus the absorption of glucose through epithelial cells (Lund *et al.* 1989; Würsch & Pi-Sunyer, 1997). The mobility of the digestive fluids at the level of intestinal microvilli is thus greatly reduced. There may also be interactions between soluble fibre and the mucopolysaccharides of the digestive mucosa (Johnson & Gee, 1981; Flourie *et al.* 1984). Several types of fibre have been successfully tested: oat fibre (Holm & Björck, 1992), barley fibre rich in β-glucans (Liljeberg *et al.* 1996), arabinoxylans (Lu *et al.* 2000, 2004) or the use of cereal varieties naturally rich in soluble fibre (Holm & Björck, 1992).

Thus, Liljeberg *et al.* (1996) have shown with whole barley-based breads rich in soluble fibre (β-glucans) (50 and 80 % substitution of the barley flour) that it was possible to lower the GI (in comparison with a reference bread) by 30 and 40 units, respectively. The hypoglycaemic effect was all the more important because the β-glucan content of the barley flour was high (Cavallero *et al.* 2002). However, in order to have a positive effect, soluble fibres must be incorporated into the food or consumed at the same time as the tested food. Moreover, the fibre must not be destructured, since there is a risk that their rheological properties (especially viscosity) will be modified in the intestine, thus decreasing the GI reduction (Wood *et al.* 1994). For instance, due to their linear structure, barley and oat β-glucans are very sensitive to depolymerisation during the technological process (baking or isolation of β-glucan-rich fraction by water), which in turn reduces their viscosity *in vivo*. The viscosity of β-glucans therefore depends not only on their molecular weight but also on quantity added. Würsch & Pi-Sunyer (1997) thus conclude in their review that a 50 % reduction of the glycaemic peak can be achieved with a 10 % β-glucans concentration in the cereal product. We thus succeeded in reducing the glycaemic response of bread by 46 % in diabetic patients (type 2) by incorporating oat bran concentrates (9 g β-glucans/d) to white-wheat bread (Pick *et al.* 1996).

In addition to β-glucans found in barley and oat fibre, arabinoxylan (about 88 % of NSP in endosperm and 64–9 % in the bran fraction), a by-product of wheat flour processing (but also found in rye in significant proportion), was also shown to reduce glycaemic response when incorporated in bread at a level of 7 and 14 % (Lu *et al.* 2000, 2004).

Arabinoxylans is a hemicellulose composed of a backbone of xylose with arabinose side chains. The mechanism by which it reduces GI is supposed to be the same as that of β-glucans: delayed gastric emptying and lowering of the rate of diffusion of nutrients from the intestinal lumen to the absorptive membrane (Lund *et al.* 1989). The arabinoxylans must be incorporated at high levels in bread recipes (7–14 %) to have a physiological effect, well above the 5 % naturally found in wholewheat flour.

It seems that the hypoglycaemic effect is stronger when soluble fibre forms an intrinsic part of the food matrix than when it is added to the food (Brennan *et al.* 1996). From this point of view, the preservation of intact cellular structure would favour interactions with other components of the food matrix, and thus influence their subsequent digestion. The use of oat bran or barley varieties naturally rich in β-glucans (for instance, the variety *prowashonupana*: 18 % β-glucans) may therefore be preferable to the addition of various cereal fibres or other sources of soluble fibre (gums or mucilages such as guar gum or psyllium fibre; Würsch & Pi-Sunyer, 1997*a*). Another advantage of using viscous soluble fibres is their positive effect on the reduction of LDL-cholesterol (Glore *et al.* 1994).

Organic acids in breads and glycaemic response

It is well known that some organic acids, such as acetic, propionic and lactic acids, have the ability to slow gastric emptying when they are included as bread ingredients or naturally produced by leaven fermentation. A reduction in the gastric emptying rate has thus been shown with breads enriched with sodium propionate (Darwiche *et al.* 2001), lactic acid (Liljeberg & Bjorck, 1996), acid salts (calcium lactate and sodium propionate) (Liljeberg *et al.* 1995) or consumed with vinegar (Liljeberg & Bjorck, 1998) (Table 1). In addition to a decrease in gastric emptying rate, organic acids could also contribute to reinforcing the interactions between starch and protein (gluten), thus limiting enzymic accessibility (Ostman *et al.* 2002*b*). The effect is positive if the acid is present during the gelatinisation of starch, but not after the thermal treatment (Ostman *et al.* 2002*b*). Sourdough bread, using a leaven prepared from the previous day's dough, has a globally slightly lower GI than regular bread baked with yeast (Adam *et al.* 2003), but it is difficult to know whether we can attribute these differences to the increase in their density or to the specific effects of the organic acids they contain. Due to other beneficial effects of leaven (for example, the partial hydrolysis of phytic acid leading to enhanced mineral bioavailability), it should therefore be preferable to use leaven instead of yeast in order to produce natural organic acids rather than simply adding organic salts.

Baking conditions and glycaemic response

Different baking conditions have been tested to reduce the GI of bread. Thus a GI reduction of 30 % has been obtained with a high-amylose barley bread baked 20 h at 120°C (i.e. pumpernickel-baking conditions) instead of the conventional 45 min at 200°C (Akerberg *et al.* 1998). Such conditions favour the formation of crystalline amylose (annealing) and increase the resistant starch content of about 10 %.

Conclusion and perspectives

The parameters governing the glycaemic response of bread are complex. Four factors are particularly important in slowing gastric emptying and digestion rate: the preservation of the food structure's cohesiveness during the digestive process; the degree of starch crystallinity; the viscosity of the digestive medium; the presence of organic acid. The physical structure of bread is the most important; the more compact the structure (particle state is maintained longer during the digestive process and area accessible to α-amylase is thus reduced), the lower the glycaemic response. Physical structure is more preponderant than degree of starch gelatinisation or presence of viscous fibre in determining glycaemic response (Granfeldt *et al.* 1995*b*). Studies carried out with other cereal foods, i.e. intact cereal grains or pasta, led to the same conclusions (Granfeldt *et al.* 1991). Breads with a high-food-structure cohesiveness are mainly breads with intact cereal grains or sourdough breads.

The development and consumption of bread products of high density should thus be encouraged. This could be achieved by reducing the kneading time and increasing the duration of fermentation (about 15 h), together with a reduction in yeast quantity. This kind of bread would exhibit a more compact crumb and a less porous food structure, leading to a moderate GI; moreover, this baking process would also prevent the oxidation of vitamin E and carotenoids.

A reduction in GI of starchy foods is often accompanied by a significant increase in resistant starch content (Björck *et al.* 2000) (resistant starch mainly includes retrograded starch upon cooling and physically inaccessible starch). This has positive consequences on colonic physiology since resistant starch behaves like fibre and is fermented by the colonic microflora into short-chain volatile fatty acids, in particular butyric acid, a preferred substrate for colonic mucosal cells. This acid may play a protective role against colon cancer. Consumption of low-GI foods also induces a prolonged satiety effect after the meal (Ostman *et al.* 2002*a,b*). This physiological effect is very interesting because it may limit snacking, which is often considered a risk factor for metabolic diseases such as obesity.

The data reviewed in the present paper allow us to envisage an ideal bread composed of a mix of cereals: wholewheat or brown flour (with a high nutritional density, rich in protective micronutrients) enriched with flour containing a proportion of soluble fibre (derived from rye, oats or barley) compatible with the baking process, and containing a small quantity of intact cereal grains. Last, it would be preferable to apply a baking procedure with leaven instead of yeast alone, in order to obtain a bread rich in organic acids and not too porous. The combination of steam rye grains, oat bran concentrate with 17 % β-glucans, and of sourdough has thus been successfully attempted, leading to a significant reduction in the glycaemic response (GI about 50) in comparison with usual white bread (white-wheat flour; GI 100) (Ostman *et al.* 2006). However, one may question whether such a bread would fulfil consumer

demand. In traditionally white-bread-consuming countries (as in France), we should try to enhance the density of the bread and use type 80 flour (that is 0·8 g ashes/100 g flour); and for this, it is interesting to mix white-wheat flour with about 25–40 % coarsely ground wheat grains after a pre-fermentation to hydrate fibre, destroy phytic acid and improve the baking process. In Scandinavian countries and Germany, it is undoubtedly easier to use whole flour or to add intact cereal grains since these countries are already used to eating these kinds of bread. In the end, it seems that many consumers are now ready to make the switch from white bread to a brown bread with a better physical structure and nutritional quality.

The overly high GI of bread has often been underlined; however, nutritional quality cannot be reduced to this sole parameter. For example, many countries incorporate fats in bread mixes. This reduces GI, but also increases fat intake. In fact, provided whole or brown flour is used, bread has a higher nutritional quality due to the presence of minerals and micronutrients, and its consumption can certainly be recommended, in particular in complex and well-balanced meals. This can be made possible by promoting a change in eating habits and by informing the consumer of the nutritional advantages of such breads.

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