Glycaemic index and metabolic disease risk

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There is growing evidence that the type of carbohydrate consumed is important in relation to metabolic disease risk, and there is currently particular interest in the role of low-glycaemic-index (GI) foods. Observational studies have associated low-GI diets with decreased risk of type 2 diabetes and CHD, and improvements in various metabolic risk factors have been seen in some intervention studies. However, findings have been mixed and inconsistent. There are a number of plausible mechanisms for the effects of these foods on disease risk, which arise from the differing metabolic responses to low- and high-GI foods, with low-GI foods resulting in reductions in hyperglycaemia, hyperinsulinaemia and late postprandial circulating NEFA levels. Low-GI foods may also increase satiety and delay the return of hunger compared with high-GI foods, which could translate into reduced energy intake at later time points. However, the impact of a low-GI diet on body weight is controversial, with many studies confounded by dietary manipulations that differ in aspects other than GI. There is currently much interest in GI from scientists, health professionals and the public, but more research is needed before clear conclusions can be drawn about relationships with metabolic disease risk.

Glycaemic index: Metabolic disease: Carbohydrate

Obesity and obesity-related metabolic diseases are major public health concerns. More than one billion adults worldwide are overweight, with ≥300 million clinically obese (World Health Organization, 2002). Obesity is an important predisposing factor for chronic non-communicable diseases, including type 2 diabetes and CVD. Non-communicable diseases account for approximately 75% of deaths worldwide, and this percentage is predicted to increase as rates rise in developing countries (World Health Organization, 2003). These diseases are also related to diet and lifestyle independently of body weight. It is therefore vital to develop strategies to prevent and treat obesity that target these diet and lifestyle factors.

Evidence for adverse effects of high-fat diets on metabolic disease risk has led to recommendations in the UK that total dietary fat should contribute ≤33% energy intake, with <10% energy intake from saturated fats (Department of Health, 1994). Reductions in fat usually lead to reciprocal increases in carbohydrate intake. However, less-detailed recommendations have been issued in relation to the quality of dietary carbohydrate. Different types of carbohydrate have differing metabolic effects, especially in the extent to which they raise blood glucose and insulin levels. It is therefore hypothesised that they will affect metabolic risk profiles in different ways. Carbohydrates are commonly classified according to their chemical and physical properties, e.g. ‘simple’ (mono- and disaccharides) v. ‘complex’ (polysaccharides), based on the belief that the digestion rate of a carbohydrate is determined by its saccharide chain length. This assumption is now known to be inaccurate, and a more physiologically-relevant classification system has been sought (Food and Agriculture Organization/World Health Organization, 1998).

The glycaemic index

The glycaemic index (GI) is a system for the classification of carbohydrate-containing foods that is based on their blood-glucose-raising potential. It is defined as ‘the incremental area under the glucose response curve to a test food providing a fixed amount of carbohydrate, relative to the response to a standard control food (glucose or white bread) providing the same amount of carbohydrate’ (Jenkins et al., 1981; Food and Agriculture Organization/World Health Organization, 1998). Foods with a high GI produce
a higher peak and greater overall blood glucose response than those with a low GI, which release glucose into the blood at a slower rate (Fig. 1). A low-GI food is defined as having a GI of \( \leq 55 \), and a high-GI food has a GI of \( \geq 70 \).

The blood-glucose response to a food, and thus the GI, is determined by the rate of digestion and absorption of the carbohydrate, which is affected by a number of factors. These factors include chemical properties: the type of monosaccharide (fructose and galactose give a lower GI than glucose; Englyst et al. 2003); amylose:amylopectin in starch (the branched amylopectin is more rapidly digested than the straight-chain amylose, and so gives a higher GI; Granfeldt et al. 1995); the presence of viscous soluble fibres such as guar and \( \beta \)-glucan, which can lower GI because of their gel-forming properties (Björck et al. 2000). Physical properties of foods also influence the GI: foods with an intact botanical structure tend to have lower GI values, as the starch is protected from enzymic degradation by the outer layer of the grain kernel (Juntunen et al. 2002); GI tends to increase with the extent of ripeness (Hermansen et al. 1992), cooking, processing and refining (Jenkins et al. 1988; Holt & Miller, 1994), which render the carbohydrate more digestible, although some methods of processing, such as parboiling, can lower GI (Larsen et al. 2000). The presence of other food components also influences the GI: fat and protein in foods lower GI by slowing gastric emptying; \( \alpha \)-amylase inhibitors lower GI by slowing starch digestion (Augustin et al. 2002).

**The glycaemic load**

It is not only the GI of the carbohydrate in the diet that affects glucose and insulin responses, but also the quantity of carbohydrate consumed. Both these variables are represented by the glycaemic load (GL). A low-GL diet can be achieved either by reducing carbohydrate intake or by reducing the GI of the carbohydrates consumed. The GL is calculated as the amount of carbohydrate in a food, multiplied by its GI and the quantity eaten, summed for all foods (GL = \( \Sigma \) (amount of food consumed \( \times \) carbohydrate content of food \( \times \) GI); Willett et al. 2002).

**Measurement of the glycaemic index of various foods**

The GI of a food cannot easily be predicted from the basic food components, and must be measured as an *in vivo* response relative to a standard. Lists of the GI values of many foods have been published (Foster-Powell et al. 2002). However, these lists are by no means complete, especially since GI can vary with only subtle differences in processing. Thus, it may not always be appropriate to apply published GI values to similar products that differ in brand or country of origin from those that have been measured. Inappropriate application of data is a potential problem in studies of GI and health in which published values are frequently used to calculate dietary GI or to determine intervention diets.

Intervention studies that use prescribed foods should first establish the GI of the foods by means of standardised methodology (Food and Agriculture Organization/World Health Organization, 1998). In studies at MRC Human Nutrition Research, Cambridge, UK, foods were tested in ten subjects who each performed three tests with a 50 g glucose standard. Glucose was measured in capillary blood obtained by finger-prick in the fasted state and at six further time points over the 2 h following commencement of consumption of the test food. The portions of food tested contained 50 g glycaemic carbohydrate, defined as total carbohydrate minus dietary fibre. As values for fibre (the manufacturers’ values) are determined according to the AOAC International (1995) procedure, some, but not all, resistant starch is included. Foods were tested as they might typically be consumed: breakfast cereals with semi-skimmed milk, which provided 15% of the available carbohydrate in the test portion; other foods (breads, potatoes, pasta and rice) with 10 g margarine per test portion. Although this procedure would have affected the absolute GI of the foods, adding the same quantity to each food should not have affected their hierarchical relationship (Collier et al. 1986). As the intention was to identify high- and low-GI versions of foods that could be substituted for each other, it was this relative difference in GI that was of primary importance.

In general, results were found to be close to published values for similar foods; e.g., low GI values (43–54) for pastas and relatively high ratings (69–102) for all potatoes. The differences between GI values for various cereals were found to be smaller than expected, with many clustering at approximately 60–65. Cereals were tested with milk, which has a disproportionately large insulinemic effect for the glucose response it produces (Ostman et al. 2001), and the resulting high insulin:glucose may have attenuated glucose responses. The magnitude of the inter-individual variability across foods was found to be large, with the 95% CI for a number of foods spanning low, medium and high GI ranges. This variability raises concerns where foods with only small GI differences are used in interventions.

The findings illustrate some of the factors affecting GI. Porridge made from larger more-intact oats was found to have a lower GI (40) than that made from more-finely-ground oats (61; \( P=0.019 \)). Differing effects of different types of fibre were also observed; while wheat fibre was
Metabolic effects of low- and high-glycaemic-index diets

Evidence from observational studies

Observational studies indicate that the GI of the diet may be an important determinant of metabolic risk. The major sources of carbohydrate in the Western diet (highly-refined cereal and potato products) tend to have high GI values, which has been linked to the widespread occurrence of type 2 diabetes and CVD.

Lower dietary GI has been associated with reduced risk of developing type 2 diabetes in large cohorts of both men (Salmerón et al. 1997a) and women (Salmerón et al. 1997b), with risk increased by 37% in the highest quintiles of energy-adjusted GI compared with the lowest quintiles, after adjustment for potential confounders including cereal fibre intake (Fig. 2(a)). However, this difference in risk is not a totally consistent finding, as no relationship was found between GI and diabetes risk in a 6-year follow-up of 35,988 post-menopausal women from the Iowa Women’s Health Study (median GI for lowest and highest quintiles: 53 and 89; Meyer et al. 2000). These disparities may relate to imprecision in the assessment of GI, especially since many studies have used food-frequency questionnaires that were not designed to measure GI.

Associations have also been observed between both GI and GL of diets and CHD risk in the Nurses’ Health Study (Liu et al. 2000). After adjustments for potential confounders, including dietary fibre intake, risk of CHD was shown to be increased by 98% in the highest quintile of energy-adjusted GL v. the lowest quintile, and by 31% in the highest quintile of energy-adjusted GI v. lowest quintile (Fig. 2(b)). No association with total carbohydrate intake was found, indicating that the majority of the effect of GL is related to GI. Again, this association is not a consistent observation, as no relationship was found between GI and CHD risk in 646 men aged 64–85 years from the Zutphen Elderly Study (van Dam et al. 2000), although this study was much smaller and may not have had sufficient power to detect a relationship.

GI has also been shown to be positively associated with the prevalence of the metabolic syndrome and insulin resistance in a cross-sectional study of 2834 subjects from the Framingham Offspring cohort (McKeown et al. 2004). Odds of having metabolic syndrome were reported to be 41% higher in the highest quintile of dietary GI compared with the lowest quintile (median GI values 84 and 72 respectively), and insulin resistance was found to be increased across quintiles (P<0.001 for trend). Other dietary carbohydrate factors that were shown to be related to lower insulin resistance include higher intakes of total fibre, cereal fibre and whole grain. In contrast, no association between GI and insulin resistance was found in a cohort of 5675 subjects aged 30–60 years from the Danish Inter99 study, after adjustment for potential confounders including dietary fibre (Lau et al. 2005).

Associations have also been reported between GI and both unfavourable lipid profiles and raised inflammatory status. In 280 women aged 45–70 years from the Nurses’ Health Study fasting triacylglycerol levels were shown to be positively related to GI (Liu et al. 2001). Serum HDL levels have been found to be negatively related to GI in...
Evidence from intervention studies
The effect of GI on health outcomes in intervention studies has been mixed. Studies have varied widely in duration, sample size, subject type and intervention diet, and many have used diets not matched for energy, macronutrient or fibre content. There have, however, been some reports of improvements in insulin sensitivity, β-cell function, dyslipidaemia and thrombolytic function.

Several studies have investigated the effects of a low-GI diet on insulin sensitivity. In thirty patients with advanced CHD insulin sensitivity was found to be improved in 4 weeks in the low-GI group, with the dietary GI reduced by 10 (from 86 to 76), compared with the high-GI group (Frost et al. 1996). In sixteen women at increased risk of CHD as a result of parental history of the disease, those randomised to a low-GI diet for 3 weeks, with the dietary GI reduced by 24 (from 91 to 67), were found to have improved insulin sensitivity compared with the high-GI group (Frost et al. 1998). No effects of lowering GI were seen in control subjects with no parental history of CHD, suggesting that benefits may only be achievable in those subjects either predisposed to, or already having some extent of, insulin resistance. In support of this explanation no effects of a low-GI diet on insulin sensitivity were seen in seven lean insulin-sensitive men, following nutrient-matched high- and low-GI diets (mean GI difference 24) for 30 d (Kiens & Richter, 1996). Furthermore, no effect on insulin sensitivity or β-cell function was found in a 10-week parallel study of forty-five overweight women for effects on other lipids.

There is some evidence to suggest that low-GI diets may improve insulin secretion. First, the glucose disposition index (the ability of β-cells to compensate for changes in insulin sensitivity by increasing insulin secretion) was found to be improved in subjects with impaired glucose tolerance after 4 months on a low (mean GI 54.4, n 13)-GI diet compared with high (mean GI 59.3, n 11)-GI diet (Wolever & Mehling, 2002). While a trend towards improvements in insulin sensitivity was reported in the low-GI diet, it did not reach significance. However, the fibre intake in the low-GI group was shown to be higher, so the effects cannot confidently be attributed to GI. Second, an 8-week cross-over study in twenty post-menopausal women has compared the effects of high-fibre rye bread and white wheat bread (Juntunen et al. 2003). The rye bread was found to enhance insulin secretion without any effect on insulin sensitivity, suggesting an improvement in β-cell function. While the rye bread had a lower GI than the wheat bread, it was also higher in soluble fibre, phytates and tannins, which could act by reducing GI, or via other independent effects.

Some studies in subjects with type 2 diabetes and impaired glucose tolerance, in whom dyslipidaemia is common, have demonstrated improvements in lipid profiles with lowered GI. These improvements include decreases in total cholesterol, LDL-cholesterol and triacylglycerol, and increases in HDL-cholesterol with differences in dietary GI of 20–28 over 4–6-week periods (Fontvieille et al. 1992; Wolever et al. 1992; Järvi et al. 1999; Luscombe et al. 1999; Wolever & Mehling, 2002). However, a 6-month study in subjects with type 2 diabetes with a GI difference of 10 has reported no effects on blood lipids (Tsilihas et al. 2000). Evidence suggests any beneficial effects of low-GI diets are most marked in those subjects with the worst dyslipidaemia (Brand-Miller, 1994). In forty-five overweight women LDL was found to be different between groups after 10 weeks on low- or high-GI diets, with a reduction of 10% in the low-GI group, and a slight increase (2%) in the high-GI group (Sloth et al. 2004). A tendency towards a greater decrease in total cholesterol in the low-GI group was observed, but it was not significant. These findings are not conclusive, however, and a Cochrane meta-analysis investigating the role of low-GI diets in CHD risk (Kelly et al. 2004) that has reviewed fifteen randomised controlled trials in subjects with pre-existing CHD risk factors has concluded that whilst there is some limited evidence for slight reductions in total cholesterol with low-GI diets, there is no evidence for effects on other lipids.

A low-GI diet may have beneficial effects on thrombolytic function. The activity of plasminogen activator inhibitor-1, a thrombolytic factor that increases clot and plaque formation, has been found to be 53% lower after 24 d on a low (56.8)-GI diet compared with a high (82.7)-GI diet in twenty subjects with type 2 diabetes (Järvi et al. 1999). Plasminogen activator inhibitor-1 has also been shown to be decreased in the low-GI group of a weight-loss intervention compared with a low-fat-diet group, despite no differences in weight loss (Ebbeling et al. 2005); however, the low-GI diet was also lower in carbohydrate.

Potential mechanisms for effects of low-glycaemic-index diets
The mechanisms by which low-GI diets may reduce metabolic disease risk are still unclear. They may include direct metabolic effects, and also reductions in body weight with concomitant improvements in health. A number of plausible biological mechanisms arise from the differing metabolic responses to low- and high-GI foods, which may underpin differential effects on metabolic disease risk.

Metabolic responses to high- and low-glycaemic-index foods
The rapid large rise in blood glucose following consumption of high-GI foods triggers a large insulin response and
strongly inhibits glucagon release. For most foods a good correlation exists between glycaemic and insulinaemic responses, with high-GI foods eliciting large insulin responses (Björck et al. 2000), which trigger rapid uptake of nutrients by insulin-responsive tissues and suppress nutrient mobilisation. Glucose uptake and glycogen synthesis in skeletal muscle and liver, and lipogenesis in adipose tissue, are increased. Simultaneously, gluconeogenesis and glucose output by liver and lipolysis and NEFA release by adipose tissue are suppressed. Low-GI foods produce an attenuated glucose response, and so the resulting hormone responses and effects are less dramatic.

As a result of the rapid absorption of nutrients from a high-GI meal the rate of entry of exogenous glucose into the circulation decreases sooner than it would following a low-GI meal. However, the effects of the high insulin:glucagon persist, so that nutrient storage continues and mobilisation from tissues remains suppressed. Blood glucose falls rapidly, often dropping below fasting levels. This hypoglycaemic undershoot triggers release of counter-regulatory hormones, including glucagon, adrenaline and growth hormone. These hormones act to restore circulating fuel levels by increasing hepatic glucose output and decreasing glucose uptake by skeletal muscle. However, they also trigger lipolysis and NEFA release by adipose tissue, causing a rebound in circulating NEFA levels (Wolever et al. 1995). In contrast, as a result of the prolonged and continued absorption of nutrients from the gastrointestinal tract following a low-GI meal, the hypoglycaemic undershoot does not occur, and the fasted state is not reached until much later. This slower release of nutrients and gradual drop in blood glucose levels allows adjustment of hepatic glucose output to maintain circulating glucose levels without dramatic rises and falls, or a large rebound in NEFA levels.

Low-GI diets therefore give a more stable diurnal profile, reducing postprandial hyperglycaemia and hyperinsulinaemia, and attenuating late postprandial rebounds in circulating NEFA, all factors that exacerbate various components of the metabolic syndrome (Fig. 3).

**Insulin resistance**

High circulating NEFA levels result in lipid accumulation in skeletal muscle and liver, causing insulin resistance in these normally insulin-responsive tissues (Frayn, 2001; Petersen & Shulman, 2002), which reduces insulin-stimulated glycogen synthesis in skeletal muscle (the primary pathway for non-oxidative glucose disposal in normal subjects; Kelley et al. 2002) and decreases the ability of insulin to suppress hepatic glucose production and output. High circulating NEFA levels also inhibit insulin-stimulated suppression of NEFA release from adipose tissue, so further increasing circulating levels, and triggering a vicious cycle of insulin resistance and increased fatty acid levels (Frape et al. 2000).

Attenuation of the NEFA rebound may be a mechanism by which low-GI diets could improve insulin sensitivity. This mechanism is supported by findings from ‘second meal’ studies showing that low-GI-preload meals compared with high-GI-preload meals may improve (attenuate and prolong) glycaemic responses to standard subsequent meals (Jenkins et al. 1982; Liljeberg & Björck, 2000). The glucose response curve to a standard lunch has been shown to be related to plasma NEFA concentration immediately before the lunch (Wolever et al. 1995), and preload meals that improve glucose and insulin responses to a standard lunch are those that prevent a hypoglycaemic undershoot until the second meal (Liljeberg et al. 1999).

**Insulin secretion**

There are several plausible explanations for a beneficial effect of low-GI diets on β-cell function. The large insulin demand created by high-GI meals leads to overstimulation of β-cells, which may cause β-cell ‘exhaustion’ (Ludwig, 2002). High glucose levels have a glucotoxic effect on β-cells, probably as a result of free radical oxidative damage (Augustin et al. 2002). Hyperinsulinaemia may reduce β-cell function by causing excess amyloid deposition (Wolever, 2000). High NEFA levels lead to triacylglycerol accumulation in β-cells, which reduces insulin secretion (Goldstein, 2002). Accordingly, by reducing hyperglycaemia, hyperinsulinaemia and NEFA levels low-GI foods may decrease the factors contributing to β-cell failure.

**Dyslipidaemia**

Low-GI diets may reduce insulin-stimulated activity of 5-hydroxy-3-methylglutaryl-CoA reductase, the rate-limiting enzyme involved in cholesterol synthesis, by reducing insulin levels. The benefits of low-GI diets may also be associated with attenuation of NEFA rebounds, since raised circulating NEFA increase triacylglycerol-rich lipoproteins. Other benefits may arise as a result of a typically high fibre content of low-GI foods. Dietary fibre tends to reduce bile acid and cholesterol re-absorption from the ileum, and also increases colonic fermentation.
and production of the SCFA propionate, which may inhibit hepatic cholesterol synthesis (Augustin et al. 2002).

Other cardiovascular risk factors

Hyperglycaemia is a continuous risk factor for CVD morbidity and mortality (Coutinho et al. 1999), and reductions in chronic hyperglycaemia associated with low-GI diets may impact on a number of cardiovascular risk factors. Hyperglycaemia exacerbates oxidative stress, which is associated with inflammation, increased blood pressure, accelerated clot formation and decreased endothelium-dependent blood flow (Augustin et al. 2002; Ludwig, 2002), and which may also worsen insulin resistance (Ceriello, 2000). Reduced hyperinsulinaemia associated with a low-GI diet may reduce CVD risk through effects on oxidative stress, blood pressure, serum lipids, coagulation factors, inflammatory mediators, endothelial function and thrombolytic function (Ceriello, 2000; Augustin et al. 2002; Goldstein, 2002; Ludwig, 2002; Davy & Melby, 2003).

Effects on body weight

Modest weight loss, or reduction of weight gain, is an additional potential mechanism by which low-GI diets may contribute to reduced risk of metabolic disease. The most likely mechanism for this effect is via reductions in energy intake. Low-GI foods may increase satiety and delay the return of hunger in comparison with high-GI foods, which may be translated into reduced energy intake at later meals. The hormonal environment following a high-GI meal reduces the availability of the two major metabolic fuels (glucose and fatty acids), signalling a fasted state. Hypoglycaemia is a signal for hunger, and the rate of change of blood glucose may also be important, with more rapid falls triggering more rapid return of hunger (Pawlak et al. 2002). The hypoglycaemic undershoot frequently seen following high-GI meals would therefore be predicted to trigger hunger. In one study (Ludwig et al. 1999) in which subjects ate more following a high-GI breakfast than following a low-GI breakfast the ad libitum energy consumption at lunch has been shown to be strongly predicted by the blood glucose nadir. Initial low levels of NEFA as a result of the high insulin response to high-GI foods may also trigger hunger. Low circulating NEFA levels caused by the consumption of high-GI foods predict intra-subject variability in energy intake following meals of differing GI (Ludwig et al. 1999). Together the NEFA levels and area under the glucose response curve following the preload meal predict 85% of the intra-subject variability in energy intake. Satiety is also inversely related to the area under the insulin response curve for various meals, with increased processing of grains increasing glucose and insulin responses and decreasing satiety ratings (Holt & Miller, 1994).

Low-GI foods may also delay the return of hunger by slowing gastric emptying. Many low-GI foods are high in fibre, which prolongs distension of the gastrointestinal tract, causing increased and prolonged secretion of the gut peptides cholecystokinin, ghrelin, glucagon, glucagon-like-peptide-1 and glucose-dependent insulinotropic polypeptide, all of which have been suggested as potential satiety factors (Burton-Freeman et al. 2002; Pawlak et al. 2002).

A number of short-term feeding studies have investigated the effects of low-GI meals on subsequent satiety, hunger and energy intake. However, many of these studies are confounded by the use of meals that differ in aspects other than GI, and findings have not been wholly consistent. One meta-analysis of cross-over studies investigating the effects of low- and high-GI preloads matched for energy and macronutrient content (Roberts, 2000) has found that subsequent energy intake averages 29% more after high-GI meals v. low-GI meals (P = 0.005). Another review of studies using low-GI preloads v. high-GI preloads with similar energy, macronutrient and fibre contents (Raben, 2002) has found that in twelve of twenty-four studies low-GI meals decrease hunger or increase satiety, and in six of twelve studies energy intake is lower at a later meal following a low-GI meal compared with a high-GI meal.

If low-GI foods do increase satiety, they may aid compliance to hypocaloric diets. However, longer-term effects on body weight are unclear. In a study in which a low-GI diet was compared with a standard hypocaloric reduced-fat diet for 4 months in 107 obese, but otherwise healthy, children (Spieth et al. 2000), with the low-GI diet not being energy-restricted and subjects instructed to eat to satiety, reductions in weight and BMI were achieved with the low-GI diet, but not with the standard treatment. However, subjects were not randomised, so selection bias cannot be discounted.

Comparing diets with differing nutrient contents is a problem in many interventions, such that effects cannot confidently be attributed to GI. A review of studies using diets with similar energy, macronutrient and fibre contents (Raben, 2002) has identified six studies with isoenergetic weight-maintaining diets, but none observed any difference in weight between diets. Of three studies using energy-restricted diets only one study reported weight loss in the low-GI group. However, prescribing energy intake reduces the possibility of effects via satiety mechanisms, and few studies have investigated effects of ad libitum low-GI diets on weight. In a recent 10-week parallel trial in forty-five overweight women (Sloth et al. 2004) subjects were instructed to incorporate certain minimal quantities of low- or high-GI versions of key carbohydrate-rich foods into their diets, to replace 75% of the carbohydrate intake. Subjects consumed the rest of their habitual diets ad libitum. Low- and high-GI intervention foods were matched for energy, macronutrient and fibre content, and differed in GI by 24. It was reported that weight decreased for both groups, but no significant differences were found between the groups. Furthermore, no differences in energy intake or fat mass were found. In a randomised cross-over study of eleven overweight men consuming low- or high-GI diets for 5 weeks each (Bouché et al. 2002) a trend towards greater decreases in body weight and energy intake on the low-GI diet compared with the high-GI diet was found, but the differences were not significant. However, a significant decrease (P < 0.05) in fat mass and a...
tendency to increase lean mass more \((P=0.07)\) on the low-GI diet were reported. Subjects in this study were provided with substitution lists allowing exchanges of low-GI or high-GI foods within food groups. GI was found to be different between diet periods \((41 \div 71)\), but fibre content was also found to be higher for the low-GI diet. The potential importance of fibre above GI is also highlighted in a cross-over study of twenty normal-weight women in which \textit{ad libitum} high-starch and high-sucrose diets (with the high-sucrose diet having a lower GI than the high-starch diet; Raben \textit{et al.} 2001) were compared for a period of 14 d (Raben \textit{et al.} 1997). A decrease in weight was found with the high-starch (higher-GI) diet, but no change was found with the high-sucrose (lower-GI) diet. However, the high-starch diet was also higher in fibre content and had a lower energy density than the high-sucrose diet.

From animal studies there is evidence for an effect on nutrient partitioning. Rats fed high-GI diets develop larger epididymal fat pads and adipocyte volumes than those fed low-GI diets (Brand-Miller \textit{et al.} 2002; Pawlak \textit{et al.} 2002). This outcome could plausibly be explained by the differing metabolic responses to high-GI and low-GI foods. The hormonal environment following high-GI foods may favour fat deposition, with nutrients directed towards storage rather than oxidation. Physiological changes observed in the rats fed high-GI diets \textit{v.} low-GI diets would also tend to favour adipogenesis. These changes include increased expression and activity of fatty acid synthase complex in adipose tissue, increased glucose uptake into adipocytes, increased GLUT4 expression in adipose tissue and increased hepatic lipogenesis (Brand-Miller \textit{et al.} 2002). However, the effects on nutrient partitioning during weight loss in human subjects are not clear. In one study, despite no differences in weight loss between low- and high-GI diets, selective loss of fat mass with an increase in lean mass has been reported (Bouché \textit{et al.} 2002). However, a study investigating the acute effects of low- and high-GI meals on fuel partitioning has found that, despite higher insulin levels following the high-GI meal, there are no differences in substrate oxidation (Díaz \textit{et al.} 2005).

Finally, there is limited evidence to suggest that the magnitude of the decreases in resting energy expenditure associated with hypoenergetic diets is smaller on low-GI diets \textit{v.} high-GI diets, thus contributing to a greater energy deficit. A randomised cross-over study of high- and low-GI diets for 9 d each in ten overweight men (Agus \textit{et al.} 2000) has found that resting energy expenditure decreases by 10.5\% on the high-GI diet compared with 4.6\% on the low-GI diet \((P=0.04)\). Another study comparing a low-GI diet with a conventional low-fat hypoenergetic diet (Pereira \textit{et al.} 2004) has found that, with a 10\% body-weight loss on each diet, resting energy expenditure decreases more on the low-fat diet compared with the low-GI diet \((10.6\% \div 5.9\%\), equivalent to 334 kJ \((80 \text{ kcal})/\text{d}, P=0.05\)). However, these diets were not matched for macronutrient content.

### Table 1. Glycaemic index (GI) values of intervention foods

<table>
<thead>
<tr>
<th>Low-GI foods</th>
<th>High-GI foods</th>
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<tr>
<td>Breakfast cereals</td>
<td>40–60</td>
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<tr>
<td>Bread</td>
<td>55</td>
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<tr>
<td>Basmati rice</td>
<td>43</td>
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<tr>
<td>Penne pasta</td>
<td>43</td>
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**Ongoing research**

To address some of the limitations of previous trials a dietary intervention study has been designed to assess how carbohydrates of varying GI affect metabolic disease risk and to explore some potential mechanisms for any effects. It is a randomised cross-over study of low-GI and high-GI diets in forty-four women aged 18–65 years with a BMI of \(\geq 25 \text{kg/m}^2\) and fasting insulin level of \(\geq 40 \text{ pmol/l}\) (sample size calculated to be sufficient to detect a 10\% difference in insulin sensitivity). The study consists of two consecutive 12-week periods of low-GI and high-GI diets, with measurements of a number of markers of metabolic disease risk at baseline and at the end of each diet period.

Subjects are provided with low-GI and high-GI versions of breakfast cereals, breads and rices, plus pasta during the low-GI period and potatoes on the high-GI period (intervention foods being selected by measurement of the GI of a number of carbohydrate-rich UK ‘staple’ foods; Table 1). Subjects maintain their normal habitual diets, substituting the intervention foods where they would normally eat them, in the quantity they would normally consume. They are asked to eat the foods approximately three times daily, but quantity is not specified, and subjects are instructed to eat \textit{ad libitum}. They are given guidance for foods to choose and avoid when eating away from home, but are not told of the GI concept. This dietary intervention is designed to avoid broader dietary changes that frequently occur when individuals are advised to follow a low-GI diet, such as increases in pulse, fruit, vegetable and whole-grain consumption. By concentrating on ‘staple’ foods it is intended to be easily achievable, and so maximise applicability to public health.

Measurable changes have been seen in other studies in which GI has been reduced by \(\geq 11\) by exchanging approximately half the dietary carbohydrate from high-GI to low-GI foods (Brand-Miller, 1994). Data from the National Diet and Nutrition Surveys reveal that the types of foods provided in the intervention supply 60–70\% of the total dietary carbohydrate (assuming a diet with 45–55\% energy from carbohydrate; Office of National Statistics, 2002). An estimated achievable difference of approximately 15 in dietary GI has been calculated from the GI values of the intervention foods (Table 1), and assuming a total daily carbohydrate intake of 250 g (calculated as: dietary GI = (carbohydrate provided by food (g)/total dietary carbohydrate (250 g)) × GI).

The study will investigate a range of outcomes, covering many potential effects of low-GI foods. These outcomes include: insulin sensitivity measured by the fasting indices of fasting glucose, insulin and homeostasis model assessment index of insulin resistance, and in the dynamic state by the area under the insulin response curve for a 75 g oral glucose load and also by a novel orally-stimulated
intraVenous glucose tolerance test, using isotopically-labelled glucose; glucose tolerance, assessed by fasting and postprandial glucose levels after a glucose load and after a mixed meal; body weight, waist circumference and body fat (determined by dual-energy X-ray absorptiometry); blood pressure; fasting lipid profile; various markers of inflammatory status and thrombolytic function.

The study is not powered to look at weight change, but does have sufficient power to investigate a 10% difference in subjective ratings of appetite (Flint et al. 2000). An appetite investigation day is incorporated during each diet period. Subjects are given a fixed low-GI or high-GI breakfast and then they complete subjective ratings of hunger and fullness over the following 4 h. They are given an ad libitum snack 2 h after breakfast and an ad libitum lunch after a further 2 h. The intention is to investigate the short-term impact of low GI on between-meal snacking and on energy intake at the subsequent meal to determine whether any differences in intake of the snack are compensated for at lunch. Intake at main meals may be more strongly habituated than between-meal snacks, and so may be less affected by perceived hunger.

Compliance is being monitored by completion of food-frequency questionnaires, 4 d food diaries and day-to-day recording of intervention foods consumed. Subjects are also fitted with continuous glucose monitors for 24 h during each diet period to determine whether the intervention foods consumed ad libitum as part of a mixed diet have differing effects on day-long glucose levels.

This work and other ongoing work into the effect of low-GI diets on health, including large studies funded by the Food Standards Agency (RISCK, 2005) and EU (The Diogenes Project, 2005) will, over the next few years, provide clearer answers to some of the many questions that the present review has raised. Until then, the specific effects of GI on metabolic health and body weight remain uncertain.

Acknowledgements

The author would like to thank S.A. Jebb for her supervision, many other colleagues at MRC HNR for their expertise and involvement in the studies described here, and all the volunteers for their time and commitment. L.M.A. is supported by a Medical Research Council Studentship.

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