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Whole grain consumption and weight gain: a review of the epidemiological evidence, potential mechanisms and opportunities for future research

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The epidemiological data that directly examine whole grain *v.* refined grain intake in relation to weight gain are sparse. However, recently reported studies offer insight into the potential role that whole grains may play in body-weight regulation due to the effects that the components of whole grains have on hormonal factors, satiety and satiation. In both clinical trials and observational studies the intake of whole-grain foods was inversely associated with plasma biomarkers of obesity, including insulin, C-peptide and leptin concentrations. Whole-grain foods tend to have low glycaemic index values, resulting in lower postprandial glucose responses and insulin demand. High insulin levels may promote obesity by altering adipose tissue physiology and by enhancing appetite. The fibre content of whole grains may also affect the secretion of gut hormones, independent of glycaemic response, that may act as satiety factors. Future studies may examine whether whole grain intake is directly related to body weight, and whether the associations are primarily driven by components of the grain, including dietary fibre, bran or germ.

Whole grains: Refined grains: Dietary fibre: Body weight

The prevalence of obesity in the USA is at its highest levels in history; an estimated 97 million adults are overweight (Expert Panel on the Identification, Evaluation and Treatment of Overweight in Adults, 1998). Obesity dramatically increases the risk of morbidity from chronic diseases, including hypertension, dyslipidaemia, type 2 diabetes, cardiovascular disease and certain types of cancer (Lapidus *et al*. 1984; Larsson *et al*. 1984; Lundgren *et al*. 1989; Freedman *et al*. 1995; Expert Panel on the Identification, Evaluation and Treatment of Overweight in Adults, 1998). Despite its public health importance, there is no scientific consensus on the optimal diet for the prevention and treatment of obesity. Much controversy exists over the roles that specific nutrients have on the aetiology of obesity, including the effects of dietary fats and carbohydrates. Due to the complex physical and chemical nature of foods, the investigation of whole foods in the development of obesity deserves further scientific analysis. In particular, diets that are characterized by high whole grain content and low glycaemic load may be of particular importance in the age-related progression to hyperinsulinaemia and obesity, due to their potential influence on metabolic and hormonal effects. However, few studies to date have examined the potential roles of whole grain intake on body weight.

Whole grain consumption and chronic disease risk

Walker (1947), Burkitt (1952), Cleave (1956) and Trowell (1972) pioneered the concept that highly-refined foods contribute to Western diseases including coronary artery disease. Since that time, whole-grain foods have been associated with a reduced risk for several chronic diseases including CHD (Rimm *et al*. 1996; Jacobs *et al*. 1998; Willett, 1998; Liu *et al*. 1999), diabetes (Salmeron *et al*. 1997*a,b*) and certain types of cancer (Adlercreutz, 1990). Whole-grain foods may protect against chronic diseases by altering serum cholesterol profiles, exerting antioxidant properties and anti-thrombotic action, and through their favourable effects on vascular reactivity and insulin sensitivity (Anderson & Hanna, 1999). Whole grains are rich sources of dietary fibre, resistant starch, vitamins, minerals, phyto-oestrogens, antioxidants and other important nutrients

Abbreviation: GI, glycaemic index.
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(Anderson *et al.* 2000). Structurally, whole grains are composed of the endosperm (approximately 80 %, w/w), the germ and the bran of the grain (Anderson *et al.* 2000). Bran contains the seed coat that comprises fatty acids, phytochemicals and fibre (Southgate, 1995). During the milling process, the bran (outer layer) and germ (inner layer) are separated from the starchy endosperm (middle layer), which leads to the loss of many nutrients and fibre (Slavin *et al.* 1997). For this reason, refined grains are nutritionally inferior to whole grains because they contain lower amounts of fibre, minerals, vitamins, phenols, phyto-oestrogens and unsaturated fatty acids (Jacobs *et al.* 1998; Willett, 1998). The whole-grain foods that are commonly consumed in Western cultures include dark bread, whole-grain breakfast cereals, popcorn, oatmeal and brown rice (Liu *et al.* 1999). However, most of the grain products consumed in the USA are highly refined (Slavin, 1994).

While whole-grain foods have been hypothesized to protect against obesity, epidemiological data that directly examine whole grain *v.* refined grain intake in relation to obesity are sparse. In the Iowa Women's Health Study whole grain intake was inversely correlated with body weight and fat distribution in comparison with a weaker direct relationship for refined grain consumption and body size (Jacobs *et al.* 1998). In the Coronary Artery Risk Development in Young Adults (CARDIA) study whole grain intake was inversely related to BMI at 7-year follow-up of the participants of the study. No association was observed between whole grain intake and the waist:hip ratio (Pereira *et al.* 1998).

While there are few direct studies on the association between whole grain intake and obesity, there are several studies that indicate an association between whole grain intake and insulin sensitivity, thereby providing indirect support for a causal role of whole grain consumption on body-weight regulation. Pereira *et al.* (1998) reported that whole grain intake was negatively related to fasting insulin levels even after adjustment for BMI, Mg and fibre. Similar associations were observed for cereal-bran intake and insulin levels. In the Framingham Offspring Study diets rich in whole grains were inversely associated with BMI, the waist:hip ratio, total cholesterol and LDL-cholesterol, and fasting insulin levels (McKeown *et al.* 2002). In another study among US male health professionals a dietary pattern characterized by higher intakes of fruit, vegetables, whole grains and poultry was inversely associated with plasma biomarkers of obesity, including insulin, C-peptide and leptin concentrations (Fung *et al.* 2001). In a clinical trial the isoenergetic replacement of refined rice with whole grain and legume powder as a source of carbohydrate in a meal showed marked beneficial effects on glucose and insulin concentrations in patients with coronary artery disease (Jang *et al.* 2001).

Carbohydrates with different physical forms, chemical structures, particle sizes and fibre content can induce distinct plasma glucose and insulin responses (Jenkins *et al.* 1981). The glycaemic index (GI) classifies foods based on the physiological response that they entail in comparison with the same amount of carbohydrate from a standard source, either white bread or pure glucose (Wolever & Jenkins, 1986). The glycaemic load represents the combination of quality and quantity of carbohydrates consumed (Liu *et al.* 1999). Whole-grain foods tend to have low GI values due to their starch content, particle size, extent of refinement and high content of viscous fibre (Liu *et al.* 2000). In contrast to refined-grain products, whole-grain foods are digested and absorbed more slowly, resulting in smaller postprandial glucose responses and insulin demand on the pancreatic β cells (Slavin, 1994). Refined-grain foods more than double the glycaemic and insulinaemic responses compared with whole-grain foods (Jacobs *et al.* 1998; Liu *et al.* 1999). Metabolic studies have shown that the insulin demand induced by various types of carbohydrate largely depends on the type or extent of digestibility of the starch content (Jenkins *et al.* 1981; Wolever & Jenkins, 1986). The starch in grains is composed of both long chains of glucose (amylose) and highly-branched chains of glucose (amylopectin). Since fewer glucose molecules are released when amylose chains are hydrolysed as compared with amylopectin chains, a high amylose:amylopectin content is associated with decreased glucose responses and insulin demand (Hallfrisch & Behall, 2000). Behall *et al.* (1988) observed that insulin responses were lower among men and women who consumed maize crackers containing 70 % amylose compared with 70 % amylopectin. Jenkins *et al.* (1988*a*) reported that lower glycaemic responses were associated with an increasing proportion of whole cereal grains in test breads.

Based on the epidemiological data, increased consumption of whole grains has been recommended to improve insulin sensitivity and to lower serum insulin concentrations (Jacobs *et al.* 1998; Willett, 1998; Anderson & Hanna, 1999). High insulin levels may promote obesity by altering adipose tissue physiology, shunting metabolic fuels from oxidation to storage and by increasing appetite (Ludwig *et al.* 1999*b*). Hyperinsulinaemia has been associated with excessive weight gain among adults and children in some (Odeleye *et al.* 1997; Folsom *et al.* 1998) but not all epidemiological studies (Folsom *et al.* 1998). In one crossover study researchers assessed the effects of high-GI foods on eating patterns and obesity among obese teenage boys. On three separate occasions subjects consumed identical test meals at breakfast and lunch that had low, medium or high GI values. The high- and medium-GI meals were designed to have similar macronutrient composition, fibre content and palatability, and all meals for each subject had equal energy content. Voluntary energy intake after the high-GI meal was 53% greater than after the medium-GI meal. In addition, the high-GI meal resulted in higher serum insulin levels, lower plasma glucagon levels, lower post-absorptive plasma glucose and serum fatty acid levels, and elevated plasma adrenaline (Ludwig *et al.* 1999*a*).

Dietary fibre component of whole grains

The carbohydrates in starchy foods with a low GI are mainly from less-processed grain products and dried legumes that maintain their original fibre content (Salmeron *et al.* 1997*a,b*). Indeed, dietary fibre has been found to explain approximately 40 % of the variance in the glycaemic response to foods (Trout *et al.* 1993). Fibre is a complex class of substances that can be broadly classified into soluble and

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insoluble fibre types. The solubility of fibre depends on the extent to which the fibre dissolves in water or forms a gel (Howarth *et al*. 2001). In practical terms fibre consists of the edible NSP portion of plant foods that includes cellulose, hemicellulose, pectins, β-glucans, fructans, gums, mucilages and algal polysaccharides.

In cross-sectional observational studies fibre generally has been inversely associated with body weight (Alfieri *et al*. 1995) and body fat (Miller *et al*. 1994; Nelson & Tucker, 1996). The beneficial effects of fibre on energy regulation have been observed with soluble and insoluble fibres, although there are relatively few data that directly compare the effects of different fibre types (Howarth *et al*. 2001). Furthermore, the studies that have investigated the effects of dietary fibre on body weight have been limited by factors including cross-sectional design or short duration of follow-up, inadequate adjustment for confounding factors, and over-adjustment for total energy intake (Pereira & Ludwig, 2001). In one longitudinal investigation fibre was inversely associated with BMI at all levels of fat intake after adjustment for lifestyle factors and other confounding factors among young adults in the CARDIA study (Ludwig *et al*. 1999*b*). Fibre consumption further predicted insulin levels, 10-year weight gain and other cardiovascular disease risk factors including blood pressure and cholesterol levels after adjustment for possible confounding influences (Ludwig *et al*. 1999*b*).

Fibre may regulate body weight through its intrinsic effects and hormonal responses. High-fibre food may promote satiation (lower meal energy content) and satiety (longer duration between meals) due to its bulk (Raben *et al*. 1994) and relatively low energy density (Pereira & Ludwig, 2001), leading to decreased energy intake. Importantly, whole-grain products provide 20–50% of their fibre in the soluble or viscous forms (Chen & Anderson, 1986). Grains with high levels of soluble fibre, such as oats, rye and barley, may improve insulin sensitivity by slowing absorption of macronutrients (Hallfrisch & Behall, 2000). In contrast to insoluble fibre, soluble fibre results in highly viscous intestinal contents with gel-like properties that may delay gastric emptying and/or intestinal absorption (Hallfrisch & Behall, 2000). In the small intestine soluble fibre may blunt postprandial glycaemic and insulinaemic responses (Jenkins *et al*. 1988*b*) that are linked to reductions in the rate of return of hunger and subsequent energy intake in several previous studies (Roberts, 2000). It was observed that oat gum added to a glucose solution reduced glucose and insulin responses of healthy adults (Jenkins *et al*. 1978). Similar results were observed when highly viscous oat extracts were consumed by middle-aged men and women (Hallfrisch & Behall, 2000).

Fibre may also affect secretion of gut hormones, including cholecystokinin, independent of glycaemic response, that may act as satiety factors or alter glucose homeostasis (Pereira & Ludwig, 2001). Some studies have shown prolonged increases in circulating cholecystokinin after ingestion of fibre-rich meals relative to energy-matched low-fibre meals (Holt *et al*. 1992; Bourdon *et al*. 1999). Cholecystokinin is secreted from cells in the small intestine on ingestion of food, and functions in the stimulation of pancreatic secretion, regulation of gastric emptying and central inducement of satiety (Liddle, 1997). While fibre has been thought to promote satiety and alter metabolic fuel partitioning in favour of fat oxidation due to its hormonal effects (Ludwig, 2000), it is unknown whether the type of fibre is differentially related to body weight. Salmeron *et al*. (1997*a,b*) found that diets with a high glycaemic load and low cereal fibre content were positively associated with risk of non-insulin-dependent diabetes mellitus among both adult males and females in the USA. Hyperinsulinaemia, a manifestation of insulin resistance, plays an important role in the development and progression of diabetes (Salmeron *et al*. 1997*a,b*) and is further associated with obesity. It is plausible that the chronically-high insulin demand that is induced by the high glycaemic load and low fibre may contribute to obesity.

Antioxidant role in insulin sensitivity

The antioxidants that are contained within whole grains may also contribute to insulin sensitivity by protecting against oxidative stress (Slavin *et al*. 1997). Most of the antioxidants in grains are contained in the bran and germ, which have a thick-walled cellular structure that inhibits extraction (Miller *et al*. 2000). Oxidative stress has been associated with reduced insulin-dependent glucose disposal and diabetic complications (Oberley, 1988). Mg and vitamin E in particular are thought to be involved in insulin metabolism (Frost *et al*. 1996; Slavin *et al*. 1997) that may prevent or mitigate hyperinsulinaemia (Fukagawa *et al*. 1990; Feskens *et al*. 1994; Marshall *et al*. 1997). In clinical trials Mg supplementation provided beneficial effects on insulin sensitivity among patients with non-insulin-dependent diabetes mellitus (Paolisso *et al*. 1989) and in normal subjects (Paolisso *et al*. 1992). Furthermore, in the Health Professionals Study (Salmeron *et al*. 1997*a*) and Nurses' Health Study (Colditz *et al*. 1992) an independent inverse association between Mg intake and risk of non-insulin-dependent diabetes mellitus was observed.

It is currently unknown whether bran or germ intakes are independently associated with body weight, as there are no current studies in this area. However, it is plausible that the bran component of whole grains may be involved in body-weight regulation due to its insulin-sensitizing effects. Researchers have reported that wheat bran consumption improves glucose tolerance (Anderson & Chen, 1979), and it was reported that long-term wheat bran administration improved glucose tolerance better than pectin administration (Brodribb & Humphreys, 1976). Further, in the Nurses' Health Study CHD analysis (Liu *et al*. 1999) bran itself was more strongly inversely associated with CHD than most whole grains. It is unknown whether these effects were mediated in part by influence of wheat bran on postprandial insulin levels.

Future research directions

Future prospective studies may address the question of whether whole grain intake is directly related to body weight and obesity, and whether the associations are primarily driven by fibre, some other dietary component of whole-grain foods, or some other related aspect of diet. Thus, it will be of interest

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to ascertain the independent effects of bran, germ and the different types of fibre on body weight. Furthermore, the classification of whole-grain foods that was developed by Jacobs *et al*. (1998) was a semi-quantitative estimate based on the number of servings of whole grains consumed per d. In this classification cereals that contained at least 25% by weight whole grain content were considered as whole-grain foods. Future studies may employ quantitative estimates of whole grain intake that adhere to the recent US Food and Drug Administration (1994) guidelines that restrict the whole grain label to foods with ≥ 51% by weight whole grain ingredient per reference amount customarily consumed. The potential application of these studies is high, given the rising prevalence of obesity in the USA, and the opportunity for increased intake of whole grains and dietary fibre. It has been estimated that the average whole grain intake in the USA is less than one serving per d (Cleveland *et al*. 2000). The low whole grain intake has been attributed to lack of consumer awareness of the benefits and sources of whole-grain foods (Adams & Engstrom, 2000). It has been further estimated that Americans only consume an average of 14–15 g fibre/d (Alaimo *et al*. 1994), far short of the recommended daily intake of 20–35 g.

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