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Health benefits of cereal fibre: a review of clinical trials

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Abstract

Cereal fibre and whole-grain intakes have been consistently associated in the epidemiological literature with reduced mortality and risk of chronic disease including obesity, CVD and type 2 diabetes. The present review focuses on intervention trials with three primary aims: (1) understanding the mechanisms through which fibre consumption improves health (for example, examination of intermediate endpoints reflecting improved lipid, glucose and energy metabolism); (2) close evaluation of qualitative factors which modify fibre's effectiveness including physiochemical properties (for example, solubility, fermentability and viscosity), fibre extract molecular weight, fibre particle size and botanical structure of the fibre source grain; and (3) identification of areas in which additional research is needed. The first two aims typify the goals of nutrition research, in that improved understanding of the specific factors which determine fibre's health benefits has critical implications for dietary recommendations as well as improving understanding of physiological mechanisms. The third aim acknowledges the substantial gap between recommended and actual fibre intakes in many developed countries including the USA and the UK. In recognition of this deficit in total fibre intake, food manufacturing processes increasingly utilise fibre extracts and concentrates as food additives. However, whether fibre extracts provide similar health benefits to the fibre supplied in the constituents of whole grain is largely unexplored. The relative benefits of fibre extracts compared with whole-grain fibre sources therefore represent a critical area in which additional research is needed.

Keywords

Dietary fibre; Whole grains; Clinical trials; Cereal fibre

Introduction: epidemiological evidence

The role of dietary factors in the prevention of CVD and type 2 diabetes has been a focus of nutrition research for decades, and these efforts have included dietary fibre. A universal definition of fibre does not exist; however, part of a working definition recently developed by the international Codex Alimentarius Commission states that 'Dietary fibre means

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carbohydrate polymers with three or more monomeric units, which are neither digested nor absorbed in the human small intestine⁽¹⁾. Epidemiological and experimental evidence demonstrating the health benefits of dietary fibre have often highlighted whole grains, many of which are a rich source of fibre. Whole-grain consumption has been associated with reduced total and CVD mortality in observational studies from a variety of populations^(2–8). In the Physicians' Health Study, in which 86 190 US men were followed for 5.5 years, those consuming one serving of whole-grain breakfast cereals per d had 17 and 20 % lower total and CVD-specific mortality, compared with never or rare consumers. Benefits were associated with intake of whole grains, but not with intake of refined grain cereals – from which most of the bran and germ components are removed through refining processes. Whole grains contain the endosperm, the bran and the germ, and whole-grain foods were defined in the above study and other epidemiological studies as those containing at least 25 % whole grain or bran by weight. A new definition that has been applied to the US Department of Agriculture (USDA) MyPyramid Equivalents Database⁽⁹⁾ excludes added bran and pearly barley but is otherwise similar to previously accepted definitions. The new USDA definition was used in the 1999–2004 National Health and Nutrition Examination Survey⁽¹⁰⁾, but whether it will be applied more universally is unclear.

Similarly, in the Nurses' Health Study of 75 521 women followed for 10 years, increasing quintiles of whole-grain intake, with dietary fibre ranging from 14 to 20 g/d, were associated with greater protection from fatal and non-fatal CVD. A 30 % risk reduction was seen in the highest compared with lowest intake quintiles⁽²⁾. Women in the top category consumed a median of 2.5 servings/d. In this study, whole-grain intake was positively correlated with dietary fibre, suggesting that the benefits may be due to the fibre. In addition, women with high whole-grain intake were more likely to exhibit other beneficial health behaviours including greater amounts of exercise and multivitamin intake, and lesser intakes of fat, alcohol and cholesterol, indicating the need for additional studies, including clinical trials to isolate the effect of whole grain.

Evidence from observational studies outside of the USA is in agreement that dietary fibre intake reduces all-cause and CVD mortality. In the Zutphen Study, a 40-year study of 1373 Dutch men, a 10 g increase in fibre intake reduced all-cause mortality by 9 % and CVD mortality by 17 %, with no differences detected by fibre source (for example, cereal, potato, legume, vegetable or fruit)⁽⁶⁾. However, breads and breakfast cereals were the major single contributor of total dietary fibre (29–34 %), with over 60 % being supplied by other dietary sources. The higher reduction in CVD mortality than all-cause mortality suggests that CVD protection may have been the major contributor to improved all-cause mortality in the Dutch population. Evidence from a cross-sectional French study, with 2532 men and 3429 women, similarly supports an association between fibre and CVD, including protective effects on intermediate markers of CVD risk⁽⁵⁾. The highest total fibre intakes were associated with significantly lower blood pressure, apoB concentration, apoB:apoA1 ratio, cholesterol and TAG. As in US populations, the largest source of dietary fibre was breakfast cereals, which contributed 8 g/d (37 % of total) in men and 6 g/d (33 %) in women.

In addition to reduced CVD risk, whole-grain and fibre intakes have been associated with lower risk of type 2 diabetes⁽¹¹⁾. In the Nurses' Health Study, this relationship was strongest

for cereal fibre (median intake 5.2 g/d), which, in this cohort, consisted mainly of wheat and maize⁽¹²⁾. Data from the same study showed that the reduction of diabetes risk with whole grains was more strongly associated with the bran than with the germ component of the grain kernel. However, these components may vary by cereal type⁽¹³⁾.

Whole-grain intake was inversely associated with metabolic risk factors for type 2 diabetes, including BMI, waist-to-hip ratio, total cholesterol, LDL-cholesterol and fasting insulin in the Framingham Offspring Study of 2941 men and women⁽¹⁴⁾. However, adjustment for fibre eliminated the significant association between whole grain and fasting insulin, supporting a role for fibre in the mediation of fasting insulin. The relationships between fibre, overweight and diabetes risk are reinforced by data from the Black Women's Health Study of 59 000 women followed for 8 years, which also showed an inverse relationship between cereal fibre intake and risk of type 2 diabetes in overweight and non-overweight women⁽¹⁵⁾. Risk of diabetes was reduced by 18 % in participants with the highest quintile of cereal fibre intake (5.9 g/d).

In light of the large number of observational studies which strongly support the hypothesis that whole grains, and, particularly, cereal fibre, reduce mortality, CVD and type 2 diabetes, clinical trials have been conducted to investigate mechanisms and establish causal relationships between specific fibre forms or types of grain and beneficial effects on anthropometric, glucose and lipid intermediate markers for obesity, CVD and type 2 diabetes. Two major categories of fibre, soluble and insoluble, have different physical and chemical properties which may exert different metabolic effects, and these two categories form the basis for many comparative studies. Major sources of soluble fibre include barley, oats, apples, pears and most legumes⁽¹⁶⁾. Commonly used cereal grains, including wheat, maize and rice, are major sources of insoluble fibre. However, other groups have proposed categories based on the physico-chemical properties of viscosity and fermentability, as these properties may be most relevant to metabolic pathways⁽¹⁷⁾. Proposed mechanisms by which whole-grain sources of fibre intake reduce CVD mortality and diabetes risk include reduced obesity, improved lipid profile and improved glucose metabolism. These major metabolic categories frame the reviewed clinical trials that are representative of major research areas, but are not all-inclusive.

Obesity and fibre: protective mechanisms

Fibre and whole-grain intakes have been associated with reduced risks of obesity, overweight and high waist-to-hip ratio (Table 1)^(3,5) and effects of fibre on appetite and satiety have been proposed as major mechanisms. Satiety is a complex response that may be influenced by macronutrient composition, palatability, energy density and physical properties of foods. Fibre may delay hunger and increase satiety by slowing the rate of gastric emptying⁽¹⁸⁾. Soluble fibres such as pectins and gums are hydrophilic, and form viscous compounds which distend the stomach and slow gastric emptying⁽¹⁹⁾. Psyllium fibre has been shown to delay gastric emptying, increase satiety and reduce hunger⁽²⁰⁾. Alternatively or additionally, fibre-rich foods may reduce energy intake by displacing energy-dense foods that contribute to obesity (for example, dilution of energy intake).

Fibre may also modulate energy balance through mechanisms unrelated to energy intake, and the consequences may differ for soluble and insoluble forms. A recent study using an animal model demonstrated that soluble and insoluble fibre supplementation differentially affected weight gain and insulin sensitivity in mice⁽²¹⁾. SCFA production and increased energy availability associated with soluble fibre intake were proposed as mechanisms underlying the less favourable energy balance achieved through soluble compared with insoluble fibre supplementation. Earlier research had estimated that absorption of nutrients in the human large intestine could supply up to 10 % of the total energy requirement⁽²²⁾. Confirmation of the proposed mechanistic links between fibre solubility, intestinal utilisation of energy from SCFA and weight management in human subjects is warranted.

Fibre and satiety

Clinical trials have examined effects of types and sources of fibre on satiety and appetite, but results are inconsistent, which may reflect the complexity of appetite regulation and eating behaviour. Consumption of cereal supplying insoluble fibre (26 g) was associated with lower energy intake at breakfast and lunch compared with a low-fibre cereal, apparently through beneficial effects on short-term satiety⁽²³⁾. Using equal weight rather than isoenergetic portions of cereal, the authors determined that high-fibre cereal achieved a greater change in appetite per kJ of cereal. Whether fibre affects total daily energy intake is less clear. In a study comparing fibre quantity and types on appetite over 24 h, consumption of a high-insoluble fibre (wheat bran) breakfast was associated with lower snack intake compared with a high-soluble fibre (psyllium gum) breakfast, although the high-soluble fibre breakfast suppressed subsequent snack intake better than a low-energy breakfast⁽²⁴⁾. However, in spite of these differences, total daily energy intake did not differ following consumption of the test breakfasts. Other trials have produced similarly inconclusive results. Test meals containing wheat bran (5 g fibre) or barley (8 g fibre) cereal were evaluated for associations with appetite and food intake at a second meal⁽²⁵⁾. The barley flour was derived from a novel cultivar with reduced starch, higher amylose and higher NSP (particularly β -glucan) compared with ordinary barley. While the barley-containing test meal was hypothesised to reduce intake at the following meal, spontaneous energy intake at the second meal was unexpectedly higher following the barley meal compared with the wheat bran meal.

Trials investigating the effects of different fibre types on satiety have also examined regulation of satiety mechanisms, such as gastric emptying rate (GER). An intervention with three test meals found no differences in satiety across bran flakes (7.5 g fibre), oat flakes (4 g fibre) or corn flakes (1.5 g fibre), but GER was reduced following the bran flakes meal compared with oat flakes or corn flakes⁽²⁶⁾. The reduction in GER was attributed to the higher, predominantly insoluble, fibre content of the bran flakes, although the question of whether GER is an important regulator of satiety or subsequent energy intake remains unclear.

Another factor that may modulate fibre's effect on satiety is the form or structure of the grain that comprises the bread or cereal product. While 'whole grain' refers to the inclusion of all three components of the grain kernel in a food product, the structure of the kernel may

be destroyed and reconstituted to make whole-meal flour. Alternatively, the botanical structure may be kept intact (whole-kernel flour). The whole-kernel form of grains has been theorised to reduce GER, which may, in turn, increase satiety. A study comparing whole-kernel and whole-meal wheat breads found that higher satiety was associated with whole-kernel bread, but GER was not different between the two bread types⁽²⁷⁾. These results are consistent with an earlier study by this group, in which GER did not appear to be a regulator of satiety⁽²⁶⁾.

Peptide YY (PYY) and ghrelin have been shown to modulate food intake^(28,29). Postprandial responses for anorectic PYY and appetite-stimulatory ghrelin were lower following intake of wheat-enriched bread (insoluble fibre) but not oat-enriched bread (soluble fibre) in test meals that were matched for energy and macronutrient composition⁽³⁰⁾. However, hunger scores were not different across groups, suggesting that factors other than PYY and ghrelin may be modulating hunger.

Fibre and weight loss

Duration of fibre intake may affect the relationship between fibre intake and weight loss. In a trial examining both satiety and actual weight loss, neither fermentable fibre (pectin and β -glucan) nor non-fermentable fibre (methyl-cellulose) supplements increased weight loss or fat loss over a 3-week period in obese and normal-weight subjects consuming an *ad libitum* diet⁽³¹⁾. Satiety was also unchanged in this short-term intervention. However, results from a study evaluating the effects of additional fibre in the context of a 30 % energy restriction regimen suggest that cereal fibre may improve energy restriction adherence and weight loss⁽³²⁾. In this study, cereal fibre supplied an additional 15.5 g to an initial fibre intake of 28.5 g, achieving a mean total fibre intake of 44 g/d. Fibre intake was positively correlated with energy restriction adherence and negatively correlated with BMI over a study phase lasting 23 weeks, although additional controlled trials are needed to establish statistical differences based on treatment group.

Conflicting or unexpected results from the preceding interventions suggest that, even in a controlled setting, regulation of appetite by fibre is not readily demonstrated, or may not be related to proposed mechanisms. Instead, food components other than fibre may modulate satiety, and foods eaten in combination with cereal grains may further modify eating behaviour. Five test meals were prepared with low-fibre wheat flour, high-fibre cracked wheat, high-fibre whole-wheat flour, low-fibre rice flakes and a low-fibre rice–legume combination⁽³³⁾. The highest satiety was associated with the rice–legume combination, which contained the lowest fibre content but the highest protein content and protein quality. The lowest satiety was associated with the low-fibre rice flakes. The second highest satiety was associated with the cracked wheat preparation, in which large particle sizes required the longest time to chew. The time required to chew high-fibre foods represents another potential mechanism by which these foods may increase satiety, reduce energy intake and thereby reduce obesity.

Summary: obesity

While forms of fibre that are capable of increasing intraluminal viscosity are associated with reduced risk of obesity, the physiological mechanisms underlying these protective effects are unclear and results from clinical trials are inconsistent. Demonstrated modulators of satiety, such as GER, PYY and ghrelin, have not been shown to underlie reduced intake or increased satiety. Further, in some studies, fibre supplements hypothesised to reduce hunger have not been shown to reduce hunger or body weight. In spite of these inconclusive results, strong observational evidence supports a role for increased fibre intake in the reduction of obesity.

Fibre and lipid reduction

Observed reductions in CVD risk associated with cereal and fibre consumption have been attributed primarily to the lipid-lowering effects of fibre⁽³⁴⁾, and have led to a series of clinical trials designed to identify the specific types and sources of fibre which achieve hypolipidaemic effects most effectively (Table 1). Dietary fibre and fat intakes tend to be inversely related, and the extent to which displacement of SFA by fibre may improve plasma lipids is unknown. However, even in the context of a low-saturated fat (< 4 %), low-cholesterol (10–12 mg/1000 kcal; (4180 kJ)) and low-fat (18–19 %) diet, the inclusion of high levels of soluble fibre (16 g/1000 kcal (4180 kJ)), combined with twice as much insoluble fibre (34 g/1000 kcal (4180 kJ)), reduced total and LDL-cholesterol to a greater extent than a diet containing less soluble fibre (10 g/1000 kcal (4180 kJ)) but much greater amounts of insoluble fibre (58 g/1000 kcal (4180 kJ))⁽³⁵⁾. Food sources of insoluble fibre in this study included: wheat cereal, wheat bran crackers and wheat bran bread. Sources of soluble fibre included barley, lentils, dried peas and beans, oat bran and psyllium.

This strong evidence for the hypolipidaemic effects of soluble, as opposed to insoluble, fibre has been consistently replicated and quantified. A meta-analysis of sixty-seven controlled trials⁽³⁶⁾ showed that intakes of isolated fibre sources or fibre-enriched products containing 2–10 g of soluble fibre per d supplied by pectin, guar gum, psyllium and oat bran were associated with 0.047 mmol/l lower total cholesterol and 0.057 mmol/l lower LDL-cholesterol. Accumulating evidence led to a series of Food and Drug Administration (FDA) health claims from 1997 to 2006 recommending the use of oat-based soluble fibre in the reduction of CVD risk⁽³⁷⁾. In a study designed to evaluate the amounts of soluble fibre recommended in the FDA health claims, foods were supplemented with either 0.75 g β -glucan or 1.78 g psyllium per serving and consumed four times per d. Compared with control foods, the high-soluble fibre foods (8 g additional soluble fibre/d) reduced total cholesterol by 2.1 %, total:HDL-cholesterol ratio by 2.9 % and LDL:HDL-cholesterol ratio by 2.4 %⁽³⁸⁾. These reductions in lipids and lipid ratios are modest but are likely to reduce CVD risk at the population level.

Mechanisms of lipid reduction

Proposed mechanisms for the hypolipidaemic effects of soluble fibre include reduced absorption of fat and cholesterol, decreased bile acid absorption, increased bile acid synthesis, altered cholesterol synthesis and altered 3-hydroxy-3-methylglutaryl (HMG)-Co

A reductase activity^(39–41). SCFA such as propionate, which are produced through colonic fermentation of dietary fibre, lower cholesterol synthesis in rat tissue. Whether this mechanism accounts for the hypocholesterolaemic effects of fibre in human subjects is unknown⁽⁴²⁾.

In spite of the large body of evidence supporting a role for soluble fibre in the reduction of lipids, remaining questions have continued to stimulate recent research. Some clinical trials have failed to show a reduction in lipids with soluble fibre intake. In one study, normocholesterolaemic subjects (total cholesterol < 6.2 mmol/l) receiving high fibre (15.9 g)/high soluble fibre (8.1 g) from oat bran showed no differences in total, LDL-cholesterol, HDL-cholesterol or TAG compared with those receiving low-fibre (2.7 g)/low-soluble fibre (0.9 g) dietary supplements⁽⁴³⁾. Over the course of the study, the macronutrient composition of the background diet did not change, and no changes were observed in waist, BMI or glucose measures. Whether the lack of response is related to the choice of normocholesterolaemic, rather than hypercholesterolaemic, subjects is unknown. In a trial comparing two hypoenergetic diets in normocholesterolaemic, normotensive subjects, soluble fibre (7.2 g) supplied by oats was more effective than a lower-soluble fibre diet (3.5 g) in reducing total and LDL-cholesterol as well as systolic blood pressure⁽⁴⁴⁾. Weight loss was similar in both diets, suggesting that lipid and blood pressure improvements were independent of weight reduction.

Barley

While clinical trials of oats as a source of soluble fibre are the most numerous, barley contains a higher proportion of soluble fibre. β -Glucan, a component of the cell walls derived primarily from endosperm, is the active component of the soluble fibre in oats (up to 7 %, w/w) and barley (up to 15 %, w/w)⁽⁴⁵⁾. Barley was evaluated in a trial in which hypercholesterolaemic men (mean LDL 4.01 mmol/l) consumed varying amounts of soluble fibre (0.4, 3 and 6 g) but similar amounts of dietary fibre (27–33 g)⁽⁴⁶⁾. Test foods contained brown rice/whole wheat (low soluble fibre), a half barley and a half brown rice/whole wheat (medium soluble fibre) or barley alone (high soluble fibre). Total and LDL-cholesterol values decreased in all three diets but were significantly lower in the high-soluble fibre diet compared with the other two. HDL increased in all three diets although weight did not change in most (sixteen out of eighteen) subjects. Mean LDL particle number also decreased in all three diets, with the greatest decrease from the high-soluble fibre diet, reflecting a greater anti-atherogenic effect.

Rye

Another lesser-studied but potentially important source of soluble fibre, especially in northern and eastern Europe, is rye⁽⁴⁷⁾. Most of the fibre in rye bread is insoluble, but Finnish rye bread contains more soluble fibre (1.7 g per 100 g) than oat bread (1.2 g per 100 g)⁽⁴⁸⁾. The major component of soluble fibre in rye is arabinoxylan (60 % of soluble fibre) although β -glucan also provides 9 % of soluble fibre⁽⁴⁹⁾. Compared with a refined wheat bread-based diet (12–15 g dietary fibre per d, 4 g soluble fibre per d), a rye bread-based diet (26–31 g dietary fibre per d, 6–7 g soluble fibre per d) reduced total and LDL-cholesterol in men but not in women, and this effect was dose-related up to a level corresponding to eight

to ten slices of bread per d⁽⁴⁷⁾. The mean intake of bread for men was five to nine slices per d and no upper limit for bread intake was proscribed. The absolute intakes of soluble fibre did not differ between men and women, but the proportion of soluble fibre obtained from rye was greater in men than in women. Compared with the men, the women obtained more soluble fibre from non-cereal sources such as vegetables, fruit and berries. While the study raises important questions about sources of soluble fibre (cereal v. non-cereal, β -glucan v. arabinoxylan), the results are difficult to interpret in view of the large difference in dietary fibre (12–15 v. 26–21 g/d) between the two test diets.

Psyllium

Although less familiar by name to the public, the cereal grain psyllium has been studied in many clinical trials. Psyllium, which is derived from the husks of blond psyllium seed, provides the soluble fibre component of the laxative product Metamucil[®] (Procter & Gamble Co., Cincinnati, OH, USA), but has also been incorporated into ready-to-eat grain-based products including cereals, breads and pastas. In a meta-analysis of 8 controlled trials of mild-moderate hypercholesterolaemic subjects, psyllium lowered total and LDL-cholesterol, LDL:HDL ratio and total cholesterol:HDL, in the context of a low-fat diet⁽⁵⁰⁾. HDL and TAG were unchanged by psyllium. In all of these trials, the source and dose of psyllium was constant (10.2 g provided by Metamucil[®] given two or three times/d). In a single trial comparing psyllium and oat bran, the cereals were similarly effective in reducing plasma cholesterol in a population of hypercholesterolaemia men from Northern Mexico⁽⁵¹⁾. However, in the same study, oat bran cookies, which contained a higher proportion of soluble fibre, also reduced plasma TAG, an effect that was not observed with the psyllium. Whether these results are generalisable to other populations is unknown.

Whole food v. fortification and concentrates

Whole food sources of nutrients are generally considered preferable to fortification or supplementation with isolated food components, as whole grains may supply additional beneficial nutrients beyond that of fibre alone. Whole grains supply polyphenols, antioxidants, minerals, B vitamins and other phytochemicals that are often not present in fibre extracts. Data from the Continuing Survey of Food Intakes by Individuals (CSFII) showed that only 5 % of US adults aged 20–59 years consumed the adequate intake of dietary fibre (38 g/d for men and 25 g/d for women up to age 50 years) as recommended by the Institute of Medicine^(17,52). Gaps between recommended and actual intakes observed in the USA were also detected in a UK study, in which recommended intakes of fibre for women were achieved only in those consuming an exclusively plant-based diet⁽⁵³⁾. Similarly, the median intake of soluble fibre in the USA as estimated from National Health and Nutrition Examination Survey (NHANES) data is 2.4 g/d⁽³⁴⁾ whereas intake recommended by the National Cholesterol Education Program Adult Treatment Panel III guidelines is 10–25 g viscous soluble fibre per d⁽⁵⁴⁾. The large discrepancy between the recommended doses of fibre to achieve clinically important reductions in lipids and actual intakes has led to a series of trials investigating fibre-supplemented foods or concentrated sources of β -glucan, the grain component that has been identified as the active hypolipidaemic component in barley and oats. Recent efforts have focused on the evaluation

of fibre supplements, including concentrated forms of β -glucan, and factors that may modify the effectiveness of fibre supplements (for example, viscosity and molecular weight).

Concentrated forms of β -glucan have been shown to be effective at reducing plasma cholesterol, regardless of the source grain. In a trial using 6 g of concentrated oat β -glucan in hypercholesterolaemic subjects, cholesterol and LDL decreased significantly (by 0.30 mmol/l) compared with control⁽⁵⁵⁾. Another study was designed to test not only two concentrated doses of barley β -glucan, but also two forms – low molecular weight (LMW) and high molecular weight (HMW) – supplied in cereal and juice drinks⁽¹⁶⁾. The two forms differ with respect to viscosity and to their effects on the sensory qualities of food. HMW β -glucan has greater viscosity, so might be expected to have greater physiological effects, but LMW β -glucan is more acceptable when added to food. In hypercholesterolaemic subjects consuming various dose/form combinations, total and LDL-cholesterol decreased in all groups, but the decrease was greatest in the high-dose HMW treatment group. TAG decreased significantly only in the high-dose HMW β -glucan group, but body weight and HDL did not change. In a subsequent study, LMW concentrate achieved small reductions in total cholesterol:HDL ratio, while HMW β -glucan was associated with a small increase⁽⁵⁶⁾. Additional studies of the effects of molecular weight on β -glucan and lipids are warranted.

Insoluble fibre: wheat

Observational evidence supports a beneficial effect of insoluble fibre in the reduction of CVD risk, but most clinical trials have failed to demonstrate hypolipidaemic effects for this form of fibre. Wheat, the most widely consumed grain in the USA, supplies primarily insoluble fibre. Whether or not the beneficial effects of cereal grains supplying primarily insoluble fibre could be attributed to factors other than the amount of insoluble fibre is unknown. Two proposed alternative aspects of wheat, the bran particle size and protein content (gluten), were investigated in hyperlipidaemic (LDL > 4.1 mmol/l) and mostly normolipidaemic subjects in two separate experiments of 2 weeks' or 1 month's duration⁽⁵⁷⁾. Complete diets containing breads and cereals with 19 g dietary fibre from the wheat bran of varying particle sizes and of different gluten contents were compared. No differences were observed for total, LDL- or HDL-cholesterol based on different particle sizes or gluten content, but intake of wheat gluten was associated with a 13 % reduction in serum TAG in the hyperlipidaemic subjects following the month-long intervention. These data raise the possibility that grain components other than fibre may contribute to the variability of the hypolipidaemic response.

Insoluble fibre: rice

Rice, like wheat, supplies primarily insoluble fibre, and is the main source of dietary carbohydrate in many regions worldwide. White rice provides 1.8 g insoluble fibre, 0.1 g soluble fibre and 3.5 mg fat per 100 g rice. The higher-fibre Goami no. 2 rice, which provides 3.4 g insoluble fibre, 0.6 g soluble fibre and 6.8 mg fat per 100 g rice, has been evaluated for its effects on blood lipids and body weight. In an intervention trial of obese and non-obese Korean subjects, Goami no. 2 rice replaced half of the usual rice consumption for 4 weeks. Intake of Goami rice was associated with reduced total and LDL-

cholesterol, and TAG in obese subjects only, which was accompanied by weight loss, which itself may have contributed to the improved lipid profile⁽⁵⁸⁾.

While the increased fibre content of Goami rice appears to mediate its hypolipidaemic effects, other rice components may also play a role in altering lipids. In a study comparing oat bran and rice bran, both brans reduced total and LDL-cholesterol and the LDL:HDL ratio⁽⁵⁹⁾. Rice bran contains less soluble fibre than oat bran (7–13 % in rice bran and 40–47 % in oat bran), and defatted rice bran has been shown to be ineffective in reducing lipids⁽⁶⁰⁾. In the Gerhardt study, full-fat rice bran was added to a low-fat diet, and the improved lipid profile was attributed to the oil in rice bran, which contains tocotrienols, γ -oryzanol and β -sitosterol as well as 40 % unsaturated fatty acids, 20 % MUFA and 20 % SFA⁽⁶¹⁾. A subsequent trial with rice bran oil replicated the hypolipidaemic effect of the oil⁽⁶⁰⁾. These results provide additional evidence that consumption of whole grains in their less processed forms may provide greater benefits, and that less well-studied food components in grains may contribute to their protective effects.

Summary: lipids

Evidence for a reduction of plasma total and LDL-cholesterol by soluble fibre is strong. Lower TAG in response to increased fibre intake has also been reported, but more studies are needed. Fibre dose, background diet, intervention duration, and aspects of the fibre itself including source and form may all contribute to variability in the hypolipidaemic response. Subject characteristics may also affect responses; specifically, hypercholesterolaemic individuals appear to demonstrate greater responses than normocholesterolaemic individuals. Whether genetic variability contributes to the intra-individual variability of hypolipidaemic responses to fibre is unknown, and deserves further attention.

Glucose metabolism and fibre: observational evidence and proposed mechanisms

Observational evidence for a role of cereal fibre in the reduction of diabetes risk has led to a large number of clinical trials evaluating the acute and chronic effects of cereal fibre on glucose metabolism (Table 1). In several epidemiological studies, insoluble fibre, rather than soluble fibre, appeared to be protective against type 2 diabetes^(62,63). Insoluble fibre makes up the greater proportion of dietary fibre intake in most populations, which may be related to its greater observed protective effect at the population level.

Explanations for the protective effects of fibre on glucose metabolism include both short-term and longer-term mechanisms, which are consistent with clinical trials showing benefits at various time points. In the short term, reduced postprandial glucose concentration, associated with increased fibre content of a test meal, may reflect delayed and possibly reduced carbohydrate absorption in the context of accompanying viscous fibre intake⁽⁶⁴⁾. Several other hypotheses have been postulated for the mechanisms by which fibre reduces the glycaemic response. Viscous soluble fibre, but not all soluble fibre, absorbs liquid in the intestine to form a gelatinous solution which may limit enzyme access to digestible carbohydrate, slowing the process of enzymic action and digestion. Alternatively, soluble

fibre may create an unstirred layer adjacent to the luminal surface of the intestine, which acts to slow absorption of nutrients⁽⁶⁵⁾. Over a longer period of time, bacterial fermentation of certain fibres in the colon generates SCFA that enter the portal circulation. SCFA may increase glucose oxidation and insulin clearance, and decrease fatty acid release, all of which may improve insulin sensitivity⁽⁶⁶⁾.

Glucose metabolism and soluble fibre: acute effects

Intervention trials using soluble fibre, often at relatively high doses, have been shown to alter glucose and insulin responses. In one trial with individuals with non-insulin-dependent diabetes, the addition of 4–8 g soluble fibre (β -glucan) to a cereal meal reduced glycaemia by 30–60 % and insulin responses by 30–40 %⁽⁶⁷⁾. As the results of clinical trials are variable, many studies have sought to elucidate which dietary components are the most important determinants of acute glucose- and insulin-related responses.

Whether the anti-glycaemic effects differ for soluble fibre that is added to flour compared with that which occurs naturally in the grain cultivar is one such question. In a study comparing pasta made with β -glucan-enriched barley flour to pasta made with a naturally high- β -glucan barley flour, both barley flours reduced insulin, but not glucose, responses compared with a control white flour pasta consumed by healthy, non-obese subjects⁽⁶⁸⁾. β -Glucan-processing methods may affect viscosity levels and altered viscosity may influence metabolic responses. Comparison of equal amounts of β -glucan extracted through two different methods revealed that enzymic rather than conventional aqueous extraction of β -glucan from oat concentrates better preserved viscosity and reduced postprandial glucose more effectively than β -glucan extracted through conventional methods⁽⁴⁵⁾. More studies investigating the effects of extraction and processing methods on the anti-glycaemic benefits of β -glucan are needed.

Other investigators have proposed that differences in glucose and insulin metabolism in response to fibre are related to the type and botanical structure of the grain supplying the fibre, as opposed to the amount of fibre. In a comparison of three rye breads with differing amounts of insoluble (3, 11, 24 g) and soluble (3, 4, 5 g) fibre, insulin responses did not differ⁽⁶⁹⁾; all produced similarly lower insulin responses compared with a control white wheat bread with 2.7 g of total dietary fibre. The authors theorised that structural differences other than fibre content between wheat and rye may have accounted for the differences. Specifically, they demonstrated that the close packing of starch granules in rye bread, compared with wheat bread, was associated with lower rates of starch hydrolysis for rye compared with wheat. Differences in starch hydrolysis may contribute to altered physiological responses.

Metabolic responses to cereal fibre may also vary based on whether grain kernels are intact, cracked, or whether they are processed into flour. Earlier work established that particle size altered postprandial metabolic benefits associated with wheat and maize meals⁽⁷⁰⁾. In a recent study of healthy subjects, postprandial glucose areas above fasting concentrations did not differ between those consuming two rye products: whole-kernel rye bread (12.8 g dietary fibre, 3.8 g soluble fibre), whole-meal rye bread enriched with oat β -glucan (17.1 g dietary fibre, 6.8 g soluble fibre), or a control low-fibre food (white bread)⁽⁷¹⁾. However,

postprandial insulin responses, along with glucose-dependent insulinotropic polypeptide, were similarly lower following both rye breads compared with the control. The lack of a difference in insulin responses between the whole-kernel and whole-meal rye breads, in spite of the greater fibre content in the enriched rye bread, suggests that intact kernels are as effective as large amounts of fibre in reducing the insulin response.

Glucose metabolism and fibre: delayed effects

The beneficial effects of fibre on postprandial glucose are not limited to the acute postprandial period, but have also been shown to extend across subsequent meals within a 24 h period, often called the 'second-meal effect'. In one trial, a test meal (breakfast) of barley resulted in lower postprandial glucose and insulin responses following a subsequent meal (lunch) when compared with a wheat-based breakfast meal⁽²⁵⁾. Subsequent trials have attempted to differentiate between the trans-meal effects of low-glycaemic foods and soluble fibre-containing cereal foods, which overlap considerably but not completely. A comparison of four low-glycaemic evening meals (wheat kernels, barley kernels, spaghetti, spaghetti with added wheat bran) on glycaemic tolerance following the next breakfast demonstrated lower glucose (but similar insulin) responses with barley kernels compared with the spaghetti + wheat bran. Barley kernels were also associated with higher breath H₂ excretion and lower NEFA following breakfast, compared with spaghetti + wheat bran or wheat kernels, implying a higher level of colonic fermentation of non-digestible carbohydrates supplied by the barley kernels⁽⁷²⁾. Subsequent studies by the same group have demonstrated similar results and provided additional support for a mechanism of improved delayed glucose response based on colonic fermentation of fibre⁽⁷²⁻⁷⁴⁾. Plasma propionate and butyrate, which are produced as a consequence of colonic fermentation of fibre, were inversely related to the total glucose response following breakfast when large amounts of barley fibre (19.6 g/meal) were added to the previous evening meal, although the addition of fibre did not alter the insulin response in healthy young subjects⁽⁷⁴⁾.

Although several studies have provided evidence for a role of fermentation in the second-meal effect, other trials suggest that mechanisms other than colonic fermentation are primary. For example, second-day carbohydrate metabolism was similarly improved by the intake of fermentable fibre sources (oat hulls or insoluble resistant starch) and by a non-fermentable source (wheat) in individuals with normal glucose tolerance⁽⁷⁵⁾. Improved insulin sensitivity has been demonstrated for resistant starch following both short-term⁽⁷⁶⁾ and longer-term (4 weeks) supplementation⁽⁷⁷⁾, although the mechanisms for the beneficial effects of this form of carbohydrate are not well understood.

Glucose metabolism and fibre: chronic effects

Beneficial effects associated with longer-term fibre intake have been demonstrated for total dietary fibre, soluble and insoluble fibre. A 6-week trial of whole-grain compared with refined-grain consumption (six to ten servings/d) decreased fasting insulin and improved insulin sensitivity in overweight and obese, hyperinsulinaemic adults without diabetes. Body weight did not differ between the two diets during the follow-up period. Differences in fibre content between the diets were due primarily to differences in insoluble fibre; the whole-grain diet supplied 19.7 g insoluble fibre and 7.7 g soluble fibre and the refined-grain diet

supplied 10.8 g insoluble fibre and 6.7 g soluble fibre⁽⁷⁸⁾. Similarly, in a 12-week intervention in subjects with non-insulin-dependent diabetes, the addition of an oat bran concentrate to bread (34 g total fibre, 9 g soluble fibre/d) reduced the total glucose response by 46 % and the total insulin response by 19 % compared with white bread (19 g total fibre/d)⁽⁷⁹⁾. Body weight did not change as a result of the intervention. The reduced insulin response observed in this study may reflect decreased glucose absorption but may also reflect improved insulin sensitivity.

In a trial comparing the long-term effects of insoluble and soluble fibre in the context of a hypoenergetic diet, both types of fibre reduced fasting glucose and insulin, and reduced insulin resistance. However, after adjustment for weight loss, the cereal-based insoluble fibre (supplied by fermented wheat) was associated with a greater improvement in insulin resistance compared with the soluble fibre (supplied by a meal replacement dietary product)⁽⁸⁰⁾. In this study of overweight insulin-resistant subjects, consumption of a fermented wheat-based diet product (11 g fibre/serving) for 4 weeks reduced fasting insulin and improved insulin resistance compared with the meal replacement product in which fibre (14 g fibre/serving) consisted primarily of inulin. Inulin is supplied in the diet primarily through vegetables and is soluble, but does not increase the viscosity of gastrointestinal contents. Fermentation of wheat reduces its starch content. This study in which insoluble fibre supplied by fermented wheat improved insulin sensitivity is consistent with previous studies⁽⁸¹⁾, but mechanisms for the greater benefits observed for insoluble fibre are unclear and deserve further study.

Long-term effects of fibre consumption on glucose metabolism are not always consistent with effects seen acutely. Consumption of a high-fibre rye bread diet (46 g/d fibre, 9 g soluble, 33 g insoluble) over 8 weeks did not alter fasting plasma glucose, fasting plasma insulin or insulin sensitivity in overweight women compared with a lower-fibre wheat bread diet (14 g fibre, 6 g soluble, 6 g insoluble)⁽⁸²⁾, although the acute insulin response following a glucose tolerance test was greater with the rye-based diet. In that study, none of the women had impaired fasting glucose and only three of twenty women had impaired glucose tolerance, as evaluated by an oral glucose load.

Glucose metabolism and insoluble fibre

Although mechanisms for fibre's benefits on glucose metabolism have primarily focused on soluble fibre, interventions with insoluble fibre have also shown benefits for glycaemic response and insulin sensitivity⁽⁸³⁾. In one study, highly purified insoluble oat fibre (31 g/d, chiefly cellulose and hemicellulose) consumption over 3 d was associated with improved whole-body insulin sensitivity by 13 % in overweight and obese women compared with white bread intake⁽⁸¹⁾. Glucose and insulin concentrations and insulin clearance were unaltered, but insulin action was enhanced. In another study in healthy men, a similar dose of insoluble cereal fibre (33 g/serving) improved the postprandial glucose response to a meal eaten 75 min later, compared with a low-fibre cereal⁽⁸³⁾.

Comparative studies: effects of cereal and legume sources of fibre on glucose metabolism

A small number of interventions have compared the beneficial effects of whole-grain cereals with that of legumes, which comprise a relatively minor part of the US diet but are a staple source of proteins and carbohydrates globally. Epidemiological studies report inverse associations between legume intake, and the risk of diabetes or CVD^(84,85), and legumes often contain more dietary fibre or more soluble fibre than cereals. For example, while the ratio of soluble to insoluble fibre is similar in legumes and whole grains, chickpeas contain slightly higher dietary fibre content per 100 g (17 g for chickpeas v. 13 g for wheat).

Although legumes and grains differ substantially from a nutritional perspective, a small number of researchers have designed studies to explore differences in their metabolic benefits. In a study comparing the intake of wheat-based foods and chickpea-based foods in healthy overweight but non-insulin-resistant subjects, a single meal of chickpea foods decreased plasma glucose and insulin concentrations and homeostasis model assessment of insulin resistance responses compared with the wheat-based meal⁽⁸⁶⁾. The higher amylose content of chickpeas compared with wheat may cause them to be more resistant to digestion in the small intestine, so that glucose is less available, which may account for the differences in acute response. Over a period of 6 weeks, however, neither fasting nor post-glucose load concentrations of glucose, insulin or homeostasis model assessment of insulin resistance differed between the wheat- and chickpea-based diets. In another study comparing a high-fibre wheat diet with a chickpea-based diet over 5 weeks, no differences in acute measures of glucose tolerance or insulin resistance were observed⁽⁸⁷⁾. The chickpea-based diet supplied a mean of 28.4 g and the wheat diet 29.3 g of dietary fibre per d. As in the previous study, subjects were normoglycaemic, which may be relevant to the observation that no additional benefit to glucose metabolism was observed.

While comparative studies of legumes and grains are interesting, in practice, legumes and grains are complementary sources of plant proteins, with different constituent micronutrients, and are often consumed together. In recognition of the differing nutritional contributions of each type of food, a study comparing a refined rice-based diet with one based on a combined grain–legume powder consisting of brown rice, barley, black beans, sesame and Job's tears (a cereal grain) demonstrated benefits for the combined food⁽⁸⁸⁾. Subjects were limited to men with a history of CVD; subjects with and without diabetes were analysed separately. The cereal–legume mixture was associated with reduced insulin demand (representing improved insulin sensitivity) and reduced hyperinsulinaemia compared with the refined rice diet in all subjects, but improvements in fasting glucose and insulin were observed only in those without diabetes. These results highlight the difficulty in interpreting glucose and insulin responses in individuals with varying metabolic responses.

Summary: glucose metabolism

Benefits attributed to both soluble and insoluble fibre have been demonstrated for glucose metabolism, although results are variable. A larger number of trials reporting favourable benefits for soluble fibre relative to insoluble fibre on blood glucose metabolism have been published, but whether this reflects a true biological effect or a publication bias based on earlier work with soluble fibre and blood lipids is unclear. Observational evidence for a

reduction in diabetes risk is strongest for insoluble fibre, but may be related to higher insoluble compared with soluble fibre consumption in the populations from which most epidemiological evidence is drawn. For lipid metabolism, evidence from clinical trials is stronger for soluble, rather than insoluble, fibre, and these data may have provided the impetus for investigating the effects of soluble fibre on glucose metabolism as well. Interpretation of trials is also complicated by the metabolic variability of the subjects who range from healthy, non-obese individuals with normal insulin sensitivity, to hyperinsulinaemic subjects without diabetes, to those with diabetes. Whether metabolic adaptations to increased fibre intake occur with long-term consumption, and whether adaptation may differ according to the solubility or fermentability characteristics of the fibre, is also unknown. A limited number of comparative studies evaluating legumes and cereals have demonstrated comparable benefits for both sources of fibre, and expand the set of established benefits of consuming these food groups in combination. Finally, whether genetic variability may modify altered glucose metabolism in response to increased fibre intake is unexplored, and warrants further research.

Conclusions

Whole-grain and dietary fibre intakes have been associated with lower mortality and lower risks of CVD, obesity and diabetes in epidemiological studies, and intervention trials have demonstrated improvements in glucose and lipid metabolism, particularly for soluble fibre. A strong consensus exists for increasing fibre intakes to reduce the risk of chronic diseases, many of which are metabolically linked and responsive to diet. Considerable variability in hypolipidaemic and hypoglycaemic responses to fibre interventions has led to a series of trials evaluating varying quantities and types of fibre from a range of grains including oats, barley, rye, wheat and psyllium. Differential metabolic responses may depend, in part, on previously unexplored properties of the fibre, including viscosity, molecular weight, fermentability and botanical structure, which ongoing studies are examining. However, questions remain in several areas and further research is needed. For example, the mechanisms linking fibre to reduced obesity risk are not well understood, and trials evaluating relationships between modulators of satiety such as gastric emptying and regulation of energy intake have not yielded consistent results. Additional research is also warranted in the use of fibre extracts, which are added to food to increase fibre content. Although fibre additives provide a practical approach to bridging the large gap between recommended and actual fibre intakes, fibre isolates may lack components of whole grains that confer potential additional health benefits of whole grains. Clinical trials establishing the relative benefits of whole grain *v.* fibre extracts are absent, and the implications of the widespread use of fibre extracts are unclear.

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Abbreviations

GER	gastric emptying rate
HMW	high molecular weight
PYY	peptide YY

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Table 1

Intervention studies of fibre on obesity, satiety and appetite

Study	Study subjects	Duration	Outcomes (s)	Fibre source or type	Major results
Hamedani <i>et al.</i> (2009) ⁽²³⁾	Young, normal-weight adults (<i>n</i> 32)	Two meals	Energy intake, satiety	Insoluble (ready-made cereals)	↑ Satiety, ↓ energy intake at breakfast and lunch
Gilhooley <i>et al.</i> (2008) ⁽³²⁾	Healthy adults (<i>n</i> 34)	48 weeks	Energy restriction adherence, BMI	Insoluble (ready-made cereal)	Fibre intake correlated with energy restriction adherence and BMI decreases
Hlebowicz <i>et al.</i> (2008) ⁽²⁷⁾	Healthy, young adults (<i>n</i> 13)	Single meal	Satiety, gastric emptying, glucose	Whole-meal or whole-kernel wheat bread	↑ Satiety with whole-kernel wheat but gastric emptying not altered
Nilsson <i>et al.</i> (2008) ⁽⁷⁴⁾	Healthy, young adults (<i>n</i> 20)	Second-meal effects	Glucose, insulin, propionate	Barley, oats	Barley ↓ glucose but not insulin, glucose inversely related to propionate
Nilsson <i>et al.</i> (2008) ⁽⁴⁹⁾	Healthy adults (<i>n</i> 12)	1 d	Glucose, breath H ₂	Barley, wheat, oat, rye	Day-long glucose ↓ by barley or rye kernel breakfast
Hlebowicz <i>et al.</i> (2007) ⁽²⁶⁾	Healthy adults (<i>n</i> 12)	Single meal	Glucose, satiety, gastric emptying	Wheat bran and whole-meal oat cereals	Bran slowed gastric emptying but neither wheat nor bran altered postprandial glucose or satiety
Keenan <i>et al.</i> (2007) ⁽¹⁶⁾	Hypercholesterolaemic men and women (<i>n</i> 155)	10 weeks	Lipids	Barley β-glucan	TC and LDL ↓ by high- and low-molecular-weight glucan, ↓ TAG with high-molecular-weight glucan only
Keogh <i>et al.</i> (2007) ⁽²⁵⁾	Healthy women (<i>n</i> 14)	1 d	Satiety, glucose, insulin	Reduced-starch barley	Barley ↓ glycaemic, insulinaemic responses but ↑ energy intake
Queenan <i>et al.</i> (2007) ⁽⁵⁵⁾	Hypercholesterolaemic adults (<i>n</i> 75)	6 weeks	Lipids, glucose, insulin, BMI, colonic fermentability	Concentrated oat β-glucan	↓ TC and LDL, ↑ TAG. No changes in BMI, glucose or insulin. Oat β-glucan was highly fermentable
Samra & Anderson (2007) ⁽⁸⁵⁾	Healthy men (<i>n</i> 31)	Two meals	Appetite, intake, glucose	Insoluble (ready-made cereals)	Insoluble fibre ↓ appetite, glucose and short-term (75 min) food intake
Panahi <i>et al.</i> (2007) ⁽⁴⁵⁾	Healthy, young adults (<i>n</i> 11)	Single meal	Glucose, extract viscosity	Oat β-glucan extract (enzymic and aqueous forms)	Enzymic extract ↓ glycaemic response and had higher viscosity than aqueous
Pitaway <i>et al.</i> (2007) ⁽⁶⁷⁾	Adults aged < 70 years (<i>n</i> 25)	5 weeks	Lipids, glucose, HOMA-IR, satiety	Chickpeas, wheat	Chickpea ↓ TC and LDL, no differences in glucose measures. Wheat ↑ satiety
Rave <i>et al.</i> (2007) ⁽⁸⁰⁾	Obese adults with elevated glucose (<i>n</i> 31)	4 weeks	Glucose, insulin, HOMA-IR	Inulin v. fermented wheat	Fermented wheat ↓ insulin measures compared with inulin
Chen <i>et al.</i> (2006) ⁽⁴³⁾	Normocholesterolaemic adults (<i>n</i> 110)	3 months	Lipids, waist, glucose, insulin	Oat bran	No significant changes in any outcomes

Study	Study subjects	Duration	Outcomes (s)	Fibre source or type	Major results
Lee <i>et al.</i> (2006) ⁽⁵⁸⁾	Obese and non-obese adults (<i>n</i> 21)	4 weeks	Lipids, obesity	High fibre Goami no. 2 rice	Body weight ↓ in obese and non-obese; ↓ TAG, TC and LDL in obese only
Nilsson <i>et al.</i> (2006) ⁽⁷²⁾	Healthy adults (<i>n</i> 15)	1 d or overnight	Glucose, insulin, breath H ₂	Wheat, barley (kernel and pasta forms)	↓ Glucose and ↑ breath H ₂ but no change in insulin with kernel form of barley
Weickert <i>et al.</i> (2006) ⁽³⁰⁾	Healthy women (<i>n</i> 14)	Single meal	Satiety, peptide YY and ghrelin	Oat and wheat bread	Wheat ↓ peptide YY and ghrelin but satiety was not altered
Weickert <i>et al.</i> (2006) ⁽⁸¹⁾	Overweight and obese women (<i>n</i> 17)	3 d	Insulin sensitivity, lipids	Purified insoluble oat fibre	↑ Whole-body insulin sensitivity
Most <i>et al.</i> (2005) ⁽⁶⁶⁾	Healthy adults (<i>n</i> 40)	Variable (up to 10 weeks)	Lipids	Rice bran oil v. defatted rice bran	Rice bran oil ↓ TC and LDL but defatted rice bran did not
Pai <i>et al.</i> (2005) ⁽³³⁾	Healthy, young women (<i>n</i> 22)	Single meal	Satiety	Rice, wheat or rice-pulse combined meals	↑ Satiety with rice-pulses combined
Behall <i>et al.</i> (2004) ⁽⁴⁶⁾	Hypercholesterolaemic men (<i>n</i> 18)	5 weeks	Lipids, LDL particle number, body weight	Low, medium or high soluble fibre from barley	High soluble ↓ TC, LDL and LDL particles more than other two diets, ↑ HDL in all, no changes in body weight
Nestel <i>et al.</i> (2004) ⁽⁶⁶⁾	Healthy, middle-aged adults (<i>n</i> 19 and <i>n</i> 20)	Single meal and 6 weeks	Glucose, insulin, HOMA-IS, TAG	Chickpeas and wheat	Single meal chickpeas ↓ glucose, insulin and HOMA-IS acutely but no change in insulin sensitivity over time
Howarth <i>et al.</i> (2003) ⁽³¹⁾	Adults (<i>n</i> 11)	3 weeks	Energy intake, body weight, body fat	Fermentable and non-fermentable fibre supplements	Neither type of fibre was associated with changes in energy intake, weight or body fat
Juntunen <i>et al.</i> (2003) ⁽⁶⁹⁾	Postmenopausal, overweight women (<i>n</i> 19)	Single meal	Postprandial insulin, starch hydrolysis rate	Three rye breads compared with wheat bread	↓ Insulin responses for all rye breads compared with wheat
Juntunen <i>et al.</i> (2003) ⁽⁸²⁾	Postmenopausal, overweight women (<i>n</i> 20)	8 weeks	Glucose, insulin secretion and sensitivity	High-fibre rye bread	Greater acute insulin response with rye, no change in insulin sensitivity or glucose
Juntunen <i>et al.</i> (2002) ⁽⁷¹⁾	Young adults with normal glucose tolerance (<i>n</i> 20)	Single meal	Postprandial glucose, insulin	Various rye and wheat breads and pasta	Intact kernels were as effective as high fibre in ↓ insulin responses
Pereira <i>et al.</i> (2002) ⁽⁷⁸⁾	Hyperinsulinaemic obese or overweight adults (<i>n</i> 11)	6 weeks	Fasting insulin and HOMA-IR	Mixed whole grains (mostly insoluble fibre)	Whole grain ↑ insulin sensitivity and ↓ fasting insulin
Jang <i>et al.</i> (2001) ⁽⁸⁸⁾	Men with coronary artery disease (<i>n</i> 76), some with diabetes	16 weeks	Glucose, insulin	Mixed grains- <i>legume powder</i>	↓ Insulin and insulin demand, variable results by diabetes status
Saltzman <i>et al.</i> (2001) ⁽⁴⁴⁾	Normocholesterolaemic, normotensive adults (<i>n</i> 43)	8 weeks	Lipids, blood pressure	Soluble fibre from oat cereal	Soluble fibre ↓ TC and LDL-cholesterol and systolic blood pressure
Anderson <i>et al.</i> (2000) ⁽⁵⁰⁾	Hypercholesterolaemic adults (<i>n</i> 656; meta-analysis of eight clinical trials)	Range: 6 weeks to 6 months	Lipids	Psyllium (Metamucil®*)	↓ TC and LDL-cholesterol, apoB:apoA1 ratios

Study	Study subjects	Duration	Outcomes (s)	Fibre source or type	Major results
Leinonen <i>et al.</i> (2000) ⁽⁴⁷⁾	Hypercholesterolaemic adults (<i>n</i> 40)	4 weeks	Lipids	Rye v. wheat bread	Rye ↓ TC and LDL-cholesterol in men only
Bourdon <i>et al.</i> (1999) ⁽⁶⁸⁾	Healthy men (<i>n</i> 11)	Single meal	Glucose, insulin	Pasta with barley flours (two types) or wheat	Barley flours associated with ↓ insulin, unchanged glucose
Brown <i>et al.</i> (1999) ⁽³⁶⁾	Meta-analysis of sixty-seven trials (total <i>n</i> 2975)	> 14 d	TC and LDL	Soluble fibre (oat, pectin, guar gum, psyllium)	2–10 g soluble fibre ↓ TC (18 mg/l) and LDL (22 mg/l)
Jenkins <i>et al.</i> (1999) ⁽⁵⁷⁾	Hyperlipidaemic (<i>n</i> 24) and normolipidaemic adults (<i>n</i> 24) in two studies	1 month and 2 weeks	Lipids	Wheat bran	Wheat bran particle size did not affect lipids but higher gluten content ↓ TAG
Romero <i>et al.</i> (1998) ⁽⁵¹⁾	Normocholesterolaemic and hypercholesterolaemic men (<i>n</i> 30)	8 weeks	Lipids	Psyllium or oat bran	Either psyllium or oat bran ↓ TC and LDL but ↓ TAG only with oat bran
Gerhardt & Gallo (1998) ⁽⁵⁹⁾	Hypercholesterolaemic adults (<i>n</i> 44)	6 weeks	Lipids	Full-fat rice bran and oat bran	Rice and oat bran similarly ↓ LDL:HDL ratios
Delargy <i>et al.</i> (1997) ⁽²⁴⁾	Non-obese men (<i>n</i> 16)	24 h	Appetite, energy intake	Psyllium gum, wheat bran	Fibre did not alter total daily energy intake
Pick <i>et al.</i> (1996) ⁽⁷⁹⁾	Men with type 2 diabetes (<i>n</i> 8)	12 weeks	Glucose, insulin, lipids	Oat bran concentrate	Oat bran ↓ glucose and insulin responses, TC, LDL and LDL:HDL ratio
Tappy <i>et al.</i> (1996) ⁽⁶⁷⁾	Adults with type 2 diabetes (<i>n</i> 8)	Single meal	Glucose, insulin	β-Glucan in cereal	↓ Glucose and insulin
Jenkins <i>et al.</i> (1993) ⁽³⁵⁾	Hyperlipidaemic adults (<i>n</i> 43)	4 months	Lipids	High doses soluble or insoluble	High soluble fibre ↓ TC, LDL-cholesterol and HDL-cholesterol

↑, Increased; ↓, decreased; TC, total cholesterol; HOMA-IR, homeostasis model assessment of insulin resistance; HOMA-IS, homeostasis model assessment of insulin sensitivity.

* Procter & Gamble Co. (Cincinnati, OH, USA).