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A whole-grain cereal-based diet lowers postprandial plasma insulin and triglyceride levels in individuals with metabolic syndrome☆

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KEYWORDS
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Abstract *Background and aim:* Until recently, very few intervention studies have investigated the effects of whole-grain cereals on postprandial glucose, insulin and lipid metabolism, and the existing studies have provided mixed results. The objective of this study was to evaluate the effects of a 12-week intervention with either a whole-grain-based or a refined cereal-based diet on postprandial glucose, insulin and lipid metabolism in individuals with metabolic syndrome.

Methods and results: Sixty-one men and women age range 40–65 years, with the metabolic syndrome were recruited to participate in this study using a parallel group design. After a 4-week run-in period, participants were randomly assigned to a 12-week diet based on whole-grain products (whole-grain group) or refined cereal products (control group). Blood samples were taken at the beginning and end of the intervention, both fasting and 3 h after a lunch, to measure biochemical parameters. Generalized linear model (GLM) was used for between-group comparisons. Overall, 26 participants in the control group and 28 in the whole-grain group completed the dietary intervention. Drop-outs (five in the control and two in the whole-grain group) did not affect randomization. After 12 weeks, postprandial insulin and triglyceride responses (evaluated as average change 2 and 3 h after the meal, respectively) decreased by 29% and 43%, respectively, in the whole-grain group compared to the run-in period. Postprandial insulin and triglyceride responses were significantly lower at the end of the intervention in the whole-grain group compared to the control group ($p = 0.04$ and $p = 0.05$; respectively) whereas there was no change in postprandial response of glucose and other parameters evaluated.

Conclusions: A twelve week whole-grain cereal-based diet, compared to refined cereals, reduced postprandial insulin and triglycerides responses. This finding may have implications for type 2 diabetes risk and cardiovascular disease.

Abbreviations: ARs, alkylresorcinol homologues; CVD, cardiovascular disease; FFA, free fatty acids; GI, glycemic index; GLP-1, glucagon like peptide-1; Homa-IR, homeostatic model assessment-insulin resistance; LPS, lipopolysaccharides; T2D, type 2 diabetes.

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Introduction

Diet is an important lifestyle component able to influence the development of chronic diseases. Based on observational studies, a large body of evidence has shown that increased whole-grain consumption is consistently associated with a reduced risk of developing type 2 diabetes (T2D) and cardiovascular diseases (CVD) [1]. However, the mechanisms for this association have not been completely elucidated. The benefits of habitual whole-grain and cereal fiber intake can be mediated by improving one or more risk factors, such as insulin resistance, dyslipidemia, inflammation or oxidative stress. However, intervention studies investigating the effect of whole-grain in the regulation of glucose/insulin metabolism have thus far provided conflicting results. Some clinical trials have shown an improvement in insulin sensitivity [2–4], while other studies have reported no effect on either glucose or insulin metabolism [5–7]. Similarly, there is conflicting data on the effects of increased whole-grain consumption on markers of inflammation [8,9]. As for the effects of whole-grain consumption on lipid metabolism, there is general consensus that whole-grain cereals rich in β-glucans, such as oats and barley, are able to reduce fasting plasma concentrations of both total and LDL cholesterol [10,11]. However, clinical trials utilizing whole-wheat and/or whole-grain rye products have reported mixed results [5,7,12,13].

It is possible that the benefits of whole-grain consumption on reduction of T2D and CVD risk could also be mediated by mechanisms that have not yet been investigated, such as postprandial metabolism. A large body of evidence indicates that metabolic abnormalities in prediabetic insulin-resistant subjects and in diabetic patients are more closely related to the postprandial condition than to the fasting state [14]. Indeed, an increase in blood glucose, insulin and lipid concentrations in the postprandial period are risk factors for adverse cardiovascular events that can also be detected in the absence of altered fasting parameters [15]. It can be hypothesized that whole-grain intake exerts its metabolic effects mainly during the postprandial period with minimal impact, at least in the short/medium term, on fasting parameters. In this regard, very few studies have investigated specifically the effects of whole-grain cereals on postprandial metabolism or suggested a beneficial impact of whole-grain on glucose/insulin metabolism. In fact, in acute experimental settings, a reduction in insulin response has been reported with whole-kernel rye/whole-rye bread when compared with white wheat bread [16,17]. This has been confirmed in longer term experimental conditions that demonstrated a reduction of both insulin and glucose postprandial responses after a 2–4 weeks of whole-grain rye or wheat diet in overweight men [18]. A reduction in 2-h glucose response to OGTT after a 12 week diet based on whole-grain cereal products was observed in another study performed in individuals with metabolic syndrome [9,19]. However in this study consumption of whole-grain cereal products was associated with increased fatty fish and bilberry intake and when the impact of whole-grain was evaluated per se the diet failed to show any significant effect on metabolic parameters.

To clarify the impact of whole-grain on postprandial metabolism, the present study aimed at evaluating the effects of a 12-week intervention comparing a whole-grain-based diet to a refined cereal-based diet on postprandial glucose, insulin and lipid metabolism in individuals with metabolic syndrome, and no weight loss. This study was part of a randomized, controlled, two center (Naples, Italy and Kuopio, Finland) intervention study in which the principal endpoint was peripheral insulin sensitivity [20]. This paper reports data on postprandial metabolism obtained by the Italian research group.

Methods

Population

One hundred and eleven individuals were assessed for eligibility in the study; thirty-five candidates did not meet the inclusion criteria, and fifteen declined to participate. Overall, sixty-one men and women aged between 40 and 65 year, with metabolic syndrome were recruited for a dietary intervention. At screening, the health status and medical history of the subjects were examined by interview, clinical examination and routine laboratory tests. In addition, a 75 g oral glucose tolerance test (OGTT) was carried out to evaluate glucose tolerance and exclude participants with undiagnosed diabetes. The diagnosis of metabolic syndrome was based on the National Cholesterol Education Program Criteria [21]. Subjects were excluded if they were diagnosed with diabetes and/or renal failure (serum creatinine $>$1.5 mg/dl), liver abnormalities (ALT/AST ratio twice normal values), anemia (Hb $<$12 g/dl), any other chronic disease, if they used any drug known to influence glucose and lipid metabolism and inflammation, had very high levels of physical activity, or alcohol intake above 40 g/day.

All participants provided written informed consent, and the study was approved by the Ethics Committee of the Federico II Naples University.

Study design

The study was based on a randomized, controlled, parallel group design and consisted of a 4 week run-in period, during which participants were stabilized on their own diet, and a 12-week test period, fully described previously [20]. At the end of the run-in period, participants were randomly assigned to one of two groups, the first assigned to a diet based on whole-grain cereal products (whole-grain group), and the other to a diet based on refined cereal products (control group). Randomization was carried out with stratification for sex, age (5 year increments) and body mass index (BMI) (25–30, 30–35 kg/m^2) by means of a computerized random allocation list. Allocation was carried out by personnel not involved in the study; investigators and dieticians were aware of the participants'

group allocation only after completion of the randomization process. Participants were advised not to change their body weight, lifestyle habits and medication unless necessary, throughout the whole duration of the study.

At baseline, 4, 8 and 12 weeks during the intervention, participants underwent clinical investigations including measurements of body weight, waist circumference and blood pressure. Blood samples were taken before and after the intervention, specifically 12 h after an overnight fast and 3 h after lunch to obtain biochemical parameters.

Experimental diets

Participants were encouraged not to change their habitual meat, dairy products, eggs, fish, fruit, vegetable and fat intake during the study; the only difference between the whole-grain and control diets was the inclusion of a fixed amount of whole-grain or refined cereal products as the main carbohydrate source. The whole-grain diet was based on whole-grain products including whole-wheat bread, whole-meal pasta, barley soup, oat biscuits and breakfast cereals plus a small portion of endosperm rye bread. The control diet contained exclusively commercial products based on refined cereals such as wheat bread, rice, pizza, cornmeal porridge, and breakfast cereals (Rice Krispies). The bread consumed by the participants was 90% sourdough whole-wheat bread (100% whole-grain flour) and 10% endosperm rye bread. Moreover, most cereal products in the experimental diet had a lower glycemic index (GI) than those in the control diet.

To improve adherence to the whole-grain and control diets, the test products in both diets were provided free of charge to participants in amounts sufficient to cover their household consumption for the whole study period. For both diets, cereal products represented approximately 60–80% of the daily carbohydrate intake; the remaining 20–40% of carbohydrates were provided by fruits and vegetables according to each participant's usual dietary habits.

The diets were controlled for energy intake to maintain the participants' body weight stable throughout the intervention.

After the run-in period and at the end of the dietary intervention, the participants spent a day at the Clinical Research Centre where their metabolic profile was evaluated in fasting and postprandial conditions, and where they were served a meal resembling the composition of the recommended diet. The two lunch meals were prepared in the metabolic ward by a dietitian utilizing standardized amounts of refined and whole-grain products in order to make the two meals similar in energy and macronutrient composition (960 kcal, 18% protein, 30% fat, 52% CHO) but different in fiber content, which was higher in the meal based on whole-grain wheat products (17 vs.12 g). The lunches were consumed in 15–20 min.

Dietary assessment

Compliance with the diets was assessed using a 7-d food record during the run-in period, before starting the intervention and at the 4th, 8th and 12th week of intervention. All 7-d food records were analyzed by a computerized program using the food database of the Italian National Institute for Food and Nutrition.

Plasma total alkylresorcinol (AR) concentration, a biomarker of whole-wheat and rye intake [22], was measured at baseline and at the end of the intervention in both groups to evaluate compliance to the whole-grain and control diets.

Methods (Appendix)

Sample size calculation and statistical analysis

The primary endpoint was postprandial insulin response. Based on previous studies performed by our group, 61 individuals had to be studied to detect a 25% difference in insulin response between the two groups with 0.05 significance level and 80% power (type II error = 0.2), assuming a 15% drop-out rate.

Energy intake and nutrient composition at the end of the run-in period and during the intervention were calculated from the food records; the intakes during the intervention were expressed as mean of three food records completed at 4, 8 and 12 weeks. Postprandial glucose and insulin response to a lunch meal were expressed as change value, calculated by subtracting the baseline value from that of each time-point of the curve and as mean change over 2 h (for glucose and insulin concentration) or 3 h (for triglyceride, FFA concentrations and other variables).

The results for continuous variables were presented as mean ± standard error (mean ± SEM), unless otherwise stated. Variables with skewed distributions by Shapiro–Wilks test were normalized with a logarithmic or square root transformation.

A generalized linear model (GLM) was used to evaluate differences between groups (calculated as change in the parameter concentration between 12-week and the end of the run-in period and indicated by Δ). A paired-samples *t* test was used to examine these changes within each group. For all analyses, the level of statistical significance was set at $p = 0.05$ (two tails). Data were analyzed using SPSS for Windows 11.5 (SPSS Inc., Chicago IL).

Results

Characteristics of participants

Fifty-four subjects completed the dietary intervention: 26 subjects (11 M/15 F) in the control group and 28 (12 M/16 F) in the whole-grain group. Five subjects (16.1%) allocated to the control group and two (6.6%) in the experimental group dropped out because of limited time due to work or family-related problems. The clinical characteristics of the participants are reported in Table 1. At the end of the run-in period, whole-grain and control groups were similar with respect to age (56.7 ± 8.8 vs. 57.7 ± 7.8 years) (mean ± SD), BMI (31.9 ± 5.8 vs. 31.6 ± 5.4 kg/m^2), body

Table 1 Anthropometric and fasting plasma metabolic parameters after run-in and intervention periods.

	Control group (n = 26)			Whole-grain group (n = 28)			p for Δ[c]
	Run-in	12-week	Δ[b]	Run-in	12-week	Δ	
Body weight (kg)	85.2 ± 19.0[a]	84.7 ± 19.3	−0.5	87.9 ± 16.7	87.4 ± 15.8	−0.5	0.99
Waist circumference (cm)	105.7 ± 12.0	105.2 ± 12.3	−0.4	107.3 ± 15.5	107.4 ± 14.6	−0.2	0.72
Glucose (mmol/L)	5.8 ± 0.5	5.8 ± 0.7	−0.0	5.6 ± 0.6	5.7 ± 0.7	0.1	0.51
Insulin (pmol/L)	97.2 ± 41.7	97.2 ± 55.6	−0.0	104.2 ± 62.6	111.1 ± 55.6	6.9	0.25
Homa-IR	3.50 ± 1.61	3.24 ± 1.62	−0.26	4.02 ± 2.61	3.99 ± 2.22	−0.03	0.43
Triglycerides (mmol/L)	1.66 ± 0.69	1.58 ± 0.64	−0.08	1.67 ± 1.59	1.62 ± 0.73	−0.05	0.95
Cholesterol (mmol/L)	5.13 ± 0.88	5.20 ± 0.80	0.07	5.23 ± 1.19	5.26 ± 1.24	0.03	0.75
HDL-cholesterol (mmol/L)	0.96 ± 0.18	0.98 ± 0.18	0.02	1.11 ± 0.34	1.09 ± 0.34	−0.02	0.18
LDL-cholesterol (mmol/L)	3.39 ± 0.80	3.47 ± 0.78	0.08	3.37 ± 1.16	3.42 ± 1.14	0.05	0.93
Apo B-48 (μg/ml)	8.05 ± 6.26	8.70 ± 6.56	0.65	7.26 ± 7.82	7.72 ± 4.89	0.46	0.90
Apo B-100 (μg/ml)	0.98 ± 0.19	1.02 ± 0.19	0.04	0.99 ± 0.26	1.00 ± 0.26	0.01	0.31
FFA (mEq/L)	0.64 ± 0.19	0.54 ± 0.15[d]	−0.10	0.60 ± 0.20	0.57 ± 0.20	−0.02	0.32
GLP-1 (pmol/L)	3.77 ± 2.04	3.64 ± 1.41	−0.13	3.03 ± 1.00	2.91 ± 0.82	−0.12	0.92
Total ARs (nmol/L)[e]	63.4 ± 58.4	43.7 ± 38.0	−19.7	52.0 ± 62.3	140.2 ± 102.0	88.3	0.0001

[a] Mean ± SD (all such values).
[b] Δ: change of the parameters calculated as 12 week − run-in values.
[c] Differences between the two groups (whole-grain vs. control) were evaluated by Generalized linear model (GLM).
[d] $p < 0.02$ paired sample t-test (12-week vs. run-in).
[e] ARs, alkylresorcinols.

weight, waist circumference, fasting plasma concentrations of glucose, insulin, lipids, Apo B 100, Apo B 48, GLP-1, total AR and Homa-IR.

Dietary compliance

Compliance was good for both diets. During the intervention, both groups reported consuming the recommended portions of breads and whole-grain or refined cereal-based product. At the end of the intervention the intake of whole-grain-ingredients was 136 ± 18 g/day dry weight in the whole-grain group and zero in the control group. After run-in, the energy intake and nutrient composition of the diets were similar between the two groups (Table 2). Compared with the end of the run-in period, both whole-grain and control groups increased their energy ($p = 0.001$) and carbohydrate intakes ($p < 0.05$) and decreased total fat and cholesterol intake ($p < 0.05$) during the intervention. As expected and according to the protocol, at the end of the intervention, the whole-grain group diet was characterized by a significantly higher total and cereal fiber intake ($p < 0.05$) and a decrease in GI ($p < 0.05$) compared with the control group diet.

There were also small differences in protein, PUFA and MUFA intakes (Table 2) but only the variation in PUFA and MUFA was significantly different between the two groups ($p = 0.01$; GLM) (Table 2) likely due to higher PUFA content in whole-grain products compared with refined ones. However GLM for univariate analysis, including Δ PUFA and Δ MUFA as covariate, confirmed the independent effect of whole-grain intake on postprandial triglyceride ($p = 0.002$) and insulin ($p = 0.009$) responses.

Fasting total plasma AR concentrations increased significantly in the whole-grain group and decreased significantly in the control group compared to the end of the run-in period. There was also a significant difference between the two groups at the end of the intervention (+88.3 vs. −19.7 nmol/L; $p < 0.0001$, GLM analysis) (Table 1).

Effects of dietary intervention on anthropometric and fasting metabolic parameters

Mean body weight and waist circumference (M ± SD) did not change during the intervention period in either group (Table 1).

No effects of the whole-grain and control diets on fasting plasma concentrations of glucose, insulin, lipids, Apo B-100, or Apo B-48 and Homa-IR were observed at the end of the intervention period. A significant decrease in fasting plasma FFA levels was observed only in the control group, but there were no differences between the two groups (Table 1).

Effects of dietary intervention on postprandial parameters

At the end of run-in period, postprandial plasma changes in glucose and insulin were similar in the whole-grain and control group at each time point (Fig. 1).

At the end of the intervention, the postprandial glucose response did not change in either group compared to the run-in period. In contrast, postprandial plasma insulin concentrations at 30, 90 and 120 min decreased significantly compared to the run-in period ($p < 0.05$) only in the whole-grain group (Fig. 1). Consequently, the average postprandial change in insulin 120 min after fasting was significantly reduced (−29%) compared to the run-in period ($p < 0.05$) in the whole-grain group, and the change was significantly different from that observed in the control group ($p = 0.04$; GLM) (Fig. 1).

Table 2 Energy intake and diet composition after run-in and intervention periods.

	Control group (n = 26)			Whole-grain group (n = 28)			p for Δ[c]
	Run-in	12-week	Δ[b]	Run-in	12-week	Δ	
Energy (kcal/d)	1736 ± 80[a]	1929 ± 58[d]	193	1778 ± 95	2058 ± 80[d]	280	0.33
CHO (%)	51 ± 1.0	55 ± 0.7[d]	4.0	50 ± 1.0	52 ± 0.7[d]	2.0	0.30
Protein (%)	17.1 ± 0.5	17.0 ± 0.3	−0.1	17.1 ± 0.6	18.2 ± 0.3[d]	1.1	0.06
Total fat (%)	32.0 ± 0.9	28.4 ± 0.7[d]	−3.6	33.1 ± 1.0	29.7 ± 0.7[d]	−3.4	0.90
SAFA (%)	9.4 ± 0.4	8.8 ± 0.3	−0.6	10.1 ± 0.4	8.7 ± 0.3[d]	−1.4	0.18
MUFA (%)	14.5 ± 0.5	14.1 ± 0.4	−0.4	14.8 ± 0.6	12.4 ± 0.5[d]	−2.4	0.01
PUFA (%)	3.9 ± 0.2	2.9 ± 0.7[d]	−1.0	4.4 ± 0.3	4.4 ± 0.2[d]	0.0	0.01
Cholesterol (mg/day)	225 ± 17	187 ± 11[d]	−38	250 ± 18	187 ± 10[d]	−62	0.28
Total fiber (g/day)	20.4 ± 1.0	22.1 ± 0.9	1.7	20.3 ± 1.1	40.2 ± 1.2[d]	20.0	0.00
Cereal fiber (g/day)	9.5 ± 0.7	11.8 ± 0.4	2.3	8.4 ± 0.6	28.9 ± 1.1[d]	20.5	0.00
Glycemic index (%)	64.1 ± 1.0	72.0 ± 0.6	7.9	64.3 ± 1.2	45.8 ± 0.4[d]	−18.5	0.00

[a] Mean ± SEM (all such values).
[b] Δ: change of the parameters calculated as 12 week − run-in values.
[c] Differences between the two groups (whole-grain vs. control) were evaluated by Generalized Linear Model (GLM).
[d] $p < 0.02$ paired sample t-test (12-week vs. run-in).

Postprandial plasma triglyceride levels were similar at baseline in the two groups (Fig. 2). At the end of the intervention, postprandial plasma triglyceride levels did not change in the control group compared to the end of the run-in period. On the contrary, in the whole-grain group, postprandial plasma triglyceride concentrations at 120 and 180 min were significantly lower than at the end of the run-in period ($p < 0.05$) (Fig. 2). Consequently, the average change in postprandial triglyceride levels after fasting for 180 min was significantly reduced (−43%) compared to the end of the run-in period ($p < 0.05$), and the change in triglyceride response observed in the whole-grain group was significantly lower than that observed in the control group ($p = 0.001$; GLM) (Fig. 2).

Postprandial responses of plasma FFA, Apo B 100, Apo B 48 and GLP-1 were similar at the end of the run-in period in the whole-grain and control group and did not change at the end of intervention in either group (Table 3).

At the end of the intervention postprandial average triglyceride change was inversely correlated with AR plasma levels ($r = -0.283$; $p = 0.05$) and cereal fiber intake ($r = -0.419$; $p = 0.003$) (Additional Figure).

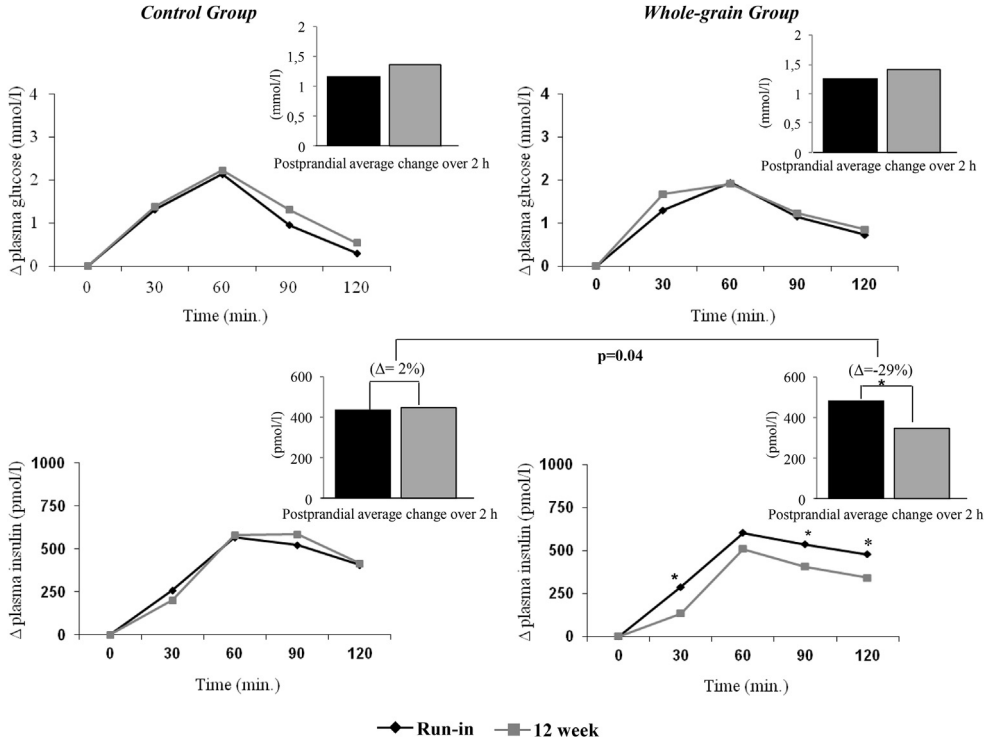

Figure 1 Postprandial plasma glucose and insulin concentrations after run-in and intervention periods (mean values); *$p < 0.05$ paired sample t-test (12-week vs. run-in); $p = 0.04$ GLM (differences between whole-grain vs. control calculated as change between 12-week and the end of the run-in periods).

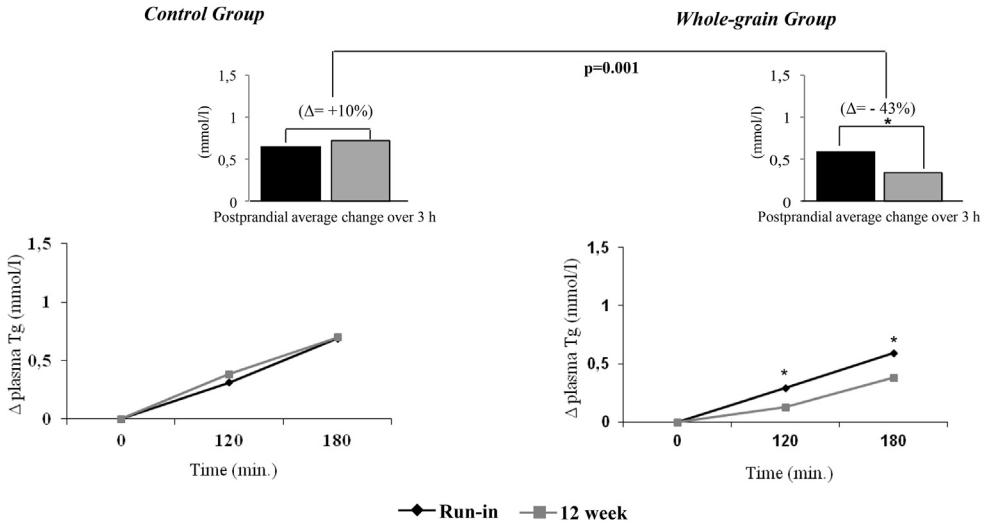

Figure 2 Postprandial plasma triglyceride concentrations after run-in and intervention periods (mean values); *$p < 0.05$ paired sample t-test (12 week vs. run-in); $p = 0.001$ GLM (differences between whole-grain vs. control calculated as change between 12-week and the end of the run-in periods).

Discussion

This study shows that a diet based on whole-grain cereal products, compared to a diet based on refined cereals, reduces postprandial insulin and triglyceride plasma concentrations in individuals with metabolic syndrome. In the whole-grain group, postprandial insulin response decreased by 29% compared to baseline, i.e., significantly lower than that observed in the group assigned to the refined cereal diet. It must be emphasized that the reduced insulin response was not paralleled by changes in plasma glucose response, suggesting that the whole-grain diet was able to improve insulin action in the postprandial period. In a larger cohort that included both these subjects and a group recruited in Kuopio, we previously evaluated peripheral insulin sensitivity in the fasting condition utilizing an intravenous glucose testing, and no effect of whole-grain supplementation was observed [20]. Our results suggest a possible effect of whole-grain diet on insulin sensitivity at the liver level, although this was not directly measured by tracer methodology.

In our study, the reduced postprandial insulin response in the whole-grain group was not mediated by changes in FFA or GLP-1 plasma concentrations – these biomarkers were not different between the two groups. However, other mechanisms linking whole-grain consumption, large intestinal events and insulin sensitivity may be involved. The fermentation of grain fiber takes place in the large intestine, beneficially affecting the composition of gut microbiota and decreasing the permeability of the gut barrier. An improved gut barrier reduces leakage of endotoxic bacterial lipopolysaccharides (LPS) into the circulation. Lower concentrations of LPS in the blood seem to alleviate peripheral inflammation and insulin resistance. The fermentation of grain fiber also leads to a continuous supply and absorption of metabolites, such as short chain fatty acids and ferulic acid derivatives, which may have anti-inflammatory effects and improve insulin resistance [23].

Whatever the mechanisms, a lower postprandial plasma insulin response has a beneficial effect on health outcomes. Indeed, an increased insulin response to ingested foods is associated with lower plasma glucose values between meals and consequently a greater appetite with a possible negative impact on body weight regulation [24,25]. In addition, postprandial hyperinsulinemia has been identified as a risk marker for the development of T2D and CVD [26,27]. Therefore, in recent years,

Table 3 FFA, apolipoproteins and GLP-1 plasma concentrations after run-in and intervention periods.

	Control group ($n = 26$)			Whole-grain group ($n = 28$)			p for Δ[d]
	Run-in	12-week	Δ[c]	Run-in	12-week	Δ	
FFA (mEq/L*180 min)[b]	−0.39 ± 0.16[a]	−0.32 ± 0.15	0.07	−0.36 ± 0.16	−0.35 ± 0.18	0.01	0.19
Apo B-48 (μg/ml*180 min)[b]	7.87 ± 0.63	6.30 ± 0.73	−1.57	6.37 ± 0.59	5.38 ± 0.68	−1.00	0.61
Apo B-100 (μg/ml*180 min)[b]	−0.07 ± 0.01	−0.09 ± 0.01	−0.013	−0.07 ± 0.01	−0.09 ± 0.01	−0.014	0.97
GLP-1 (pmol/L*180 min)[b]	0.79 ± 0.15	0.85 ± 0.13	0.04	0.79 ± 0.19	0.64 ± 0.11	−0.15	0.51

[a] Data are expressed as Mean ± SEM (all such values).
[b] Values calculated as postprandial average change from baseline value over 180 min.
[c] Δ: change of the parameters calculated as 12 week – run-in values.
[d] Differences between the two groups (whole-grain vs. control) were evaluated by Generalized linear model (GLM).

nutritional research has focused on the identification of carbohydrate-rich foods with a lower insulinemic index, such as rye, barley and other whole-grain cereals.

Finally, in the medium/long term, an improvement in postprandial insulin and glucose metabolism, which reduces β cell stress, might lead to a better preservation of β-cell function and delay the onset of diabetes [28]. In addition to this, another relevant and novel finding of our study is that the whole-grain diet was able to reduce postprandial triglyceride concentrations by as much as 43% compared to the control diet. Whole-grain consumption could reduce postprandial triglycerides by acting either on the synthesis of triglyceride-rich lipoproteins and/or on their catabolism, particularly through an increase in lipoprotein lipase activity. It is possible that the decrease in insulin concentrations in the postprandial period could help reduce the intestinal synthesis of chylomicrons and liver derived VLDL particles [29]. However, the absence of any reduction of Apo B-48 and Apo B-100 plasma concentrations in the whole-grain group does not support the hypothesis of a reduced synthesis of chylomicrons and VLDL. On the other hand, whole-grain consumption could contribute to modify the lipid composition of lipoprotein particles rather than reduce their number. In this case, the fiber present in whole-grain products might have interfered with fat absorption in the small intestine, thus leading to the synthesis of lipoproteins that are less rich in triglycerides [30]. This is consistent with data showing that the addition of wheat fiber to a meal reduced postprandial triglyceride response [31]. Furthermore, we found a significant inverse correlation between cereal fiber intake and postprandial plasma triglyceride changes from baseline in the whole-grain group ($r = -0.419$; $p = 0.003$), suggesting a key role of whole-grain fiber in reducing postprandial triglyceride response.

Whatever the mechanisms, the reduction of plasma triglycerides in the postprandial period is definitively relevant from a clinical point of view, as postprandial lipemia has been proposed as an independent CVD risk factor [15,32]. Moreover, the magnitude of the reduction in postprandial triglyceride concentrations may be clinically meaningful. In fact, based on the results of large prospective studies, we can foresee that the decrease in postprandial triglyceride concentrations obtained in this study could be associated with a significant reduction in CVD risk [15,32].

A main strength of our study was a well-controlled intervention trial of sufficient duration to evaluate the effects of a dietary intervention on glucose and lipid metabolism. An additional strength is that plasma AR was used as a biomarker for the intake of whole-grain. Moreover, our results, obtained after a 12-week period, indicated that modifications in postprandial plasma insulin and triglyceride concentrations induced by the ingestion of whole-grain wheat products were independent of small but significant differences in nutrients between the two dietary interventions, preserved over time and not neutralized by homeostatic mechanisms of counteraction. One limitation of our study is that the duration of the intervention was relatively short in relation to the natural history of T2D and CVD. However, the duration of the intervention and the sample size were greater than those reported in previous studies that showed no effect of whole-grain consumption on postprandial glucose and insulin metabolism [7,33].

In conclusion, our study indicates that the consumption of whole-grain products reduced postprandial insulin and triglyceride plasma concentrations, which are two important risk factors for T2D and CVD. These effects might partially explain the mechanisms through which increased whole-grain consumption is associated with a reduced risk of T2D and CVD. However, only intervention trials of longer duration and with hard endpoints (onset of T2D, cardiovascular events) could clarify this issue.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.numecd.2014.01.007.

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