

# Dietary fibre and incidence of type 2 diabetes in eight European countries: the EPIC-InterAct Study and a meta-analysis of prospective studies

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## Abstract

**Aims/hypothesis** Intake of dietary fibre has been associated with a reduced risk of type 2 diabetes, but few European studies have been published on this. We evaluated the association between intake of dietary fibre and type 2 diabetes in the European Prospective Investigation into Cancer and Nutrition (EPIC)-InterAct study and in a meta-analysis of prospective studies.

**Methods** During 10.8 years of follow-up, 11,559 participants with type 2 diabetes were identified and a subcohort of 15,258 participants was selected for the case-cohort study. Country-specific HRs were estimated using Prentice-weighted Cox proportional hazards models and were pooled using a random effects meta-analysis. Eighteen other cohort studies were identified for the meta-analysis.

**Results** In the EPIC-InterAct Study, dietary fibre intake was associated with a lower risk of diabetes (HR<sub>Q4 vs Q1</sub> 0.82; 95% CI 0.69, 0.97) after adjustment for lifestyle and dietary factors. Similar inverse associations were observed for the intake of cereal fibre and vegetable fibre, but not fruit fibre. The associations were attenuated and no longer statistically significant after adjustment for BMI. In the meta-analysis (19 cohorts), the summary RRs per 10 g/day increase in intake were 0.91 (95% CI 0.87, 0.96) for total fibre, 0.75 (95% CI 0.65, 0.86)

for cereal fibre, 0.95 (95% CI 0.87, 1.03) for fruit fibre and 0.93 (95% CI 0.82, 1.05) for vegetable fibre.

**Conclusions/interpretation** The overall evidence indicates that the intake of total and cereal fibre is inversely related to the risk of type 2 diabetes. The results of the EPIC-InterAct Study suggest that the association may be partially explained by body weight.

**Keywords** Case-cohort · Dietary fibre · EPIC-InterAct · Meta-analysis · Type 2 diabetes

## Abbreviation

EPIC European Prospective Investigation into Nutrition and Cancer

## Introduction

Worldwide, there is an increasing prevalence of type 2 diabetes [1], which is likely to be driven by increasing adiposity, reduced physical activity and dietary changes. The number of people living with diabetes (mostly type 2 diabetes) worldwide has been projected to increase from 366 million in 2011 to 552 million by 2030 [1], and this trend will have important public health implications in terms of morbidity [2], mortality [2, 3] and healthcare costs [4].

The intake of dietary fibre, especially of cereal origin, has been inversely associated with risk of diabetes, as has been summarised in a meta-analysis of cohort studies by Schulze et al [5]. A higher intake of cereal fibre was associated with a 33% lower risk of diabetes compared with a low intake [5]. However, most of the studies included in this meta-analysis were from the USA, and the level and sources of fibre intake

The InterAct Consortium list of authors is shown in the Appendix.

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may differ substantially between countries. For example, in European populations [6, 7] total fibre intake appears to be higher than that reported in several US studies [8–10], and this may partly be explained by a higher intake of cereal fibre in Europe compared with the US [6, 8–10]. It is also not clear why cereal fibre could exert more beneficial effects on type 2 diabetes than other sources of fibre. Most cereals contain proportionally larger amounts of insoluble fibre, while most evidence from experimental studies on the benefits of fibre has been accumulated for soluble fibres [11]. The aims of this study were to evaluate the associations between total, cereal, fruit and vegetable fibre and the incidence of type 2 diabetes in a large European cohort, the European Prospective Investigation into Cancer and Nutrition (EPIC)-InterAct Study, and to summarise the existing evidence on fibre intake and type 2 diabetes in a meta-analysis of prospective studies.

## Methods

### Study population

The EPIC-InterAct Study is embedded in EPIC, which is a multicentre prospective cohort study designed to investigate the relationship between food habits, nutritional status, various lifestyle and environmental factors, and the incidence of cancer and other chronic diseases in ten European countries [12, 13]. The EPIC-InterAct Study used data from eight European countries (Denmark, France, Germany, Italy, the Netherlands, Spain, Sweden and the UK) [14]. We used a nested case-cohort design, including incident cases of type 2 diabetes ( $n=12,403$ ) and a random subcohort ( $n=16,835$ , including 778 cases of incident diabetes), selected from 340,234 EPIC participants eligible for the EPIC-InterAct Study. All the participants gave written informed consent, and the study was approved by the local ethics committee at the participating centres and the Internal Review Board of the International Agency for Research on Cancer.

### Population for current analysis

Of the 28,460 participants in the EPIC-InterAct nested case-cohort sample, we excluded participants with prevalent diabetes ( $n=548$ ), missing information on reported diabetes status ( $n=129$ ), post-censoring diabetes ( $n=4$ ), extreme energy intake (in the top 1% and bottom 1% of the distribution of the ratio of reported energy intake over estimated energy requirement, assessed by basal metabolic rate;  $n=736$ ), and participants with missing values for educational level ( $n=479$ ), physical activity ( $n=180$ ), smoking status ( $n=131$ ) and BMI ( $n=165$ ). This left a final sample of 11,559 cases and 15,258 subcohort participants (729 of the diabetes cases being from the subcohort), for the current analysis (a total of 26,088

participants). No differences were observed in baseline characteristics between the included and excluded participants.

### Incidence of diabetes

Incident cases of diabetes were identified on the basis of self-reporting, a linkage to primary care registers or secondary care registers, medication use, hospital admissions and mortality data [14]. The identified cases were verified with further evidence, including individual medical record reviews. Cases in Denmark and Sweden were not ascertained by self-reporting but were identified via local and national diabetes and pharmaceutical registers. Follow-up was censored at the date of diagnosis, 31 December 2007 or the date of death, whichever occurred first. In total, 11,559 verified incident cases were identified during follow-up and were eligible for the current analysis.

### Fibre intake and other dietary variables

Dietary intake over the previous 12 months before recruitment was assessed by country-specific or centre-specific dietary assessment methods (food frequency questionnaires and dietary histories) that were developed and validated locally [12, 15, 16]. The food intake data were converted to nutrient intake using the European Nutrient Database [17]. The method for estimating total dietary fibre intake has previously been described [18]. In brief, the gravimetric method of the Association of Official Analytical Chemists [19] was used for estimating the total dietary fibre (which includes soluble and insoluble forms of non-starch polysaccharides and resistant starch as fibre) in all countries except the UK, where total dietary fibre was estimated by the Englyst method (which includes non-starch polysaccharides but not lignin or resistant starch). For the present study, we used measurements of total dietary fibre and fibre from cereals, fruits and vegetables, which are the main fibre sources in all eight countries.

### Lifestyle variables

Baseline information on lifestyle factors was obtained from questionnaires. Weight, height and waist circumference were measured by trained staff during standardised health checks at baseline in all centres, except for a proportion of participants in Oxford (UK) and France, for whom self-reported data were obtained, and Umeå (Sweden), where waist circumference was not measured. Physical activity was assessed by questionnaire and was classified according to the Cambridge Physical Activity Index [20, 21].

## Statistical analysis

We examined the association by country between quarters of the distribution of fibre intake in the subcohort (hereafter referred to as quartiles) adjusted for energy using the residual method [22] and the incidence of type 2 diabetes using Cox proportional hazard models modified for the case-cohort design according to the Prentice method [23]. The underlying time metric was age. In order to adjust for time to follow-up, the age at recruitment (1 year categories) was included as a stratum variable. Country-specific HRs and 95% CIs were pooled using random effects meta-analyses [24]. Between-country heterogeneity was assessed using the  $I^2$  statistic, i.e. the percentage of variation in the HR that was attributable to between-country heterogeneity [25]. The significance of linear trends across quartiles of total and different sources of fibre was tested by assigning the median value of the quartile to each participant and modelling these values as a continuous variable.

Confounders were assessed at baseline and those included in the models were age and sex (model 1), lifestyle and classical diabetes risk factors (model 2), dietary factors (model 3) and BMI (model 4). Each model was additionally adjusted for the preceding model. Lifestyle and classical diabetes risk factors included smoking status (never smoker, former smoker or current smoker), physical activity level based on an index of activity (inactive, moderately inactive, moderately active or active) [20, 21], education level (low, secondary or high) and alcohol intake (0=non-drinker, 1=0–12/0–6 g/day for men and women, respectively, 2=12–24/6–12 g/day or 3≥24/12 g/day). Dietary factors included the total energy intake and the energy-adjusted intake of carbohydrates, magnesium, vitamin B<sub>1</sub> and saturated fatty acids (continuous). The final model also adjusted for BMI (continuous). All models for subgroups of fibre were mutually adjusted for each other. Variables not included in the multivariable models because they did not change the risk estimates are listed in the electronic supplementary material (ESM) [methods](#). A number of stratified and sensitivity analyses were conducted, and these are described in the ESM [methods](#).

Analyses were conducted in SAS version 9.2 (SAS Institute, Cary, NC, USA), except for the meta-analyses, which were conducted in Stata 11.0 (Stata, College Station, TX, USA). A two-sided  $p$  value ≤0.05 was considered statistically significant for all analyses.

## Meta-analysis

We searched PubMed up to and including 24 January 2014 for prospective studies of fibre intake and risk of type 2 diabetes using the keywords ‘fiber’, ‘fibre’ and ‘diabetes’. Eighteen cohorts (20 publications) [5–10, 26–39] in addition to the present study were included in the analyses. More details of

the study selection and methods can be found in the ESM [methods](#). Random effects models were used to calculate summary RRs comparing the highest with the lowest category of fibre intake and for the dose–response analysis [24]. Dose–response analyses were conducted using the method described by Greenland and Longnecker [40]. Non-linear dose–response analyses were conducted using fractional polynomial models [41], and a likelihood ratio test was used to test for non-linearity [41]. We quantified the extent of heterogeneity by using  $I^2$  [25]. We tested for small-study bias using Egger’s test [42] and by inspecting the funnel plots. All statistical analyses for the meta-analysis were conducted using the statistical package STATA 11.0.

## Results

### The EPIC-InterAct Study

The study population consisted of 26,088 participants. The average age at baseline in the subcohort ( $n=15,258$ ) was  $52.4\pm 9.1$  years. Participants who had a high fibre intake (>26.4 g/day) were less likely to smoke, drank little alcohol and were more physically active than those with a low fibre intake (<18.9 g/day; Table 1). The proportion of men was higher in the lowest quartile of fibre intake (50% men) than in the next three quartiles (31–35%). Although the mean BMI was slightly higher in participants with a higher fibre intake (Table 1), this may have been confounded by country as fibre intake was positively associated with BMI only in Spain and the Netherlands, was not associated with BMI in Italy, and was inversely associated with BMI in the remaining countries (ESM Table 1).

The mean±SD fibre intake in the subcohort was  $22.9\pm 6.2$  g/day (ranging from 19.9 g/day in Sweden to 25.2 g/day in Denmark; data not shown). Cereals were the main source of fibre (38%) in all countries except France, where vegetables were the main source of fibre. Of the cereal fibres, 81% originated from bread (ranging from 56% in the UK to 90% in Germany), 8% from pasta and rice (with the highest amounts in Italy [23%] and France [16%]) and 7% from breakfast cereals (with the highest amount in the UK [28%]). Other sources of fibre in consecutive order were fibre from fruits and nuts (20%), vegetables (18%), potatoes and tubers (9%) and legumes (5%). Cereal, fruit and vegetable fibres together accounted for around 75% of total fibre in all countries (data not shown).

During a median of 10.8 years of follow-up, we ascertained 11,559 incident cases of type 2 diabetes. After adjusting for lifestyle factors and dietary factors, total fibre intake was associated with a lower risk of diabetes (HR<sub>Q4 vs Q1</sub> 0.82; 95% CI 0.69, 0.97;  $p$  for trend=0.02; Table 2). When evaluating the fibre sources, the highest vs the lowest quartile of intake of

**Table 1** Study characteristics (mean  $\pm$  SD, unless otherwise specified) in a random subcohort from the EPIC-InterAct study stratified by quartiles of energy-adjusted total fibre intake ( $n=15,258$ )

Variable	<i>n</i>	Q1	Q2	Q3	Q4
Cutoffs (g/day)		<18.9	18.9–<22.4	22.4–26.4	>26.4
Median (g/day)		16.3	20.7	24.2	29.7
Age (years)	15,258	52.0 $\pm$ 9.4	52.2 $\pm$ 9.1	52.6 $\pm$ 9.0	52.8 $\pm$ 8.7
Men (%)	15,258	50	35	31	35
Follow-up (years)	15,258	12.0 $\pm$ 2.5	12.0 $\pm$ 2.3	11.9 $\pm$ 2.4	12.0 $\pm$ 2.2
BMI (kg/m <sup>2</sup> )	15,258	25.8 $\pm$ 4.0	26.0 $\pm$ 4.2	26.2 $\pm$ 4.2	26.2 $\pm$ 4.3
BMI (% obese)	15,258	14	16	17	16
Waist circumference (cm)					
Men	5,282	94.8 $\pm$ 10.2	94.9 $\pm$ 9.9	95.9 $\pm$ 9.6	95.1 $\pm$ 9.8
Women	8,963	80.1 $\pm$ 11.4	81.0 $\pm$ 10.9	81.7 $\pm$ 11.0	81.9 $\pm$ 11.3
First-degree relatives with diabetes (% yes) <sup>a</sup>	7,615	17	19	21	19
Smoking (% current)	15,258	37	26	23	18
Hypertension (% yes)	14,930	18	19	20	19
Hyperlipidaemia (% yes)	11,389	18	19	19	19
Myocardial infarction (% yes)	15,007	1.4	1.3	1.5	1.4
Angina (% yes)	10,078	1.7	1.8	2.3	2.4
Stroke (% yes)	14,036	0.9	0.9	0.8	0.8
Educational level (% high)	15,258	21	21	20	21
Physical activity (% inactive)	15,258	25	24	23	22
Postmenopausal women (%)	9,484	44	46	47	51
Dietary factors					
Energy (kJ/day)	15,258	9,320 $\pm$ 2,834	8,579 $\pm$ 2,562	8,629 $\pm$ 2,516	9,286 $\pm$ 2,617
Fat (en%)	15,258	36.7	35.4	34.3	32.7
Saturated fatty acids		14.8	13.6	12.8	11.7
Monounsaturated fatty acids		13.8	13.5	13.0	12.4
Polyunsaturated fatty acid		5.4	5.6	5.7	5.7
Protein (en%)	15,258	16.5	17.0	17.3	17.4
Carbohydrates (en%)	15,258	40.6	43.35	45.1	47.0
Starch		21.6	23.7	24.5	25.4
Sugars		18.4	19.1	20.0	20.9
Magnesium (mg/day)	15,258	313 $\pm$ 64	337 $\pm$ 59	362 $\pm$ 61	398 $\pm$ 65
Cholesterol (mg/day)	15,258	373 $\pm$ 125	352 $\pm$ 105	337 $\pm$ 104	314 $\pm$ 113
Vitamin B <sub>1</sub> (mg/day)	15,258	1.2 $\pm$ 0.3	1.3 $\pm$ 0.3	1.4 $\pm$ 0.3	1.5 $\pm$ 0.4
$\beta$ -Carotene (mg/day)	15,258	1.9 $\pm$ 1.3	2.6 $\pm$ 1.6	3.1 $\pm$ 1.9	4.4 $\pm$ 3.8
Vitamin C (mg/day)	15,258	88 $\pm$ 44	111 $\pm$ 45	131 $\pm$ 52	167 $\pm$ 83
Vitamin E (mg/day)	15,258	10.1 $\pm$ 4.1	11.5 $\pm$ 3.9	12.0 $\pm$ 4.1	13.1 $\pm$ 4.9
GI (not energy adjusted)	15,258	56.6 $\pm$ 4.1	55.9 $\pm$ 3.8	55.9 $\pm$ 3.8	55.8 $\pm$ 3.9
GL (not energy adjusted)	15,258	128 $\pm$ 47	124 $\pm$ 44	130 $\pm$ 43	145 $\pm$ 47
Alcohol (g/day) median (P10; P90), not energy adjusted	15,258	12 (0; 58)	7 (0; 37)	5 (0; 31)	4 (0; 30)
Alcohol (% non-drinkers)	15,258	19	26	29	31

<sup>a</sup> Family history of diabetes was not ascertained in Italy, Spain, Oxford and Heidelberg (excluded from this summary)

en%, percentage of total energy intake; GI, glycaemic index; GL, glycaemic load; P10, 10th percentile; P90, 90th percentile

cereal fibre (HR 0.81; 95% CI 0.70, 0.93; *p* for trend <0.01) and vegetable fibre (HR 0.84; 95% CI 0.74, 0.96; *p* for trend <0.01) were inversely associated with the risk of diabetes, but fruit fibre (HR 0.98; 95% CI 0.89, 1.08; *p* for trend=0.74) was

not associated with risk of diabetes. However, when the analyses were additionally adjusted for BMI, the inverse associations were attenuated and no longer statistically significant. When comparing the highest with the lowest quartile, the

**Table 2** HRs (95% CI) for the associations between quartiles of dietary fibre and incident type 2 diabetes in the EPIC-InterAct Study ( $n=26,088$ )

Variable	Q1	Q2	Q3	Q4	<i>p</i>
Total fibre, g/day (median)	<18.9 (16.3)	18.9–22.4 (20.7)	22.4–26.4 (24.2)	>26.4 (29.7)	
Model 1 ‘age, sex’	1.00	0.91 (0.82, 1.02)	0.90 (0.79, 1.02)	0.93 (0.78, 1.11)	0.08
Model 2 ‘lifestyle’	1.00	0.92 (0.82, 1.04)	0.91 (0.81, 1.02)	0.84 (0.69, 1.02)	0.07
Model 3 ‘lifestyle and diet’	1.00	0.92 (0.83, 1.02)	0.91 (0.82, 1.01)	0.82 (0.69, 0.97)	0.02
Model 4 ‘lifestyle, diet and BMI’	1.00	0.93 (0.84, 1.03)	0.98 (0.89, 1.08)	0.91 (0.81, 1.03)	0.28
Cereal fibre, g/day (median)	<5.7 (4.3)	5.7–7.9 (6.8)	7.9–10.9 (9.3)	>10.9 (13.7)	
Model 1 ‘age, sex’	1.00	0.89 (0.80, 0.99)	0.88 (0.77, 1.00)	0.85 (0.72, 1.00)	0.03
Model 2 ‘lifestyle’	1.00	0.89 (0.80, 0.98)	0.89 (0.80, 0.99)	0.82 (0.72, 0.93)	<0.01
Model 3 ‘lifestyle and diet’	1.00	0.90 (0.80, 1.00)	0.91 (0.82, 1.00)	0.81 (0.70, 0.93)	<0.01
Model 4 ‘lifestyle, diet, and BMI’	1.00	0.90 (0.80, 1.02)	1.00 (0.90, 1.10)	0.95 (0.83, 1.08)	0.49
Fruit fibre, g/day (median)	<2.3 (1.4)	2.3–4.0 (3.1)	4.0–6.6 (5.1)	>6.3 (8.4)	
Model 1 ‘age, sex’	1.00	0.88 (0.82, 0.95)	0.91 (0.83, 1.00)	0.89 (0.81, 0.98)	0.17
Model 2 ‘lifestyle’	1.00	0.91 (0.84, 0.98)	0.96 (0.88, 1.04)	0.93 (0.85, 1.01)	0.41
Model 3 ‘lifestyle and diet’	1.00	0.93 (0.86, 1.00)	0.98 (0.90, 1.06)	0.98 (0.89, 1.08)	0.74
Model 4 ‘lifestyle, diet, and BMI’	1.00	0.91 (0.82, 1.00)	0.93 (0.84, 1.03)	0.96 (0.83, 1.10)	0.76
Vegetable fibre, g/day (median)	<2.4 (1.6)	2.4–3.6 (3.0)	3.6–5.3 (4.4)	>5.3 (6.9)	
Model 1 ‘age, sex’	1.00	0.95 (0.88, 1.02)	0.87 (0.76, 0.98)	0.93 (0.78, 1.11)	0.57
Model 2 ‘lifestyle’	1.00	0.98 (0.91, 1.06)	0.91 (0.81, 1.03)	0.98 (0.85, 1.14)	0.92
Model 3 ‘lifestyle and diet’	1.00	0.94 (0.87, 1.01)	0.82 (0.71, 0.94)	0.84 (0.74, 0.96)	<0.01
Model 4 ‘lifestyle, diet, and BMI’	1.00	0.91 (0.84, 0.99)	0.83 (0.71, 0.97)	0.93 (0.84, 1.03)	0.11

Model 1 was adjusted for age and sex

Model 2 was additionally adjusted for lifestyle factors: smoking status, physical activity, education level and sex-specific alcohol categories

Model 3 was additionally adjusted for dietary factors: energy and energy-adjusted carbohydrates, magnesium, vitamin B<sub>1</sub> and saturated fatty acids

Model 4 was additionally adjusted for BMI

All models for types of fibre were mutually adjusted

HRs were 0.91 (95% CI 0.81, 1.03;  $p$  for trend=0.28) for total fibre, 0.95 (95% CI 0.83, 1.08;  $p$  for trend=0.49) for cereal fibre, 0.96 (95% CI 0.83, 1.10;  $p$  for trend=0.76) for fruit fibre and 0.93 (95% CI 0.84, 1.03;  $p$  for trend=0.11) for vegetable fibre. Adjustment for BMI explained 50% of the association between total fibre and type 2 diabetes. We did not observe substantial between-country heterogeneity for total fibre or sources of fibre ( $I^2=2.6\%$ , 7.0%, 34.3% and 0% for total, cereal, fruit and vegetable fibre, respectively; Fig. 1). The association between dietary fibre and type 2 diabetes was not modified by sex, BMI, physical activity, smoking, magnesium intake, vitamin B<sub>1</sub> intake, glycaemic index or glycaemic load (all  $p>0.05$ ). The results were not materially altered in several sensitivity analyses (see ESM results).

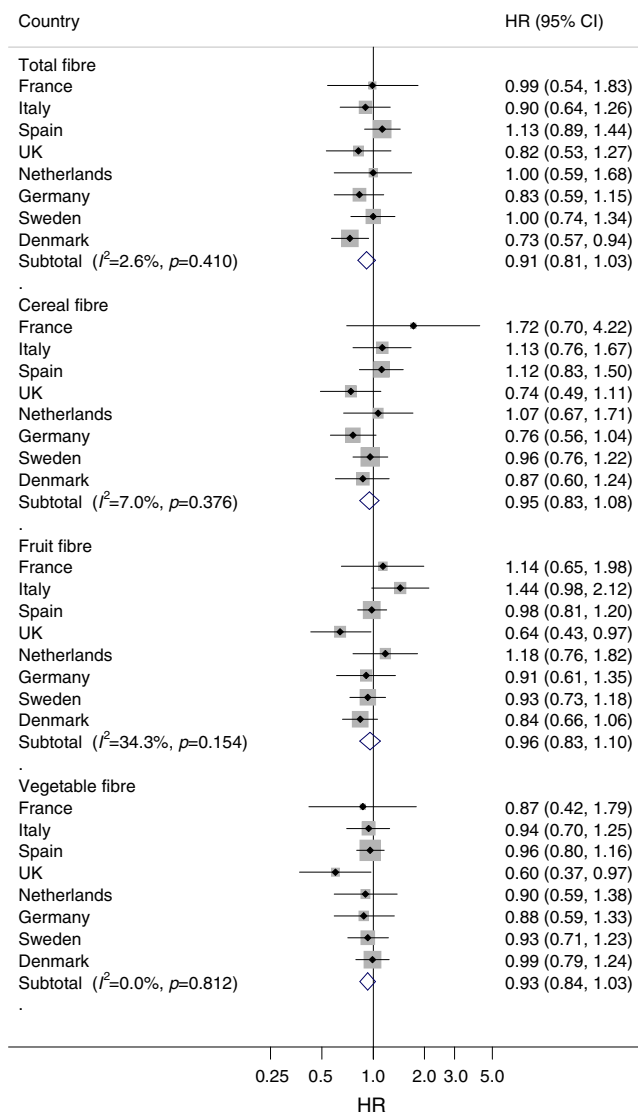
## Meta-analysis

Eighteen independent cohorts (20 publications) [5–10, 26–39] in addition to the EPIC-InterAct study were included in the meta-analysis, with a total of 617,968 participants and 41,066 incident cases of type 2 diabetes (Table 3, ESM Fig. 1). The study characteristics of the cohorts are provided in Table 3. Of

the 19 cohort studies, eight were conducted in the USA, five in Europe, three in Australia and three in Asia.

**Total fibre** Sixteen studies [6–10, 26, 28–30, 32–34, 36–39] in addition to the EPIC-InterAct Study were included in the analysis of total fibre and type 2 diabetes (36,578 cases among 572, 665 participants). Two of the studies [37, 38] were only included in the analysis of the highest vs the lowest intake. The summary RR comparing the highest vs the lowest intake was 0.85 (95% CI 0.77, 0.94;  $I^2$  61.0%,  $p_{\text{heterogeneity}}=0.002$ ,  $n=13$ ) (ESM Fig. 2a), and in the dose–response analysis the summary RR per 10 g/day was 0.91 (95% CI 0.87, 0.96;  $I^2$  29.4%,  $p_{\text{heterogeneity}}=0.14$ ,  $n=15$ ) (Fig. 2a). There was no evidence of non-linearity, with  $p_{\text{non-linearity}}=0.37$  (Fig. 2b, ESM Table 2).

**Cereal fibre** Twelve studies (13 publications) [6, 8–10, 26–33, 35] in addition to the EPIC-InterAct Study were included in the analysis (30,224 cases and 455,563 participants). One of the studies [32] was only included in the analysis of the highest vs the lowest intake. The summary RR for the highest vs the lowest cereal fibre intake was 0.77 (95% CI 0.68, 0.87;  $I^2$  77.7%,  $p_{\text{heterogeneity}}<0.0001$ ,  $n=12$ ) (ESM Fig. 2b) and per 10 g/day was 0.75 (95% CI 0.65, 0.86;  $I^2=75.1\%$ ,  $p_{\text{heterogeneity}}$



**Fig. 1** Association between cereal fibre, fruit fibre and vegetable fibre consumption and risk of type 2 diabetes in the EPIC-InterAct study ( $n=26,088$ ). Country-specific HR<sub>Q4 vs Q1</sub> (95% CIs) were pooled using random effects meta-analysis. HRs were adjusted for sex, smoking status, physical activity, education level, sex-specific alcohol categories, energy, energy-adjusted carbohydrate, magnesium intake, vitamin B<sub>1</sub> intake, saturated fatty acids and BMI. The x-axis is on a log scale

$<0.0001$ ,  $n=12$ ) (Fig. 2c). There was evidence of non-linearity ( $p_{\text{non-linearity}}=0.004$ ), with a steeper reduction in risk at higher levels of fibre intake (Fig. 2d, ESM Table 2).

**Fruit fibre** Ten studies [6, 8–10, 26, 28–30, 33, 36] in addition to the EPIC-InterAct Study were included in the analysis (25,715 cases among 408,416 participants). The summary RR for the highest vs the lowest intake of fruit fibre was 0.95 (95% CI 0.88, 1.01;  $I^2$  16.9%,  $p_{\text{heterogeneity}}=0.29$ ,  $n=10$ ) (ESM Fig. 2c) and per 10 g/day was 0.95 (95% CI 0.87, 1.03,  $I^2$  31.1%,  $p_{\text{heterogeneity}}=0.15$ ,  $n=11$ ) (Fig. 3a). There was a suggestive non-linear association between fruit fibre and risk of type 2 diabetes ( $p_{\text{non-linearity}}=0.04$ ), with a slightly

steeper curve when increasing intake from low levels, but the association was very weak (Fig. 3b, ESM Table 2).

**Vegetable fibre** Ten studies [6, 8–10, 26, 29, 30, 32, 33, 36] in addition to the EPIC-InterAct Study were included in the analysis (24,428 cases among 399,593 participants). One of the studies [32] was only included in the analysis of the highest vs the lowest intake. The summary RR for the highest vs the lowest intake was 0.96 (95% CI 0.86, 1.07;  $I^2$  48.3%,  $p_{\text{heterogeneity}}=0.04$ ,  $n=10$ ) (ESM Fig. 2d) and per 10 g/day was 0.93 (95% CI 0.82, 1.05;  $I^2=43.5\%$ ,  $p_{\text{heterogeneity}}=0.07$ ,  $n=10$ ) (Fig. 3c). There was evidence of a non-linear association between vegetable fibre and risk of type 2 diabetes, ( $p_{\text{non-linearity}}<0.0001$ ), with an inverse association restricted to a very high intake (12–14 g/day) (Fig. 3d, ESM Table 2).

**Soluble and insoluble fibre** Only three studies [5, 6, 10] investigated the intake of soluble and insoluble fibre and risk of diabetes (2,141 cases among 65,373 participants). The summary RR for the highest vs the lowest intake was 0.85 (95% CI 0.72, 1.01;  $I^2=41.9\%$ ,  $p_{\text{heterogeneity}}=0.18$ ) for soluble fibre and 0.75 (95% CI 0.57, 0.97;  $I^2=0\%$ ,  $p_{\text{heterogeneity}}=0.44$ ) (ESM Fig. 3a, b) for insoluble fibre. In the dose–response analysis, the summary RR per 10 g/day was 0.70 (95% CI 0.47, 1.04;  $I^2=0\%$ ,  $p_{\text{heterogeneity}}=0.50$ ) for soluble fibre and 0.73 (95% CI 0.62, 0.86;  $I^2=0\%$ ,  $p_{\text{heterogeneity}}=0.46$ ) for insoluble fibre (ESM Fig. 3c, d).

**Subgroup, sensitivity analyses and publication bias** The results were in general consistent across the strata in the subgroup (ESM Tables 3 and 4) and sensitivity analyses (ESM results). Most of the studies adjusted for BMI, and the results persisted among studies that adjusted for BMI (ESM Tables 3 and 4). In the analysis of cereal fibre there was a suggestion of small-study bias with Egger's test ( $p=0.08$ ) and asymmetry in the funnel plot suggesting that smaller studies with positive associations were missing (ESM Fig. 4). When restricting the analysis to four studies [10, 28, 31, 33] and the EPIC-InterAct study that had  $\geq 1,000$  cases, Egger's test was no longer significant ( $p=0.25$ ), but the inverse association was similar to the overall analysis (summary RR 0.76; 95% CI 0.63, 0.92;  $I^2=81.0\%$ ,  $p_{\text{heterogeneity}}<0.0001$ ). There was no evidence of publication bias for total fibre, fruit fibre or vegetable fibre ( $p=0.16$ ,  $p=0.73$  and  $p=0.74$ , respectively).

## Discussion

The EPIC-InterAct study showed that a high intake of total fibre compared with a low intake was associated with an 18% lower risk of incident type 2 diabetes when adjusted for life-style and dietary factors. This was mainly driven by the intake of cereal fibre and vegetable fibre, and not by fruit fibre. When

**Table 3** Prospective studies of dietary fibre intake and type 2 diabetes included in the meta-analysis

Author, publication year, country/region	Study name	Population	Follow-up (years)	Age at baseline (range in years)	No. of cases	Dietary assessment	Exposure	Quantity	RR (95% CI)	Adjustment for confounders
Hodge et al. 1993, Australia [39]	NA	350 M/W	5	>20	7	24 h dietary recall	Total fibre	Per 10 g/day	0.69 (0.16, 2.96)	Age, sex, BMI, energy
Salmiron et al. 1997, USA [8]	Nurses' Health Study	85,173 W	6	40-65	915	Validated FFO, 134 food items	Total fibre Cereal fibre Fruit fibre	24.1 vs 11.8 g/day 7.5 vs 2.0 g/day 7.6 vs 1.4 g/day	0.78 (0.62, 0.98) 0.72 (0.58, 0.90) 0.87 (0.70, 1.08)	Age, BMI, alcohol, smoking, physical activity, family history of diabetes, energy
Salmiron et al. 1997, USA [26]	Health Professionals Follow-up Study	42,759 M	6	40-75	523	Validated FFO, 131 food items	Vegetable fibre Total fibre Cereal fibre Fruit fibre	9.6 vs 3.4 g/day 29.7 vs 13.4 g/day 10.2 vs 2.5 g/day 8.3 vs 1.2 g/day	1.17 (0.93, 1.46) 0.98 (0.73, 1.33) 0.70 (0.51, 0.96) 1.01 (0.76, 1.36)	Age, BMI, alcohol, smoking, physical activity, family history of diabetes, energy
Meyer et al. 2000, USA [10]	Iowa Women's Health	35,988 W	6	55-69	1,141	Validated FFO, 127 food items	Vegetable fibre Total fibre Cereal fibre Fruit fibre	11.3 vs 3.5 g/day 26.5 vs 13.27 g/day 9.43 vs 2.66 g/day 8.72 vs 1.71 g/day	1.12 (0.84, 1.49) 0.78 (0.64, 0.96) 0.64 (0.53, 0.79) 1.17 (0.96, 1.42)	Age, BMI, WHR, alcohol, smoking, physical activity, education level, energy intake
Hu et al. 2001, USA [27]	Nurses' Health Study	84,941 W	16	34-59	3,300	Validated FFO, 61-120 food items	Vegetable fibre Soluble fibre Insoluble fibre Cereal fibre	11.74 vs 4.71 g/day 8.01 vs 4.19 g/day 19.84 vs 9.93 g/day Quintile 5 vs 1	0.97 (0.80, 1.18) 0.89 (0.73, 1.08) 0.75 (0.61, 0.91) 0.59 (0.52, 0.68)	Age, time, family history of diabetes, menopausal status, HT, smoking status, BMI, moderate-to-vigorous exercise, alcohol, TEA, PUFA/SFA ratio, GL
Stevens et al. 2002, USA [28]	Atherosclerosis Risk in Communities Study	9,529 M/W white participants, 2,722 M/W AA participants	9	45-64	971 and 478	Validated FFO, 66 food items	Total fibre, whites Cereal fibre, whites Fruit fibre, whites	Per 1 g/day Per 1 g/day Per 1 g/day	0.999 (0.987, 1.012) 0.956 (0.925, 0.987) 1.002 (0.983, 1.021)	Age, sex, BMI, smoking, physical activity, education level, field centre, energy
Montonen et al. 2003, Finland [6]	Finnish Mobile Clinic Health Examination Survey	4,318 M/W	10	40-69	156	FFQ, 100 food items	Total fibre, AA Cereal fibre, AA Fruit fibre, AA	Per 1 g/day Per 1 g/day Per 1 g/day	0.998 (0.980, 1.017) 0.982 (0.927, 1.039) 1.009 (0.985, 1.033)	
Schulze et al. 2004, USA [9]	Nurses' Health Study II	91,249 W	8	26-46	741	Validated FFO, 133 food items	Cereal fibre, whites Cereal fibre, AA Total fibre Cereal fibre Fruit fibre Vegetable fibre Soluble fibre Insoluble fibre	Quintile 5 vs 1 Quintile 5 vs 1 ≥33.2 vs ≤19.2 g/day ≥24.5 vs ≤12.0 g/day ≥3.4 vs ≤0.99 g/day ≥26.5 vs ≤3.7 g/day ≥7.4 vs ≤4.5 g/day ≥16.6 vs ≤8.7 g/day	0.75 (0.60, 0.92) 0.86 (0.65, 1.15) 0.51 (0.26, 1.00) 0.39 (0.20, 0.77) 0.92 (0.40, 2.13) 1.19 (0.46, 3.04) 0.57 (0.29, 1.12) 0.47 (0.25, 0.91)	Age, sex, geographical area, smoking BMI, intakes of energy, fruit and berries, vegetables
Schulze et al. 2004, USA [9]	Nurses' Health Study II	91,249 W	8	26-46	741	Validated FFO, 133 food items	Total fibre Cereal fibre Fruit fibre Vegetable fibre	24.9 vs 12.5 g/day 8.8 vs 3.1 g/day 6.2 vs 1.1 g/day 10.4 vs 3.4 g/day	1.00 (0.75, 1.34) 0.64 (0.48, 0.86) 0.79 (0.60, 1.02) 1.12 (0.87, 1.46)	Age, BMI, alcohol, smoking, physical activity, family history of diabetes, high blood pressure, high blood cholesterol, HT, OC use, energy intake, Mg, and caffeine, GL, mutual adjustment between fibre types
Hodge et al. 2004, Australia [29]	Melbourne Collaborative Cohort Study	31,641 M/W	4	40-69	365	FFQ, 121 food items	Fibre Cereal fibre Fruit fibre	Per 20 g/day Per 10 g/day Per 10 g/day	1.02 (0.81, 1.30) 1.08 (0.88, 1.32) 0.97 (0.81, 1.16)	Age, sex, BMI, WHR, weight change, alcohol, smoking, physical activity, family history of diabetes, education, country of birth, energy intake
Linksröm et al. 2006, Finland [7]	The Finnish Diabetes Prevention Study	172 M, 350 W	4.1	40-64	114	3 day food record	Vegetable fibre Fibre	Per 5 g/day ≥15.55 vs <10.85 g/4,1868 MI/day	1.00 (0.86, 1.17) 0.38 (0.19, 0.77)	Age, sex, baseline weight, baseline 2 h glucose, physical activity, weight change, energy
Barclay et al. 2007, Australia [30]	Blue Mountains Eye Study	1,833 M/W	10	≥49	138	Validated FFO, 145 food items	Fibre Cereal fibre Fruit fibre Vegetable fibre	Per 5 g/day Per 5 g/day Per 5 g/day Per 5 g/day	0.90 (0.79, 1.02) 0.96 (0.78, 1.20) 0.94 (0.78, 1.15) 0.76 (0.57, 0.99)	Age, sex, smoking, physical activity, family history of diabetes, triacylglycerols, HDL, cholesterol

Table 3 (continued)

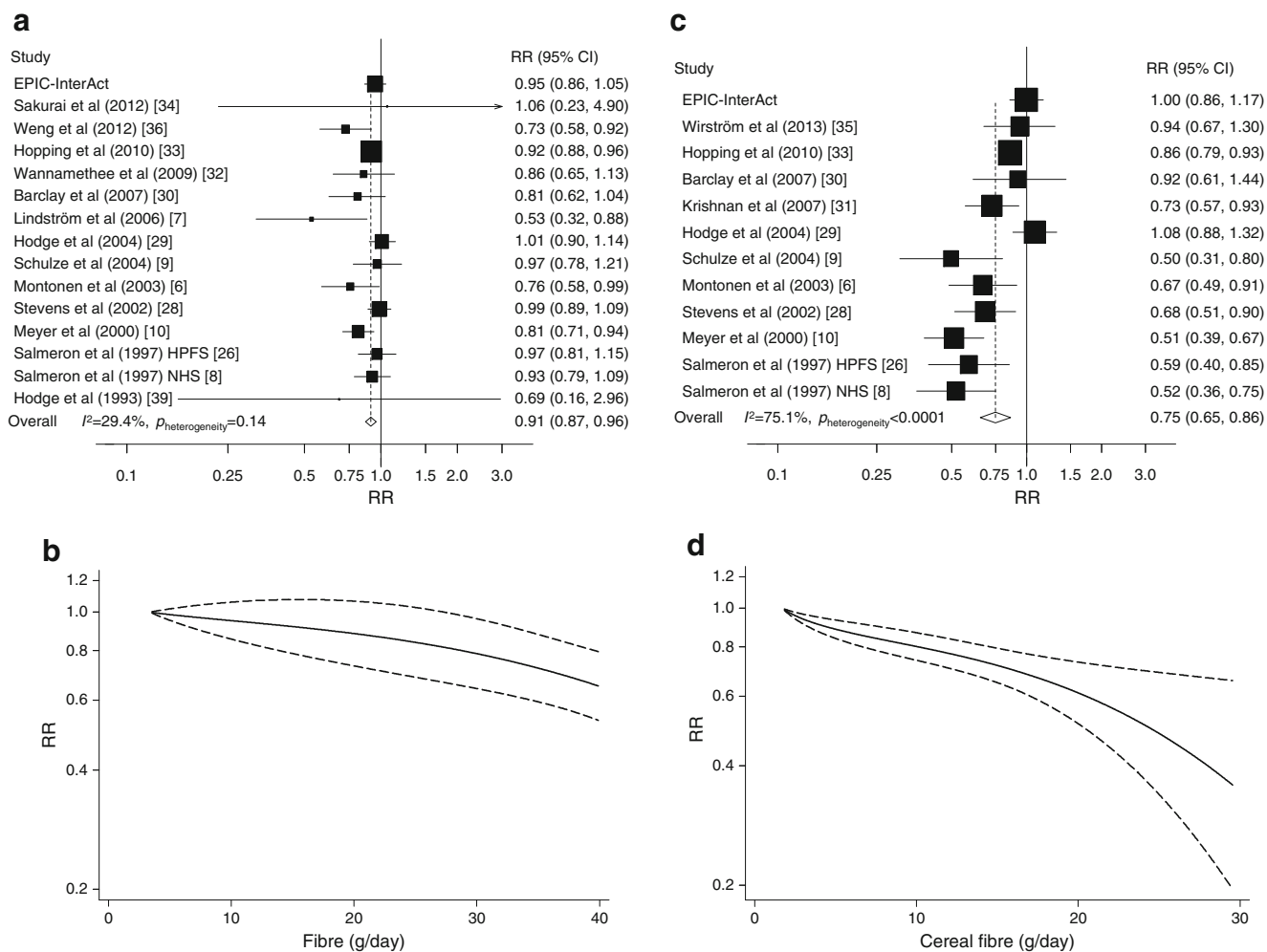
Author, publication year, country/ region	Study name	Population	Follow-up (years)	Age at baseline (range in years)	No. of cases	Dietary assessment	Exposure	Quantity	RR (95% CI)	Adjustment for confounders
Krishnan et al. 2007, USA [31]	Black Women's Health Study	40,078 W	8	21–69	1,938	Validated FFQ, 68 food items	Cereal fibre	7.6 vs 1.7 g/day	0.82 (0.70, 0.96)	Age, BMI, smoking, physical activity, family history of diabetes, total fat, protein intake, GI, energy intake
Schulze et al. 2007, Germany [5]	EPIC-Potsdam	9,702 M, 15,365 W	7	35–65	844	Validated FFQ	Soluble fibre Insoluble fibre	9.6 vs 5.3 g/day 18.4 vs 10.3 g/day	0.83 (0.57, 1.22) 0.93 (0.62, 1.40)	Age, sex, BMI, sports activities, education, cycling, occupational activity, smoking, alcohol, total energy intake, waist circumference, PUFA:SFA ratio, MUFA:SFA ratio, carbohydrate, Mg
Wannamethee et al. 2009, UK [32]	British Regional Heart Study	3,428 M	7	60–79	162	Validated 7 day recall FFQ	Total fibre Cereal fibre Vegetable fibre	≥1.0 vs ≤2.0 g/day Quartile 4 vs 1 Quartile 4 vs 1	0.82 (0.51, 1.32) 0.70 (0.44, 1.12) 0.74 (0.46, 1.19)	Age, waist circumference, alcohol, smoking, physical activity, social class, pre-existing MI or stroke, statin use, energy intake
Hopping et al. 2010, USA [33]	Multietnic cohort	36,256 M, 39,256 W	14	45–75	4,555 and 4,032	Validated FFQ	Total fibre, M Cereal fibre, M Fruit fibre, M Vegetable fibre, M Total fibre, W Cereal fibre, W Fruit fibre, W Vegetable fibre, W Fibre	14.2 vs 7.4 g/4,1868 MJ/day 4.8 vs <1.9 g/4,1868 MJ/day 3.9 vs <0.8 g/4,1868 MJ/day 5.3 vs <2.2 g/4,1868 MJ/day 16.2 vs <8.9 g/4,1868 MJ/day 5.1 vs <2.1 g/4,1868 MJ/day 5.1 vs <2.1 g/4,1868 MJ/day 5.2 vs <1.3 g/4,1868 MJ/day >6.0 vs <3.7 g/day	0.75 (0.67, 0.84) 0.91 (0.82, 1.00) 0.93 (0.84, 1.02) 0.78 (0.69, 0.88) 0.95 (0.85, 1.06) 0.88 (0.79, 0.97) 0.95 (0.85, 1.06) 0.96 (0.87, 1.08) 0.99 (0.59, 1.66)	Age, BMI, physical activity, education, ethnicity, energy intake
Sakurai et al. 2012, Japan [34]	NA	1,995 M	6	35–55	133	DHQ, 147 items	Fibre	>6.0 vs <3.7 g/day	0.99 (0.59, 1.66)	Age, BMI, family history of diabetes, exercise, hypertension, hyperlipidaemia, total energy, GI, GL
Wirström et al. 2013, Sweden [35]	NA	5,477 M/W	8–10	35–56	165	Validated FFQ, NA	Cereal fibre	Per 10 g/day >11.6 vs <7.7 g/day	0.97 (0.82, 1.14) 1.02 (0.68, 1.52)	Age, family history of diabetes, BMI, leisure-time physical activity, smoking, education, blood pressure
Liu et al. 2012, China [37]	NA	3,461 M/W	>5	35–74	162	NA	Total fibre	High vs low	0.38 (0.17, 0.87)	Age, sex, family history of diabetes, blood pressure, triacylglycerols, fasting glucose
Weng et al. 2012, Taiwan [36]	Cardiovascular Disease risk FAC for Two-township Study	1,604 M/W	4.6	>30	141	Validated FFQ, 49 food items	Total fibre Fruit fibre Vegetable fibre	43.3 vs 20.4 g/day 20.6 vs 3.1 g/day 15.8 vs 3.2 g/day	0.49 (0.28, 0.85) <sup>a</sup> 0.55 (0.32, 0.95) <sup>a</sup> 0.45 (0.25, 0.82) <sup>a</sup>	Age, sex, age-sex interaction, calories, residential area, family history of diabetes, BMI, central obesity, smoking, drinking, physical activity, hypertension, hypercholesterolaemia, hypertriglycerolaemia, low HDL-cholesterol
Qiao et al. 2014, USA [38]	Women's Health Initiative	154,493 W	7.6	50–79	10,285	Validated FFQ	Total fibre	≥13.14 vs <13.14 g/day	0.98 (0.93, 1.04)	Age, education, cigarette smoking, BMI, WHR, physical activity, family history of diabetes, study arms, HT use
Present study, Europe	EPIC-InterAct	26,088 M/W	10.8	20–79	11,559	Validated FFQs, diet history, 7 day food diaries	Total fibre Cereal fibre Fruit fibre Vegetable fibre	>26.4 vs <18.9 g/day >10.9 vs <5.7 g/day >6.3 vs <2.3 g/day >5.3 vs <2.4 g/day	0.91 (0.81, 1.03) 0.95 (0.83, 1.08) 0.96 (0.83, 1.10) 0.93 (0.84, 1.03)	Age, sex, smoking status, physical activity, education level, alcohol, energy intake, carbohydrates, Mg, vitamin B1, SFA, BMI

4.1868 MJ/day=1,000 kcal/day

<sup>a</sup> Risk estimates provided in the article were for a low vs high (reference) comparison. For consistency with the remaining studies, these risk estimates have been converted so the comparison is for the highest vs the lowest intake

AA, African-American; DHQ, diet history questionnaire; FFQ, food frequency questionnaire; GI, glycaemic index; GL, glycaemic load; HT, hormone therapy; M, men; MI, myocardial infarction; MUFA, monounsaturated fatty acids; OC, oral contraceptive; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids; TFA, *trans* fatty acids; W, women





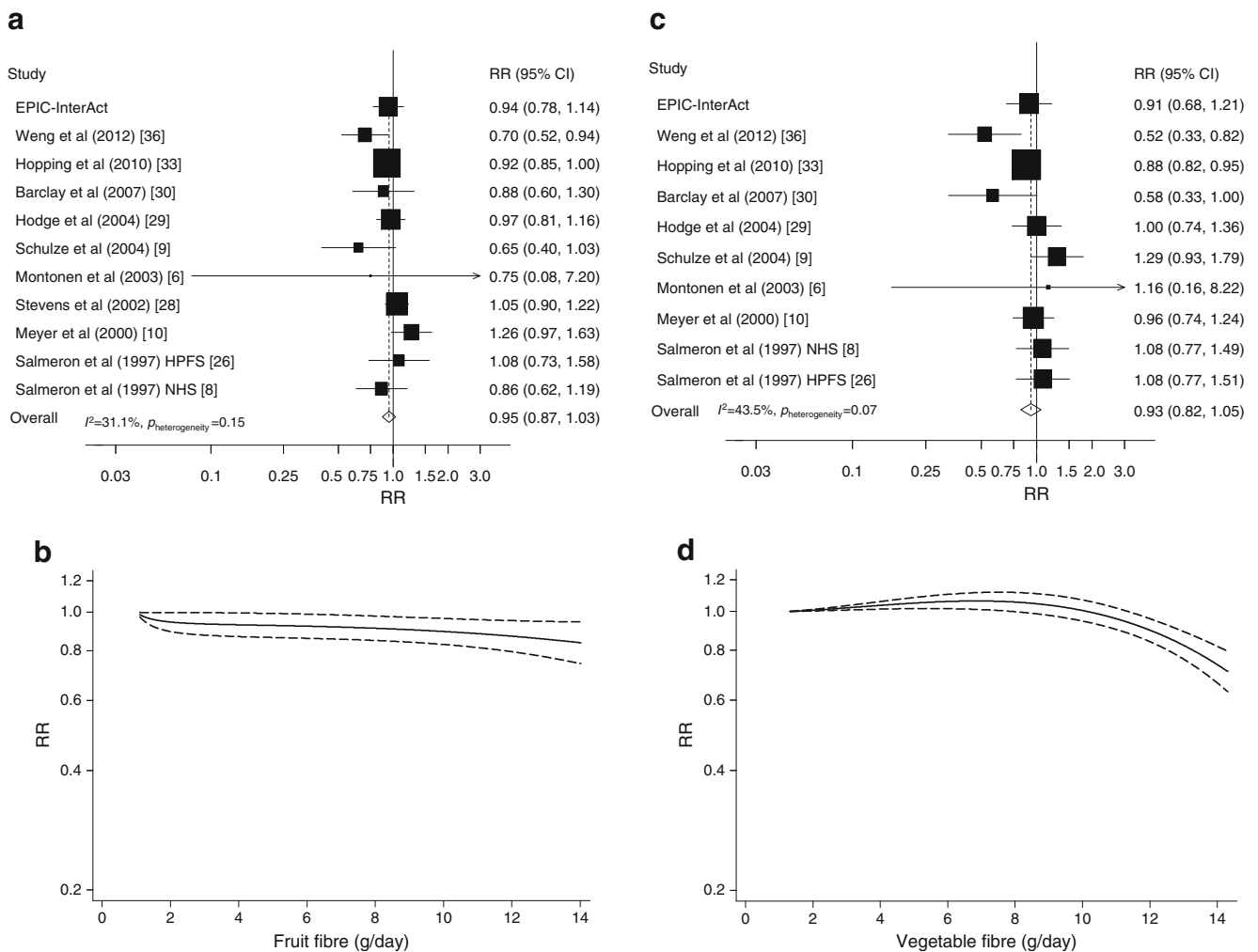
**Fig. 2** Dietary total fibre (**a, b**) and cereal fibre (**c, d**) and type 2 diabetes, linear dose–response meta-analyses per 10 g/day (**a, c**) and non-linear dose–response meta-analyses (**b, d**). In (**a**) and (**c**), the RR of each study is represented by a square, and the size of the square represents the weight of each study to the overall estimate. The 95% CIs are represented by

horizontal lines, and the diamond represents the overall estimate and its 95% CI. The x-axis is on a log scale. In (**b**) and (**d**), the solid lines represent the best-fitting fractional polynomial, and the dashed lines represent 95% CIs

the results were adjusted for BMI, total fibre and cereal and vegetable fibre were not significantly associated with risk of type 2 diabetes. However, the findings from our updated meta-analysis of prospective studies do support an inverse association between total fibre and cereal fibre intake and risk of type 2 diabetes, with a 9% and 25% lower RR per 10 g/day, respectively, independent of BMI. A stronger inverse association between cereal fibre intake and type 2 diabetes than for fruit or vegetable fibre is consistent with previous meta-analyses of fibre intake and type 2 diabetes [5, 43], and with recent meta-analyses that have shown stronger associations for whole grain intake [44] than for fruit and vegetable intake in relation to risk of type 2 diabetes [45]. Differences in the strength and shape of the dose–response relationship compared with the previous meta-analyses [5, 43] may be due to the larger number of studies that was included in the present dose–response analyses and the addition of the EPIC-InterAct data. For

example, in the linear dose–response analysis of dietary fibre, we included seven additional studies [6–8, 26, 33, 34, 39] as well as the present EPIC-InterAct study.

It has been suggested that the beneficial effect of cereal fibre observed in many studies could be explained by other nutrients co-ingested with the fibre, for example magnesium and vitamins such as B<sub>1</sub>, C and E [46]. In the EPIC-InterAct study, adding these nutrients to the models did not materially alter the association with cereal fibre. It is also possible that the low glycaemic index of diets high in total or cereal fibre could explain the relationship between fibre intake and diabetes. A low glycaemic index could lead to a lower postprandial glucose peak, which leads to a decreased insulin demand and protects the pancreas from exhaustion [47]. However, no association was observed between the glycaemic index or glycaemic load and diabetes in the EPIC-InterAct study [48], and further adjustment for both glycaemic index



**Fig. 3** Fruit fibre (**a, b**) and vegetable fibre (**c, d**) and type 2 diabetes, linear dose–response meta-analyses per 10 g/day (**a, c**) and non-linear dose–response meta-analyses (**b, d**). In (**a**) and (**c**), the RR of each study is represented by a square and the size of the square represents the weight of each study to the overall estimate. The 95% CIs are represented by

horizontal lines, and the diamond represents the overall estimate and its 95% CI. The x-axis is on a log scale. In (**b**) and (**d**), the solid lines represent the best-fitting fractional polynomial, and the dashed lines represent 95% CIs

and glycaemic load did not change our results. This is consistent with other studies that have found little impact of additional adjustments for glycaemic index, glycaemic load and/or magnesium intake [9, 31, 34]. The intake of fruit fibre was not associated with type 2 diabetes in any of the models, but it is not clear why this is as the range of fruit fibre intake was comparable to that of other studies.

Our study has some limitations that could have affected the results. Measurement error in the assessment of dietary intake by questionnaire may have attenuated an association between fibre intake and type 2 diabetes. Different degrees of measurement error in the assessment of subtypes of fibre intake might explain the different magnitude of association observed with these subtypes. Dietary intake was assessed only at baseline, so we were not able to take into account dietary changes during follow-up. The strengths of the EPIC-InterAct study

include the prospective design, the large number of cases, the extensive and validated dietary questionnaires, the wide range of dietary fibre intake in eight countries with a large variation in the different sources of fibre intake, and the detailed information on other potential confounders, including height and weight, which were measured in most of the study participants and may have reduced potential confounding by adiposity.

We cannot exclude the possibility that the inverse associations for total fibre and cereal fibre intake in the meta-analysis could be due to residual confounding as fibre intake has been associated with a healthier overall dietary pattern, a lower BMI and higher physical activity [6, 9, 10, 31]. Although most studies adjusted for BMI, physical activity, alcohol, smoking and energy intake, relatively few studies adjusted for other dietary factors. However, in the EPIC-InterAct study, adjustment for other dietary factors did not substantially alter the risk

estimates. It is not clear why our result differs from the result of the meta-analysis. Weight and height were measured (rather than self-reported) in EPIC-InterAct. In general, adjustment for confounding with an imperfect measure of that confounder leads to the possibility of residual confounding. This is possible in this context as some other studies have used more imprecise measures, such as self-reported BMI, and could therefore have more issues with residual confounding. Of 11 studies of cereal fibre that adjusted for BMI, all six studies with self-reported weight and height reported inverse associations [8–10, 26, 31, 33], while only two [6, 28] out of five of the studies [6, 28, 29, 35] (including EPIC-InterAct) with measured weight and height reported significant inverse associations. However, data for other fibre types and total fibre do not appear to vary by whether weight and height was measured or self-reported, so chance can also not be excluded as an explanation.

In the meta-analysis of cereal fibre, there was some suggestion of small-study bias. However, when the analysis was restricted to studies with a large number of cases ( $\geq 1,000$ ), there was no evidence of asymmetry in the funnel plot and Egger's test was no longer significant, although the summary estimate was similar to that of the overall analysis.

The attenuation of the inverse associations we observed between total fibre, cereal fibre and vegetable fibre and diabetes after adjustment for BMI in the EPIC-InterAct analysis suggests that the beneficial effect of fibre may be partly mediated by a lower BMI, and this is consistent with other studies [5, 33]. A previous analysis in the EPIC study found an inverse association between fibre intake, particularly cereal fibre intake, and changes in weight and waist circumference [49], and other studies have also shown an inverse association between fibre intake and overweight, obesity, weight gain or visceral adiposity [50–54], although the data are not convincing [55]. However, as the observed effects of fibre intake on adiposity and weight change are relatively modest, BMI may act as both a confounder and a mediator in the relationship between fibre intake and diabetes. Dietary fibre may affect appetite and energy intake through a range of processes including a delayed emptying rate, a prolonged release of hormonal signals, a slowing of nutrient absorption or altered fermentation in the large intestine [51, 56].

Apart from reduced adiposity, dietary fibre may affect the risk of diabetes by other mechanisms as well. Dietary fibre intake improves glycaemic control by decreasing postprandial glycaemia and insulinaemia, and increases insulin sensitivity [57, 58]. There is also a cross-sectional association between the consumption of high-fibre breakfasts and markers of diabetes risk in children [59]. The fermentation of dietary fibres in the large intestine may alter the growth of specific gut bacteria, affect the production and composition of short-chain fatty acids and thereby affect the secretion of appetite-regulating peptides [60]. Furthermore, fermentable fibres may regulate the uptake of energy from the gut by the production or activation of

signalling molecules involved in the host's metabolism, a modification of gut permeability, the release of gut hormones and inflammation [61]. Based on intervention studies, the effect on glycaemic control appears to be stronger for soluble fibre than for insoluble fibre [62, 63], while in the meta-analysis we found an association with insoluble fibre and cereal fibre (which is high in insoluble fibre), but not with soluble fibre. Limited statistical power because of the low number of studies might explain the lack of association for soluble fibre as the risk estimates were of similar size, but further studies are needed to clarify whether there is a difference in the association between soluble and insoluble fibre and risk of diabetes.

In several, but not all, studies [64, 65], dietary fibre, cereal fibre and whole grains have been associated with lower concentrations of inflammatory markers [66–69], serum uric acid [70] and  $\gamma$ -glutamyltransferase [67, 71], markers that have been associated with increased risk of diabetes [72–74] and higher concentrations of adiponectin [75–77], an adipocyte-secreted cytokine that increases insulin sensitivity and may reduce risk of diabetes [78]. Alternatively, it is possible that other components of foods rich in cereal fibre such as whole grains could contribute to the reduced risk of diabetes by as yet unidentified mechanisms.

In summary, inverse associations were observed between the intake of total, cereal and vegetable fibre and risk of type 2 diabetes in the EPIC-InterAct study, but these associations were no longer significant after adjustment for BMI. In an up-to-date meta-analysis of all published prospective studies, we found an inverse association between total fibre and cereal fibre and risk of type 2 diabetes independent of BMI. Taken together, the results indicate that individuals with a diet rich in fibre, especially cereal fibre, may have a lower risk of type 2 diabetes.

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**Contribution statement** AK, EJM and MBS were responsible for the conception of the study. AK and DA analysed the data and wrote the first draft of the manuscript. All authors contributed to the interpretation of the data, revised the article critically for important intellectual content, and approved the final version of the paper to be published. AK and DA are responsible for the integrity of the work as a whole and are the guarantors of this work.

**Conflict of interest** The authors declare that there is no duality of interest associated with this manuscript.

## Appendix

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## References

- Whiting DR, Guariguata L, Weil C, Shaw J (2011) IDF diabetes atlas: global estimates of the prevalence of diabetes for 2011 and 2030. *Diabetes Res Clin Pract* 94:311–321
- Seshasai SR, Kaptoge S, Thompson A et al (2011) Diabetes mellitus, fasting glucose, and risk of cause-specific death. *N Engl J Med* 364:829–841
- Campbell PT, Newton CC, Patel AV, Jacobs EJ, Gapstur SM (2012) Diabetes and cause-specific mortality in a prospective cohort of one million U.S. adults. *Diabetes Care* 35:1835–1844
- Anonymous (2013) Economic costs of diabetes in the U.S. in 2012. *Diabetes Care* 36:1033–1046
- Schulze MB, Schulz M, Heidemann C, Schienkiewitz A, Hoffmann K, Boeing H (2007) Fiber and magnesium intake and incidence of type 2 diabetes: a prospective study and meta-analysis. *Arch Intern Med* 167:956–965
- Montonen J, Knekt P, Jarvinen R, Aromaa A, Reunanen A (2003) Whole-grain and fiber intake and the incidence of type 2 diabetes. *Am J Clin Nutr* 77:622–629
- Lindström J, Peltonen M, Eriksson JG et al (2006) High-fibre, low-fat diet predicts long-term weight loss and decreased type 2 diabetes risk: the Finnish Diabetes Prevention Study. *Diabetologia* 49:912–920
- Salmemon J, Manson JE, Stampfer MJ, Colditz GA, Wing AL, Willett WC (1997) Dietary fiber, glycemic load, and risk of non-insulin-dependent diabetes mellitus in women. *JAMA* 277:472–477
- Schulze MB, Liu S, Rimm EB, Manson JE, Willett WC, Hu FB (2004) Glycemic index, glycemic load, and dietary fiber intake and incidence of type 2 diabetes in younger and middle-aged women. *Am J Clin Nutr* 80:348–356
- Meyer KA, Kushi LH, Jacobs DR Jr, Slavin J, Sellers TA, Folsom AR (2000) Carbohydrates, dietary fiber, and incident type 2 diabetes in older women. *Am J Clin Nutr* 71:921–930
- Kumar V, Sinha AK, Makkar HP, de Boeck G, Becker K (2012) Dietary roles of non-starch polysaccharides in human nutrition: a review. *Crit Rev Food Sci Nutr* 52:899–935
- Riboli E, Hunt KJ, Slimani N et al (2002) European Prospective Investigation into Cancer and Nutrition (EPIC): study populations and data collection. *Public Health Nutr* 5:1113–1124
- Riboli E, Kaaks R (1997) The EPIC Project: rationale and study design. *European Prospective Investigation into Cancer and Nutrition. Int J Epidemiol* 26(Suppl 1):S6–S14
- Langenberg C, Sharp S, Forouhi NG et al (2011) Design and cohort description of the InterAct project: an examination of the interaction of genetic and lifestyle factors on the incidence of type 2 diabetes in the EPIC Study. *Diabetologia* 54:2272–2282
- Kroke A, Klipstein-Grobusch K, Voss S et al (1999) Validation of a self-administered food-frequency questionnaire administered in the European Prospective Investigation into Cancer and Nutrition (EPIC) study: comparison of energy, protein, and macronutrient intakes estimated with the doubly labeled water, urinary nitrogen, and repeated 24-h dietary recall methods. *Am J Clin Nutr* 70:439–447
- Margetts BM, Pietinen P (1997) European Prospective Investigation into Cancer and Nutrition: validity studies on dietary assessment methods. *Int J Epidemiol* 26(Suppl 1):S1–S5
- Slimani N, Deharveng G, Unwin I et al (2007) The EPIC Nutrient Database project (ENDB): a first attempt to standardize nutrient databases across the 10 European countries participating in the EPIC study. *Eur J Clin Nutr* 61:1037–1056
- Cust AE, Skilton MR, van Bakel MM et al (2009) Total dietary carbohydrate, sugar, starch and fibre intakes in the European Prospective Investigation into Cancer and Nutrition. *Eur J Clin Nutr* 63(Suppl 4):S37–S60
- DeVries JW, Rader JI (2005) Historical perspective as a guide for identifying and developing applicable methods for dietary fiber. *J AOAC Int* 88:1349–1366
- Wareham NJ, Jakes RW, Rennie KL et al (2003) Validity and repeatability of a simple index derived from the short physical activity questionnaire used in the European Prospective Investigation into Cancer and Nutrition (EPIC) study. *Public Health Nutr* 6:407–413
- The InterAct Consortium (2012) Physical activity reduces the risk of incident type 2 diabetes in general and in abdominally lean and obese men and women: the EPIC-InterAct Study. *Diabetologia* 55:1944–1952
- Willett WC, Howe GR, Kushi LH (1997) Adjustment for total energy intake in epidemiologic studies. *Am J Clin Nutr* 65:1220S–1228S
- Onland-Moret NC, van der A DL, van der Schouw YT et al (2007) Analysis of case-cohort data: a comparison of different methods. *J Clin Epidemiol* 60:350–355
- Riley RD, Higgins JP, Deeks JJ (2011) Interpretation of random effects meta-analyses. *BMJ* 342:d549
- Higgins JP, Thompson SG (2002) Quantifying heterogeneity in a meta-analysis. *Stat Med* 21:1539–1558
- Salmemon J, Ascherio A, Rimm EB et al (1997) Dietary fiber, glycemic load, and risk of NIDDM in men. *Diabetes Care* 20:545–550

27. Hu FB, Manson JE, Stampfer MJ et al (2001) Diet, lifestyle, and the risk of type 2 diabetes mellitus in women. *N Engl J Med* 345:790–797
28. Stevens J, Ahn K, Juhaeri, Houston D, Steffan L, Couper D (2002) Dietary fiber intake and glycemic index and incidence of diabetes in African-American and white adults: the ARIC study. *Diabetes Care* 25:1715–1721
29. Hodge AM, English DR, O'Dea K, Giles GG (2004) Glycemic index and dietary fiber and the risk of type 2 diabetes. *Diabetes Care* 27:2701–2706
30. Barclay AW, Flood VM, Rochtchina E, Mitchell P, Brand-Miller JC (2007) Glycemic index, dietary fiber, and risk of type 2 diabetes in a cohort of older Australians. *Diabetes Care* 30:2811–2813
31. Krishnan S, Rosenberg L, Singer M et al (2007) Glycemic index, glycemic load, and cereal fiber intake and risk of type 2 diabetes in US black women. *Arch Intern Med* 167:2304–2309
32. Wannamethee SG, Whincup PH, Thomas MC, Sattar N (2009) Associations between dietary fiber and inflammation, hepatic function, and risk of type 2 diabetes in older men: potential mechanisms for the benefits of fiber on diabetes risk. *Diabetes Care* 32:1823–1825
33. Hopping BN, Erber E, Grandinetti A, Verheus M, Kolonel LN, Maskarinec G (2010) Dietary fiber, magnesium, and glycemic load alter risk of type 2 diabetes in a multiethnic cohort in Hawaii. *J Nutr* 140:68–74
34. Sakurai M, Nakamura K, Miura K et al (2012) Dietary glycemic index and risk of type 2 diabetes mellitus in middle-aged Japanese men. *Metabolism* 61:47–55
35. Wirström T, Hilding A, Gu HF, Ostenson CG, Bjorklund A (2013) Consumption of whole grain reduces risk of deteriorating glucose tolerance, including progression to prediabetes. *Am J Clin Nutr* 97:179–187
36. Weng LC, Lee NJ, Yeh WT, Ho LT, Pan WH (2012) Lower intake of magnesium and dietary fiber increases the incidence of type 2 diabetes in Taiwanese. *J Formos Med Assoc* 111:651–659
37. Liu JC, Guo ZR, Hu XS, Zhou ZY, Wu M, Luo WS (2012) Impact of lifestyle and obesity to the risk of type 2 diabetes: a prospective study in Jiangsu province. *Zhonghua Yu Fang Yi Xue Za Zhi* 46:311–315
38. Qiao Y, Tinker L, Olendzki BC et al (2014) Racial/ethnic disparities in association between dietary quality and incident diabetes in postmenopausal women in the United States: the Women's Health Initiative 1993–2005. *Ethn Health* 19:328–347
39. Hodge AM, Dowse GK, Zimmet PZ (1993) Diet does not predict incidence or prevalence of non-insulin-dependent diabetes in Nauruans. *Asia Pac J Clin Nutr* 2:35–41
40. Greenland S, Longnecker MP (1992) Methods for trend estimation from summarized dose–response data, with applications to meta-analysis. *Am J Epidemiol* 135:1301–1309
41. Royston P (2000) A strategy for modelling the effect of a continuous covariate in medicine and epidemiology. *Stat Med* 19:1831–1847
42. Egger M, Davey SG, Schneider M, Minder C (1997) Bias in meta-analysis detected by a simple, graphical test. *BMJ* 315:629–634
43. Yao B, Fang H, Xu W et al (2014) Dietary fiber intake and risk of type 2 diabetes: a dose–response analysis of prospective studies. *Eur J Epidemiol* 29:79–88
44. Aune D, Norat T, Romundstad P, Vatten LJ (2013) Whole grain and refined grain consumption and the risk of type 2 diabetes: a systematic review and dose–response meta-analysis of cohort studies. *Eur J Epidemiol* 28:845–858
45. Cooper AJ, Forouhi NG, Ye Z et al (2012) Fruit and vegetable intake and type 2 diabetes: EPIC-InterAct prospective study and meta-analysis. *Eur J Clin Nutr* 66:1082–1092
46. Bakker SJ, Hoogveen EK, Nijpels G et al (1998) The association of dietary fibres with glucose tolerance is partly explained by concomitant intake of thiamine: the Hoorn Study. *Diabetologia* 41:1168–1175
47. Dong JY, Zhang L, Zhang YH, Qin LQ (2011) Dietary glycaemic index and glycaemic load in relation to the risk of type 2 diabetes: a meta-analysis of prospective cohort studies. *Br J Nutr* 106:1649–1654
48. Sluijs I, Beulens JW, van der Schouw YT et al (2013) Dietary glycemic index, glycemic load, and digestible carbohydrate intake are not associated with risk of type 2 diabetes in eight European countries. *J Nutr* 143:93–99
49. Du H, van der A DL, Boshuizen HC et al (2010) Dietary fiber and subsequent changes in body weight and waist circumference in European men and women. *Am J Clin Nutr* 91:329–336
50. Fogelholm M, Anderssen S, Gunnarsdottir I, Lahti-Koski M (2012) Dietary macronutrients and food consumption as determinants of long-term weight change in adult populations: a systematic literature review. *Food Nutr Res* doi:10.3402/fnr.v56i0.19103
51. Wanders AJ, van den Borne JJ, de Graaf C (2011) Effects of dietary fibre on subjective appetite, energy intake and body weight: a systematic review of randomized controlled trials. *Obes Rev* 12:724–739
52. Koh-Banerjee P, Franz M, Sampson L et al (2004) Changes in whole-grain, bran, and cereal fiber consumption in relation to 8-year weight gain among men. *Am J Clin Nutr* 80:1237–1245
53. Liu S, Willett WC, Manson JE, Hu FB, Rosner B, Colditz G (2003) Relation between changes in intakes of dietary fiber and grain products and changes in weight and development of obesity among middle-aged women. *Am J Clin Nutr* 78:920–927
54. Davis JN, Alexander KE, Ventura EE, Toledo-Corral CM, Goran MI (2009) Inverse relation between dietary fiber intake and visceral adiposity in overweight Latino youth. *Am J Clin Nutr* 90:1160–1166
55. Cho SS, Qi L, Fahey GC Jr, Klurfeld DM (2013) Consumption of cereal fiber, mixtures of whole grains and bran, and whole grains and risk reduction in type 2 diabetes, obesity, and cardiovascular disease. *Am J Clin Nutr* 98:594–619
56. Anderson JW, Baird P, Davis RH Jr et al (2009) Health benefits of dietary fiber. *Nutr Rev* 67:188–205
57. Weickert MO, Roden M, Isken F et al (2011) Effects of supplemented isoenergetic diets differing in cereal fiber and protein content on insulin sensitivity in overweight humans. *Am J Clin Nutr* 94:459–471
58. Weickert MO, Pfeiffer AF (2008) Metabolic effects of dietary fiber consumption and prevention of diabetes. *J Nutr* 138:439–442
59. Donin AS, Nightingale CM, Owen CG et al (2014) Regular breakfast consumption and type 2 diabetes risk markers in 9- to 10-year-old children in the Child Heart and Health Study in England (CHASE): a cross-sectional analysis. *PLoS Med* 11, e1001703
60. Sleeth ML, Thompson EL, Ford HE, Zac-Varghese SE, Frost G (2010) Free fatty acid receptor 2 and nutrient sensing: a proposed role for fibre, fermentable carbohydrates and short-chain fatty acids in appetite regulation. *Nutr Res Rev* 23:135–145
61. Diamant M, Blaak EE, de Vos WM (2011) Do nutrient–gut–microbiota interactions play a role in human obesity, insulin resistance and type 2 diabetes? *Obes Rev* 12:272–281
62. Jenkins DJ, Wolever TM, Leeds AR et al (1978) Dietary fibres, fibre analogues, and glucose tolerance: importance of viscosity. *Br Med J* 1:1392–1394
63. Holt S, Heading RC, Carter DC, Prescott LF, Tothill P (1979) Effect of gel fibre on gastric emptying and absorption of glucose and paracetamol. *Lancet* 1:636–639
64. Tighe P, Duthie G, Vaughan N et al (2010) Effect of increased consumption of whole-grain foods on blood pressure and other cardiovascular risk markers in healthy middle-aged persons: a randomized controlled trial. *Am J Clin Nutr* 92:733–740

65. Brownlee IA, Moore C, Chatfield M et al (2010) Markers of cardiovascular risk are not changed by increased whole-grain intake: the WHOLEheart study, a randomised, controlled dietary intervention. *Br J Nutr* 104:125–134
66. Qi L, van Dam RM, Liu S, Franz M, Mantzoros C, Hu FB (2006) Whole-grain, bran, and cereal fiber intakes and markers of systemic inflammation in diabetic women. *Diabetes Care* 29:207–211
67. Montonen J, Boeing H, Fritsche A et al (2013) Consumption of red meat and whole-grain bread in relation to biomarkers of obesity, inflammation, glucose metabolism and oxidative stress. *Eur J Nutr* 52:337–345
68. Ma Y, Griffith JA, Chasan-Taber L et al (2006) Association between dietary fiber and serum C-reactive protein. *Am J Clin Nutr* 83:760–766
69. Ma Y, Hebert JR, Li W et al (2008) Association between dietary fiber and markers of systemic inflammation in the Women's Health Initiative Observational Study. *Nutrition* 24:941–949
70. Sun SZ, Flickinger BD, Williamson-Hughes PS, Empie MW (2010) Lack of association between dietary fructose and hyperuricemia risk in adults. *Nutr Metab (Lond)* 7:16
71. Lee DH, Steffen LM, Jacobs DR Jr (2004) Association between serum gamma-glutamyltransferase and dietary factors: the Coronary Artery Risk Development in Young Adults (CARDIA) Study. *Am J Clin Nutr* 79:600–605
72. Hu FB, Meigs JB, Li TY, Rifai N, Manson JE (2004) Inflammatory markers and risk of developing type 2 diabetes in women. *Diabetes* 53:693–700
73. Sluijs I, Beulens JW, van der A DL, Spijkerman AM, Schulze MB, van der Schouw YT (2013) Plasma uric acid is associated with increased risk of type 2 diabetes independent of diet and metabolic risk factors. *J Nutr* 143:80–85
74. Fraser A, Harris R, Sattar N, Ebrahim S, Davey SG, Lawlor DA (2009) Alanine aminotransferase, gamma-glutamyltransferase, and incident diabetes: the British Women's Heart and Health Study and meta-analysis. *Diabetes Care* 32:741–750
75. Qi L, Rimm E, Liu S, Rifai N, Hu FB (2005) Dietary glycemic index, glycemic load, cereal fiber, and plasma adiponectin concentration in diabetic men. *Diabetes Care* 28:1022–1028
76. Qi L, Meigs JB, Liu S, Manson JE, Mantzoros C, Hu FB (2006) Dietary fibers and glycemic load, obesity, and plasma adiponectin levels in women with type 2 diabetes. *Diabetes Care* 29:1501–1505
77. Cassidy A, Skidmore P, Rimm EB et al (2009) Plasma adiponectin concentrations are associated with body composition and plant-based dietary factors in female twins. *J Nutr* 139:353–358
78. Li S, Shin HJ, Ding EL, van Dam RM (2009) Adiponectin levels and risk of type 2 diabetes: a systematic review and meta-analysis. *JAMA* 302:179–188