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ORIGINAL ARTICLE

Dietary fiber intake and risk of type 2 diabetes in a general Japanese population: The Hisayama Study

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ABSTRACT

Aims/Introduction: The investigation of the influence of dietary fiber intake on the incidence of type 2 diabetes in a general Japanese population.

Materials and Methods: A total of 1,892 individuals aged 40–79 years without diabetes at baseline were prospectively followed up for 14 years. The glucose tolerance status of participants was defined by a 75-g oral glucose tolerance test with the 1998 World Health Organization criteria. Dietary fiber intake was estimated by a semiquantitative food frequency questionnaire and divided to quintile levels separately by sex. A Cox proportional hazards model was applied for computing the hazard ratios and their 95% confidence intervals for the incidence of diabetes.

Results: During the follow-up period, 280 participants had developed diabetes. The age-adjusted cumulative diabetes incidence decreased significantly with higher total dietary fiber intake (*P*-for trend = 0.01). Participants in the highest quintile of total dietary fiber intake had a 0.53-fold (95% confidence interval 0.31–0.90) lower risk of developing diabetes than those in the lowest quintile after for the adjustment with potential confounding factors. Total dietary fiber intake showed a moderate positive correlation to the intake of soybean and soybean products, green vegetables, and other vegetables. Similar associations with diabetes and food sources were observed for both of the soluble and insoluble dietary fiber intake.

Conclusions: The present study showed that higher dietary fiber intake was associated with a lower risk of type 2 diabetes in a general Japanese population. The intake of high dietary fiber foods might be useful for diabetes prevention.

INTRODUCTION

Type 2 diabetes has become a worldwide epidemic[1], especially in Asian countries as a result of rapid socioeconomic development, overnutrition and lack of physical activity[2,3]. In Japan, the incidence rate of type 2 diabetes increased from 8.2% in 1997 to 12.1% in 2016[4]. Type 2 diabetes has emerged recently as one of the major risk factors for geriatric diseases, such as dementia, sarcopenia, periodontal disease and cancer, in addition to large and small vessel disease[5–9]. Therefore, for countries with aging populations, such as Japan, reducing the load of type 2 diabetes through lifestyle modification had become a public health priority. Among the strategies for preventing type 2 diabetes, the promotion of healthy dietary habits plays an important role[10,11], as nutrient intake is very closely related to diabetes etiology[11].

Dietary fiber is the edible portion of plants that is resistant to digestion and absorption in the small intestine, and therefore dietary fiber is considered to decrease macronutrient absorption by way of controlling energy intake from the diet[12]. Several meta-analyses, which were mainly carried out in Western countries, showed that higher dietary fiber intake has a significant association with a lower risk of the development of type 2 diabetes mellitus[13–15]. However, food habits are different between

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Asian and Western countries. Dietary fiber intake is generally lower in Japanese populations than Western populations[16]; thus, it would be clinically helpful to clarify the association of dietary fiber intake to the development of type 2 diabetes in Asian populations.

Dietary fiber is classified by its water solubility[17]. Several prospective studies on white populations examined the associations of the risk of type 2 diabetes with soluble and insoluble dietary fiber intake separately; however, the findings were inconsistent across these studies[18–20]. There has been only one community-based prospective cohort study investigating this subject in Asian populations[21]. In addition, the intake ratio of insoluble dietary fiber to that of soluble dietary fiber is higher in Asian countries than in Western countries[16]. Therefore, it is worth addressing the association of type 2 diabetes to different types of dietary fiber intake in an Asian population.

The Hisayama Study is a prospective population-based cohort study of lifestyle-related diseases, including cardiovascular disease and diabetes, in a Japanese community[22]. This study uses repeated 75-g oral glucose tolerance tests (OGTTs) for the reliable determination of glucose tolerance status, which is required in order to identify effective dietary factors for preventing type 2 diabetes. The aim of the current study was to examine the influence of the total dietary fiber intake, soluble and insoluble dietary fiber intake on the incidence of type 2 diabetes in a community-dwelling Japanese population.

METHODS

Study population

The Hisayama Study has been ongoing since 1961 in Hisayama town, a suburb of Fukuoka city in the north part of Kyushu Island in Japan. The town residents have undergone a 75-g OGTT as part of their annual health checkups since 1988. Detailed information on the health checkups have been published previously[22]. In brief, 2,587 (80.2%) of the total 3,227 residents aged 40–79 years underwent a baseline screening examination including a dietary survey in 1988. After exclusion of 82 participants who had already eaten breakfast, 10 participants who had been receiving insulin therapy and 15 participants who had general fatigue or nausea during the glucose ingestion, 2,480 participants completed the OGTT. Among them, we excluded 297 participants with diabetes at baseline, 78 participants who had a cardiovascular disease and/or cancer history, 201 participants who did not complete a semiquantitative dietary questionnaire at baseline, and 12 participants who had implausibly high or low total energy intake (more or less than mean energy intake ±3 standard deviations, <640 or >3,259 kcal/day for men, and <833 or >2,489 kcal/day for women). The remaining 1,892 participants (759 men; 1,133 women) were registered to this cohort study.

The present study was carried out under the approval of Kyushu University Institutional Review Board for Clinical Research, and all participants submitted written informed consent.

Follow-up survey

The enrolled participants were followed up prospectively by repeated annual health examinations from December 1988 until November 2002 (median follow-up period 14 years; range 1–14 years). For participants who had moved out of town or who did not have examinations, their health information was collected using postal mail or phone. During the follow-up period, new development of type 2 diabetes mellitus was decided by the OGTT data or the measurements of fasting or casual plasma glucose at annual health examinations with clinical information, such as medical records and the use of antidiabetic medications (e.g., oral hypoglycemic agents or insulin). The participants underwent an average of 6.9 ± 3.9 examinations during the follow-up period.

Definition of type 2 diabetes

The participants underwent the OGTT after an overnight fast (at least 12 h) at baseline and follow-up examinations. A glucose oxidase method (1988–1999) or hexokinase method (2000–2002) was used to evaluate plasma glucose levels. Diabetes was defined by 1998 World Health Organization criteria as follows: (i) normal glucose tolerance (NGT) was defined as fasting plasma glucose (FPG) <6.1 mmol/L and 2-h post-load glucose (PG) <7.8 mmol/L; (ii) prediabetes was defined as FPG 6.1–6.9 mmol/L and 2-h PG <7.8 mmol/L, or FPG <7.0 mmol/L and 2-h PG 7.8–11.0 mmol/L; and (iii) diabetes was defined as FPG ≥7.0 mmol/L or 2-h PG ≥11.1 mmol/L, or the use of antidiabetic medications.

Nutritional survey at baseline

At the 1988 baseline examination for screening, a semiquantitative food frequency questionnaire (70-item) considering food intake[23] was used to carried out a dietary survey. This questionnaire has been validated and reported previously[24]. Each participant completed the questionnaire in advance, and trained dieticians checked that at the screening examination. The frequency of meals per week and the amount of each food portion were used to calculate the average food intake per day. Nutritional intake was calculated from the food intake base on the *Standard Tables of Food Composition in Japan* (Fourth Revised Edition)[25]. The density method was used to adjust all dietary nutrient for total energy[26].

Laboratory measurements and clinical evaluation

The self-administered questionnaire of the present study covered medical history, antidiabetic and antihypertensive treatments, alcohol intake, smoking habits, and physical activity. In the analysis, current consumption or not was used for alcohol intake and smoking habits. The regular exercise group was defined as participants engaging sports at least three times per week. Body mass index (BMI) was calculated in the usual way by height and weight measured from participants wearing light clothing with no shoes. BMI ≥25 kg/m^2 was classified as obesity. Blood pressure was measured using a mercury sphygmomanometer three times in 1988 and the mean of three measurements was used in the analysis. Hypertension was classified as a systolic blood pressure ≥140 mmHg and/or a diastolic blood pressure ≥90 mmHg, or current treatment using antihypertensive agents. Serum total and high-density lipoprotein cholesterols, and serum triglycerides were decided enzymatically. A formula (FPG [mmol/L] × fasting serum insulin [μU/mL]) / 22.5[27] was used to obtain the homeostasis model assessment of insulin resistance (HOMA-IR). A modified version of the Behring latex-enhanced C-reactive protein (CRP) assay was used for deciding serum high-sensitivity CRP (hs-CRP) concentrations.

Statistical analysis

Dietary fiber intake was divided into five categories following the sex-specific quintile distribution. The values of serum triglycerides, HOMA-IR and serum hs-CRP were natural log transformed for the analysis, because of the skew of the distributions of these variables. The trends of the mean values or the frequencies of possible risk factors among the quintiles of total dietary fiber intake were analyzed by linear regression analysis or logistic regression analysis. The person-years method was applied for evaluating the incidence of type 2 diabetes. The adjusted hazard ratio (HR) with the 95% confidence interval (CI) of diabetes according to dietary fiber intake was evaluated using the Cox proportional hazards model. The age-adjusted cumulative incidences of type 2 diabetes across the intake levels of each type of dietary fiber were calculated by using regression estimates from a relevant Cox model including age[28]. The trends in the risk estimates were tested using a Cox model including the intake levels of each dietary fiber with ordinal numbers (0, 1, 2, 3 and 4) and the relevant covariates. The heterogeneity in the magnitude of the association of dietary fiber intake levels with type 2 diabetes risk across subgroups (NGT and prediabetes) was tested by the relevant Cox model with the addition of a multiplicative interaction term. The Spearman's correlation coefficients were used for estimating the correlation between dietary fiber intakes and food intakes for each food group in the Standard Tables of Food Composition in Japan[25], where we considered correlation coefficients of 0.30–0.49 (or –0.49 to –0.30) and ≥0.50 (or ≤–0.50) as weakly positive (negative) and moderately positive (negative) correlations, respectively[29]. All statistical analysis was carried out with the SAS 9.4 software (SAS Institute, Cary, NC, USA). In all analyses, two-sided *P*-values ($P < 0.05$) were used for judging the statistical significance.

RESULTS

Table 1 shows the baseline characteristics of this study population. The mean values of age, BMI, the intakes of total energy, vitamin A, vitamin C and magnesium, the ratio of polyunsaturated fatty acid : saturated fatty acid (P/S ratio), and the frequency of regular exercises all increased significantly with increasing quintile of total dietary fiber intake, whereas a higher intake of total dietary fiber was significantly associated with lower frequencies of current smoking and current alcohol drinking.

During the follow-up period, type 2 diabetes was developed by 280 participants (139 men and 141 women). The age-adjusted cumulative incidence of diabetes decreased significantly with increasing quintile of the amount of total dietary fiber intake (*P* for trend = 0.01; Figure 1). The age-adjusted HR of the development of type 2 diabetes decreased significantly with increasing amount of total dietary fiber intake (*P* for trend = 0.01) and insoluble dietary fiber (*P* for trend = 0.002), and also decreased, but not significantly with an increasing amount of intake of soluble dietary fiber (*P* for trend = 0.08; model 1), as shown in Table 2. The risk of incident type 2 diabetes significantly decreased with higher intakes of total dietary fiber, soluble dietary fiber and insoluble dietary fiber after adjustment for age, family history of diabetes mellitus, hypertension, BMI, serum total cholesterol, serum high-density lipoprotein cholesterol, serum triglycerides, current smoking, current alcohol drinking, regular exercise and dietary factors, such as total energy intake, vitamin A, vitamin C, magnesium and polyunsaturated fatty acid/saturated fatty acid ratio (model 2, all *P* for trends≤0.02). For type 2 diabetes, the multivariate-adjusted HR was significantly lower for participants at the highest quintile compared with those at the lowest quintiles of dietary fiber (with total dietary fiber HR 0.52, 95% CI 0.31–0.89; with soluble dietary fiber HR 0.50, 95% CI 0.30–0.83; with insoluble dietary fiber HR 0.54, 95% CI 0.32–0.90). These associations were unchanged even after the additional adjustment with HOMA-IR and serum hs-CRP (model 3, all *P* for trends ≤0.02). The ratio of insoluble dietary fiber to soluble dietary fiber showed no clear association with the risk of the development of type 2 diabetes (Table S1).

Next, we carried out a subgroup analysis of glucose tolerance status (NGT and prediabetes) to compare the magnitude of the association of total dietary fiber intake with the development risk of type 2 diabetes between subgroups (Table 3). The results showed a significant inverse association of the intake of total dietary fiber with type 2 diabetes risk in participants with prediabetes (*P* for trend = 0.04) after adjustment with confounders including HOMA-IR and serum hs-CRP, but there was no evidence of significant heterogeneity for participants with NGT and those with prediabetes (*P* for heterogeneity = 0.99).

Finally, the correlation of the intake of dietary fiber to that of food groups was estimated (Table 4). Total dietary fiber intake was correlated positively to intakes of soybean and soybean products, green and other vegetables, fruits, fruits juices, and algae. Similar correlations were observed on soluble and insoluble fiber intakes, except for algae intake, with soluble dietary fiber.

DISCUSSION

The present study showed that higher intake of total dietary fiber had an association with a lower risk of type 2 diabetes in

Table 1 | Baseline characteristics of potential risk factors for type 2 diabetes according to the quintile of total dietary fiber intake

Variables	Total dietary fiber intake (g/1,000 kcal)					
	Q1 (M: ≤4.13; W: ≤5.41) (*n* = 377)	Q2 (M: 4.14–5.01; W: 5.42–6.37) (*n* = 379)	Q3 (M: 5.02–5.89; W: 6.38–7.39) (*n* = 379)	Q4 (M: 5.90–7.06; W: 7.40–8.54) (*n* = 379)	Q5 (M: ≥7.07; W: ≥8.55) (*n* = 378)	*P* for trend
Dietary fiber intake (median)						
Men (g/1,000 kcal)	3.61	4.61	5.47	6.45	7.94	
Women (g/1,000 kcal)	4.65	5.90	6.90	7.93	9.62	
Clinical parameters						
Age (years)	55.6 (10.3)	56.4 (10.4)	56.2 (9.9)	57.4 (10.2)	59.0 (10.0)	<0.0001
Men (%)	40.1	40.1	40.1	40.1	40.2	0.97
Family history of diabetes (%)	8.8	5.0	7.4	7.4	9.6	0.36
Hypertension (%)	36.6	37.2	31.1	35.1	38.1	0.91
Body mass index (kg/m^2)	23.0 (3.1)	22.8 (3.1)	22.7 (3.0)	22.9 (3.0)	23.4 (2.9)	0.04
Obesity, ≥25.0 kg/m^2 (%)	24.9	21.6	19.3	23.0	27.5	0.34
Serum total cholesterol (mmol/L)	5.27 (1.05)	5.38 (1.08)	5.35(1.07)	5.38 (1.04)	5.41 (1.06)	0.49
Serum HDL cholesterol (mmol/L)	1.33 (0.32)	1.31 (0.29)	1.29 (0.29)	1.31 (0.30)	1.31 (0.28)	0.38
Serum triglycerides (mmol/L)	1.07 (0.78–1.48)	1.10 (0.76–1.56)	1.04 (0.78–1.59)	1.12 (0.85–1.54)	1.07 (0.79–1.54)	0.53
HOMA-IR	1.32 (0.90–1.86)	1.36 (0.96–1.86)	1.27 (0.93–1.79)	1.32 (0.94–1.86)	1.40 (0.92–1.97)	0.51
Serum hs-CRP (mg/L)	0.41 (0.20–0.89)	0.43 (0.22–1.03)	0.35 (0.18–0.70)	0.40 (0.18–0.89)	0.44 (0.22–0.88)	0.15
Current smoking (%)	30.0	24.8	24.0	19.0	16.9	<0.0001
Current alcohol drinking (%)	36.3	30.9	29.0	28.0	23.8	0.0002
Regular exercise (%)	6.6	9.0	9.3	14.0	13.5	0.0002
Dietary factors						
Total energy intake (kcal/day)	1,700 (395)	1,660 (348)	1,699 (383)	1,711 (363)	1,782 (391)	0.003
Vitamin A (IU/1,000 kcal)	1,426 (639)	1,572 (574)	1,771 (594)	1,881 (671)	2,167 (718)	<0.0001
Vitamin C (mg/1,000 kcal)	32.8 (13.2)	40.7 (16.1)	48.0 (18.6)	52.8 (19.1)	62.0 (23.0)	<0.0001
Magnesium (mg/1,000 kcal)	86.1 (20.4)	95.2 (16.0)	103.4 (16.7)	108.6 (15.2)	126.7 (23.2)	<0.0001
P/S ratio	1.10 (0.40)	1.21 (0.42)	1.28 (0.42)	1.40 (0.42)	1.62 (0.49)	<0.0001

The values of serum triglycerides, homeostasis model assessment of insulin resistance (HOMA-IR) and serum high-sensitivity C-reactive protein (hs-CRP) are shown as the median (interquartile range). All other values are given as the mean (standard deviations) or percentage. HDL, high density lipoprotein; M, men; P/S ratio, polyunsaturated fatty acid : saturated fatty acid ratio; Q, quintile; W, women.

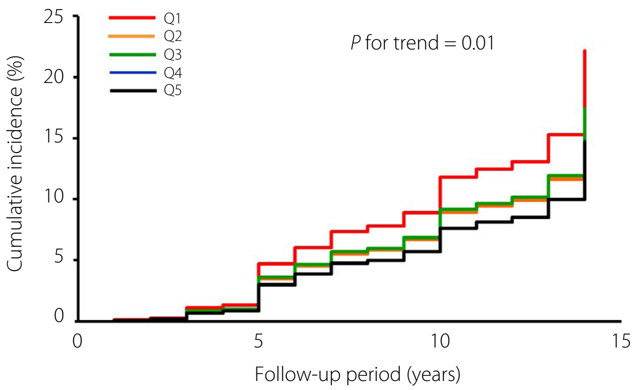

Figure 1 | Age-adjusted cumulative incidence of type 2 diabetes according to the quintile of total dietary fiber intake.

a general Japanese population. Furthermore, individuals with both higher intakes of soluble and insoluble dietary fiber had a lower risk of type 2 diabetes. This inverse association was found for both participants with prediabetes and those with NGT. In addition, dietary fiber had a positive correlation with the intakes of soybean and soybean products, green and other vegetables, fruits, fruit juices, and algae, which were considered the main sources of dietary fiber in the present study. These findings show that higher dietary fiber intake might be effective to lighten the burden of type 2 diabetes among the Japanese population.

Several prospective studies have explored the association of total dietary fiber intake with the risk of type 2 diabetes in Western populations, but the findings are inconsistent[30–35]. The Nurses' Health Study showed that women in the highest quintile of total dietary fiber intake showed the effect of lowering the risk of developing type 2 diabetes by approximately 20% compared with those in the lowest quintile[30,31]. A Finnish study showed a similar significant inverse association of intake of total dietary fiber with diabetes risk[32]. The present findings are consistent with these previous results. In contrast, several studies did not show clear associations (e.g., the Health Professionals Follow-up Study, the Atherosclerosis Risk in Communities study and the Nurses' Health Study II)[33–35]. A meta-analysis of 19 cohort studies clarified that the multivariable-adjusted risk of type 2 diabetes lowered significantly by 9% for every 10-g/day increase in intake of total dietary fiber with low between-study heterogeneity (I^2 = 29.4%)[13]. Two other meta-analyses of prospective studies showed that individuals with a higher intake level of total dietary fiber (above the median, the mean or comparing the highest and lowest categories for each study) had an approximately 20% reduced risk of diabetes compared with those with a lower intake level, but the association was heterogeneous across the studies (I^2 = 53.6%[14] and I^2 = 44.1%[15], respectively). These inconsistent results might be by over- or underestimation of the intake of total dietary fiber due to differences in the dietary assessment methods, and/or the possibility of misclassification of diagnostic criteria for diabetes. Furthermore, ethnicity is an important determinant of the etiology of type 2 diabetes[36]. A major difference between Asians and white people in regulating the postprandial glucose metabolism is the β-cell response to glucose[37]. It is widely recognized that type 2 diabetes in East Asians is characterized primarily by β-cell dysfunction rather than insulin resistance[36]. In the present study, an inverse association between dietary fiber intake and diabetes risk was observed, because dietary fiber is resistant to carbohydrate absorption in the small intestine[12], and its ability to suppress a rapid rise of blood glucose levels contributes to the prevention of type 2 diabetes in East Asians with limited insulin secretion capacity[38]. The present findings make a valuable contribution by showing that high total dietary fiber intake could play some role in the prevention of type 2 diabetes for Asian populations, as well as for Western populations. However, the effect of dietary fiber intake on the prevention of type 2 diabetes has not yet been fully addressed in Asian populations. Further epidemiological studies are required to determine whether a high-fiber diet can lessen the future risk of type 2 diabetes in Asian populations.

The present study showed that higher intake of soluble and insoluble dietary fiber clearly reduced the risk of type 2 diabetes. Previous epidemiological studies, such as the Iowa Women's Health Study and the Finnish Mobile Clinic Health Examination Survey, showed that the type 2 diabetes risk decreased significantly with higher intake of insoluble dietary fiber, but did not decrease with higher intake of soluble dietary fiber[18,19]. In contrast, neither soluble dietary fiber nor insoluble dietary fiber intake showed an association with diabetes risk in the European Prospective Investigation into Cancer and Nutrition-Potsdam Study[20]. The inconsistency in these findings might be caused by differences in the source of dietary fiber among the populations. For example, the main food sources of dietary fiber in the Japanese population are legumes, vegetables, cereals and fruits[39], and the majority (97%) of the legume intake is soybean and soybean products[40]. Also in the present study, soybean and soybean products and vegetables were the major sources of dietary fiber. In contrast, Western studies showed that cereals were the main source of dietary fiber, and small amounts of dietary fiber were derived from legumes[18–20]. Soybean and soybean products and vegetables have low carbohydrate content[25] and low glycemic indexes[41], which has the effect of suppressing an increase in postprandial blood glucose concentrations[42]. These differences in food habits among countries might influence the differential findings on soluble and insoluble dietary fiber.

Intriguingly, a significant inverse association was found between total dietary fiber intake and type 2 diabetes risk in the present participants with prediabetes. Considering the high incidence of type 2 diabetes among participants with prediabetes in the present study, it would be assumed that the absolute benefit of intake of dietary fiber for the prevention of type 2 diabetes would be greater in those with prediabetes.

Table 2 | Incidence rates and hazard ratios for the development of type 2 diabetes according to total dietary fiber, soluble dietary fiber and insoluble dietary fiber intake

Dietary fiber intake levels (g/1,000 kcal)	No. events/ PYs	Age-adjusted incidence rate (per 10^3 PYs)	Hazard ratio (95% confidence interval)		
			Model 1 (Age-adjusted)	Model 2† (Multivariable-adjusted)	Model 3‡ (Model 2 + HOMA-IR and serum hs-CRP)
Total dietary fiber intake					
Q1 (M: ≤4.13; W: ≤5.41)	70/4,345	16.5	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
Q2 (M: 4.14–5.01; W: 5.42–6.37)	55/4,497	12.2	0.75 (0.52–1.06)	0.73 (0.51–1.06)	0.72 (0.50–1.03)
Q3 (M: 5.02–5.89; W: 6.38–7.39)	59/4,651	12.4	0.76 (0.54–1.08)	0.77 (0.53–1.13)	0.76 (0.52–1.12)
Q4 (M: 5.90–7.06; W: 7.40–8.54)	49/4,599	10.6	0.64 (0.44–0.92)	0.63 (0.41–0.97)	0.63 (0.41–0.96)
Q5 (M: ≥7.07; W: ≥8.55)	47/4,456	9.9	0.63 (0.44–0.92)	0.52 (0.31–0.89)	0.53 (0.31–0.90)
P for trend			0.01	0.02	0.02
Soluble dietary fiber intake					
Q1 (M: ≤0.56; W: ≤0.77)	65/4,304	15.4	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
Q2 (M: 0.57–0.79; W: 0.78–1.08)	49/4,544	10.6	0.70 (0.49–1.02)	0.73 (0.50–1.06)	0.70 (0.48–1.03)
Q3 (M: 0.80–1.06; W: 1.09–1.39)	63/4,560	13.7	0.90 (0.64–1.27)	0.82 (0.57–1.19)	0.78 (0.54–1.14)
Q4 (M: 1.07–1.40; W: 1.40–1.76)	58/4,648	12.1	0.80 (0.56–1.14)	0.70 (0.47–1.05)	0.65 (0.44–0.97)
Q5 (M: ≥1.41; W: ≥1.77)	45/4,492	9.7	0.64 (0.44–0.94)	0.50 (0.30–0.83)	0.50 (0.30–0.82)
P for trend			0.08	0.02	0.01
Insoluble dietary fiber intake					
Q1 (M: ≤3.54; W: ≤4.53)	76/4,299	20.5	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
Q2 (M: 3.55–4.18; W: 4.54–5.28)	57/4,564	16.3	0.69 (0.49–0.97)	0.70 (0.49–1.00)	0.69 (0.48–0.99)
Q3 (M: 4.19–4.87; W: 5.29–6.04)	50/4,630	9.3	0.59 (0.41–0.84)	0.64 (0.43–0.95)	0.64 (0.43–0.95)
Q4 (M: 4.88–5.66; W: 6.05–6.91)	47/4,579	8.7	0.56 (0.39–0.80)	0.55 (0.36–0.84)	0.56 (0.37–0.86)
Q5 (M: ≥5.67; W: ≥6.92)	50/4,476	9.2	0.61 (0.42–0.87)	0.54 (0.32–0.90)	0.56 (0.34–0.94)
P for trend			0.002	0.008	0.001

†Adjusted for age, family history of diabetes mellitus, hypertension, body mass index, serum total cholesterol, serum high density lipoprotein cholesterol, log-transformed serum triglycerides, current smoking, current alcohol drinking, regular exercise, intakes of total energy, vitamin A, vitamin C, magnesium and polyunsaturated fatty acid : saturated fatty acid ratio. ‡Adjusted for age, family history of diabetes mellitus, hypertension, body mass index, serum total cholesterol, serum high density lipoprotein cholesterol, log-transformed serum triglycerides, current smoking, current alcohol drinking, regular exercise, intakes of total energy, vitamin A, vitamin C, magnesium, polyunsaturated fatty acid : saturated fatty acid ratio, log-transformed homeostasis model assessment of insulin resistance and log-transformed high-sensitivity C-reactive protein (hs-CRP). M, men; PYs, person-years; Q, quintile; W, women.

Nevertheless, there was no significant heterogeneity in the preventive effects of dietary fiber on our participants with prediabetes and those with NGT. Therefore, an optimal amount of dietary fiber intake might be one of the important protective factors preventing the incidence of type 2 diabetes not only for individuals with prediabetes, but also for those with NGT.

The exact mechanism underlying the significant association between intake of dietary fiber and the risk of type 2 diabetes remains unclear; however, several possible explanations would be shown. Dietary fiber delays the absorption of carbohydrates and adequately secretes insulin, which leads to reduced postprandial blood glucose and insulin levels[12]. Furthermore, dietary fiber is fermented and generates short-chain fatty acids inside the large intestine[12], which might improve gut microbiota balance, and short-chain fatty acids might increase the secretion of incretins[43], which stimulate insulin secretion from β-cells[44]. Higher intake of total and insoluble dietary fiber could lower markers of inflammation (e.g., plasminogen activator inhibitor-1, resistin, CRP and interleukin-6)[45,46], thereby leading to a reduced risk of type 2 diabetes[46]. Finally, soluble dietary fiber has a favorable effect on the glucose and insulin responses by delaying gastric emptying and the absorption of nutrients[12].

The strengths of the present study are its prospective population-based study design, long follow-up period, high rates of participation and the use of an OGTT for precisely determining the glucose tolerance status. Although, some potential limitations need to be addressed. At first, the dietary assessment was carried out at baseline only once using a semiquantitative food frequency questionnaire, and dietary fiber intake was evaluated only on the limited food list in the questionnaire. Additionally, the estimated dietary fiber intake based on self-reported information does not necessarily reflect actual dietary fiber intake based on a direct biological analysis[47]. These limitations are likely to have caused some degree of misclassification of dietary fiber intake. Such residual misclassification would lower the association shown in the current study and lead the results to the null hypothesis. To minimize the measurement errors, we added in-person interviews carried out by

Table 3 | Incidence rates and hazard ratios for the development of diabetes according to total dietary fiber intake in participants with normal glucose tolerance and prediabetes

Total dietary fiber intake levels (g/1,000 kcal)	No. events/PYs	Age-adjusted incidence rate (per 10^3 PYs)	Hazard ratio (95% confidence interval)		
			Model 1 (age- and sex-adjusted)	Model 2† (multivariable-adjusted)	Model 3‡ (model 2 + HOMA-IR and serum hs-CRP)
Normal glucose tolerance (*n* = 1,366)					
Q1 (M: ≤4.21; W: ≤5.45)	30/3,274	9.6	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
Q2 (M: 4.22–5.06; W: 5.46–6.35)	20/3,365	5.7	0.64 (0.37–1.13)	0.69 (0.38–1.26)	0.69 (0.38–1.25)
Q3 (M: 5.07–5.93; W: 6.36–7.31)	21/3,484	5.8	0.64 (0.37–1.12)	0.73 (0.39–1.36)	0.72 (0.38–1.35)
Q4 (M: 5.94–7.03; W: 7.32–8.46)	19/3,435	5.4	0.59 (0.33–1.06)	0.62 (0.31–1.23)	0.63 (0.31–1.25)
Q5 (M: ≥7.04; W: ≥8.47)	16/3,388	4.4	0.52 (0.28–0.96)	0.42 (0.17–1.06)	0.42 (0.17–1.07)
P for trend			0.04	0.09	0.11
Prediabetes§ (*n* = 526)					
Q1 (M: ≤4.00; W: ≤5.28)	40/1,080	38.0	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
Q2 (M: 4.01–4.93; W: 5.29–6.41)	35/1,120	32.0	0.85 (0.54–1.34)	0.77 (0.49–1.23)	0.76 (0.47–1.21)
Q3 (M: 4.94–5.80; W: 6.42–7.69)	41/1,149	35.1	0.95 (0.61–1.47)	0.83 (0.53–1.30)	0.77 (0.48–1.25)
Q4 (M: 5.81–7.28; W: 7.70–8.70)	32/1,149	28.8	0.75 (0.47–1.19)	0.66 (0.41–1.06)	0.62 (0.36–1.10)
Q5 (M: ≥7.29; W: ≥8.71)	27/1,109	23.5	0.66 (0.40–1.08)	0.53 (0.32–0.89)	0.48 (0.24–0.94)
P for trend			0.09	0.01	0.04
P for heterogeneity between subjects with normal glucose tolerance and prediabetes			0.73	0.96	0.99

†Adjusted for age, sex, family history of diabetes mellitus, hypertension, body mass index, serum total cholesterol, serum high density lipoprotein cholesterol, log-transformed serum triglycerides, current smoking, current alcohol drinking, regular exercise, intakes of total energy, vitamin A, vitamin C, magnesium and polyunsaturated fatty acid/saturated fatty acid ratio. ‡Adjusted for age, sex, family history of diabetes mellitus, hypertension, body mass index, serum total cholesterol, serum high density lipoprotein cholesterol, log-transformed serum triglycerides, current smoking, current alcohol drinking, regular exercise, intakes of total energy, vitamin A, vitamin C, magnesium, polyunsaturated fatty acid : saturated fatty acid ratio, log-transformed homeostasis model assessment of insulin resistance (HOMA-IR) and log-transformed high-sensitivity C-reactive protein (hs-CRP). §Prediabetes was defined as fasting plasma glucose 6.1–6.9 mmol/L and 2-h post-load glucose <7.8 mmol/L, or fasting plasma glucose <7.0 mmol/L and 2-h post-load glucose 7.8–11.0 mmol/L. M, men; PYs, person-years; Q, quintile; W, women.

dieticians who were trained on the dietary questionnaire. Second, it was hard to fully exclude the effects of residual confounders (e.g., health awareness, the quality of the whole meal, eating habits, the effects of other nutrients and socioeconomic status)[48] on the association between dietary fiber intake and the risk of type 2 diabetes. It is known that individuals with good lifestyle habits and high health consciousness have a low risk of type 2 diabetes[49,50]. Dietary fiber is considered to be a key component of a healthy diet, as recommended in several nutritional guidelines[51,52]. Therefore, high dietary fiber intake might serve as an index for the high quality of the whole meal, favorable eating habits for diabetes prevention or health awareness. Finally, the generalizability of the findings might be limited, because the present study was carried out only in a community in Japan.

In conclusion, the results of the present study suggest that individuals with higher total dietary fiber intake had a lower risk of type 2 diabetes in a general Japanese population. Furthermore, both the soluble and insoluble dietary fiber intakes were inversely associated with the risk of type 2 diabetes. Participants with higher total dietary fiber intake consumed soybean and soybean products, vegetables, fruits, fruits juices, and algae, and the food sources of soluble and insoluble dietary fiber were generally similar. Therefore, the intake of high dietary fiber foods might be beneficial for diabetes prevention.

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Table 4 | Spearman's correlation coefficients between food groups and total dietary fiber, soluble dietary fiber and insoluble dietary fiber intake

Food group	Total dietary fiber	Soluble dietary fiber	Insoluble dietary fiber
Rice	0.02	–0.11	0.07
Breads	0.14	0.15	0.14
Noodles and other cereals	0.16	0.21	0.14
Potatoes	0.27	0.24	0.27
Soybean and soybean products	0.60‡	0.64‡	0.57‡
Miso	0.18	0.11	0.20
Pickles	0.06	0.02	0.06
Green vegetables	0.60‡	0.42†	0.65‡
Other vegetables	0.60‡	0.39†	0.66‡
Fruits and fruit juices	0.31†	0.31†	0.30†
Algae	0.33†	0.29	0.34†
Fish	0.15	0.14	0.15
Meat	0.04	0.02	0.05
Eggs	0.17	0.19	0.20
Milk and dairy products	0.18	0.19	0.22
Fats and oils	0.13	0.12	0.13
Sugar and confectioneries	–0.07	–0.07	–0.07
Alcoholic beverages	–0.0009	0.01	–0.005
Salt	–0.01	–0.03	–0.01

†Correlation coefficients of ≥0.30 or ≤–0.30. ‡Correlation coefficients of ≥0.50 or ≤–0.50.

DISCLOSURE

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1 | Incidence rates and hazard ratios for the development of diabetes according to the insoluble : soluble dietary fiber ratio.