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Usual dietary fibre intake according to diabetes status in USA adults – NHANES 2013–2018

Derek C. Miketinas[1]*, Wesley J. Tucker[1,2], Crystal C. Douglas[3] and Mindy A. Patterson[1,2]

[1]*Department of Nutrition and Food Sciences, Texas Woman's University, Houston, TX, USA*
[2]*Institute for Women's Health, Texas Woman's University, Houston, TX, USA*
[3]*Department of Nutrition, Metabolism, & Rehabilitation Sciences, The University of Texas Medical Branch, Galveston, TX, USA*

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Abstract

It is unknown if fibre intake differs across diabetes status in USA adults and is associated with glycaemic outcomes. This cross-sectional analysis utilised National Health and Nutrition Examination Survey cycles 2013–2018 data to estimate usual total dietary fibre intake in USA adults and across diabetes status (no diabetes, prediabetes and type II diabetes (T2D)). Associations among dietary fibre intake and glycaemic outcomes were also reported across groups. Adults (≥ 19 years) with at least one dietary recall were included. Diabetes status was determined from self-report data and measured HbA1c. Independent samples *t* tests were used to compare mean (SE) intake across sub-populations. 14 640 adults (51·3 % female) with 26·4 % and 17·4 % classified as having prediabetes and T2D, respectively. Adults with T2D reported greater mean (SE) dietary fibre intake compared with no T2D for females (9·5 (0·13) *v.* 8·7 (0·11) g/1000 kcal/d and males (8·5 (0·12) *v.* 7·7 (0·11) g/1000 kcal/d; $P < 0·01$)). However, only 4·2 (0·50)% and 8·1 (0·90)% of males and females with T2D, respectively, met the adequate intake for fibre. Fibre intake was associated with lower insulin ($\beta = -0·80$, $P < 0·01$), serum glucose ($\beta = -1·35$, $P < 0·01$) and Homeostatic Model Assessment for Insulin Resistance ($\beta = -0·22$, $P < 0·01$) in adults without diabetes, and no relationships in adults with prediabetes or T2D were found. Although dietary fibre intake was highest among adults with T2D, intake was suboptimal across all groups. In adults without diabetes, dietary fibre intake was associated with improved glycaemic outcomes and insulin resistance; however, these associations were attenuated by anthropometric and lifestyle covariates.

Key words: **Prediabetes: Type 2 diabetes: Adequate intake: Obesity: Carbohydrate quality: Glycaemia**

According to recent Centers for Disease Control and Prevention estimates, roughly half (49·3 %) of all USA adults have either type 2 diabetes (T2D) or prediabetes[1] with diagnosed diabetes cases tripling by 2060[2]. Without treatment, complications from diabetes can lead to a multitude of health-related problems such as CVD, kidney failure and limb amputations[1]. T2D is a multifactorial disease, caused by a wide range (20–80 %) of genetic and environmental factors[3], including poor dietary intake[4], and physical inactivity[5]. In fact, diet and exercise-based lifestyle interventions have been shown to significantly reduce the progression of T2D in adults with overweight/obesity and impaired glucose tolerance[6–8]. Furthermore, the 2022 American Diabetes Association Standards of Medical Care recommend appropriate dietary intake combined with physical activity for diabetes prevention[9]. While a one-size-fits-all dietary plan has not been established to prevent (or treat) T2D[10], individuals with or at risk for developing T2D should consume the recommended amount, or adequate intake (AI; 14 g/1000 kcal/d, or 25 g/d for women and 38 g/d for men) for dietary fibre[11]. Although high fibre intake (≥ 50 g/d) has been shown to modestly lower HbA1c, most recommendations are based on dietary fibre's apparent benefits for coronary heart disease risk reduction[12,13].

Dietary fibre is a non-digestible carbohydrate found naturally in plant-based foods such as whole grains, fruits and vegetables, legumes, beans, peas and nuts. Fibre exhibits beneficial health effects that differ according to physiological function (viscosity and fermentability) instead of solubility. Viscous fibres can entrap nutrients, slow digestion, and promote feelings of fullness, which can attenuate postprandial glucose response[14]. Metabolites produced in the large intestine from the fermentation of certain fibres have been shown to improve insulin sensitivity[15]. In fact, intake of microbiota-accessible fibres can improve glycaemic and cardiometabolic outcomes in adults with T2D[16].

Several prospective and cross-sectional studies indicated that adequate dietary fibre intake can reduce the risk of developing

Abbreviations: AI, adequate intake; NCI, National Cancer Institute; NHANES, National Health and Nutrition Examination Survey; T2D, type II diabetes.

* **Corresponding author:** Derek C. Miketinas, email dmiketinas@twu.edu

T2D. A meta-analysis of observational trials reported that dietary fibre (25–29 g/d) reduced the risk of developing T2D by 16 % and increased dietary fibre intake (> 30 g/d) provided additional protection against CVD, T2D and colorectal and breast cancer[17]. An inverse, dose–response relationship (RR 0·70) between high-fibre, healthy plant-based food adherence and risk of T2D has also been reported[18]. Ultra-processed or 'highly processed' foods are altered from their raw state to improve characteristics such as texture or shelf-life and often possess suboptimal nutrient quality, such as low fibre[19]. A recent meta-analysis of observational studies reported a positive relationship (RR 1·74) between ultra-processed food intake and risk of T2D[20]. These results demonstrate that adequate dietary fibre intake may help in the prevention of T2D. Unfortunately, 95 % of USA adults do not meet the recommendations for dietary fibre with a mean daily fibre intake of 16·2 g/d[21].

While dietary fibre appears to have a linear, dose-dependent response on diabetes risk and consuming higher amounts can improve diabetes-related outcomes, the amount of fibre consumed by USA adults with prediabetes and T2D remains unexplored. Here, we estimated the usual intake of dietary fibre (without supplements) using data from the National Health and Nutrition Examination Survey (NHANES) cycles 2013–2018 across diabetes status: no diabetes, prediabetes or T2D. We hypothesised that there would be no differences in dietary fibre intake across groups. We also assessed the association between dietary fibre intake (g/d) and glycaemic outcomes. We hypothesised that there would be modest associations among dietary fibre intake and some glycaemic markers across diabetes groups.

Methods

Study design

This secondary analysis of the NHANES data included survey cycles from 2013 to 2018. The NHANES utilises a complex, multi-stage probability sampling design that provides a nationally representative sample of the non-institutionalised USA population. NHANES personnel collected data first from an in-home interview followed by a visit to the mobile examination centre in which dietary and laboratory measurements were collected. Details of the survey design and protocol are available online[22,23].

Subjects

Inclusion criteria for this analysis were non-pregnant adults (≥ 19 years) with at least one reliable 24-h dietary recall for the NHANES 2013–2018. Pregnancy status was determined from self-reported pregnancy status or a positive urinary pregnancy test. Respondents were grouped by diabetes category (no diabetes, prediabetes or T2D). The T2D and prediabetes groups were identified by either a self-reported physician diagnosis or having a HbA1c ≥ 6·5 % or a HgA1c between 5·7 and 6·4 %, respectively. Demographics including gender, age, race/ethnicity, family income:poverty ratio and educational attainment were collected.

Smoking status was defined as current, former and never cigarette smokers based on the two variables SMQ020 and SMQ040. Alcohol consumption categories were classified as none, moderate and excessive intake based on reported intake of no alcohol consumption, 1–2 drinks per day for women (1–3 drinks per day for men) and 3 or more drinks per day for women (four or more drinks per day for men) over the past 12 months.

Diabetes medication use and statin medication use were determined from responses to the prescription medications questionnaire. Use for either class of medication was determined by reported consumption of a medication based on the ICD-10-CM codes for each medication.

Dietary assessment

A trained dietary interviewer administered a 24-h dietary recall using the automated multiple pass method during the mobile examination centre visit[24,25]. Following the MEC visit, a second dietary recall via telephone was collected 3–11 d later. Dietary fibre intake was described as g/d and g/1000 kcal/d. Dietary fibre intake from supplements was not considered in this analysis.

Laboratory measures

HbA1c (%) was measured using the Tosoh G8 glycohemoglobin analyzer using whole blood. Serum glucose (mg/dl) was measured using the hexokinase enzymatic method on a Roche/Hitachi Cobas C Chemistry Analyzer-C311. A subsample of respondents was asked to fast for 9 h, including those with T2D, to provide fasting measurements for insulin and plasma glucose. Fasting plasma glucose (mg/dl) was also measured using the hexokinase enzymatic method. Fasting insulin (uU/ml) was measured using the Tosoh AIA-PACK IRI, a two-site immunoenzymometric assay. Homeostatic Model Assessment for Insulin Resistance was calculated using the following equation: (insulin (uU/ml) × glucose (mmol/l))/22·5. HOMA-%B was calculated using the following equation: (20 × insulin (uU/ml))/(glucose (mmol/l)–3·5).

Statistical analyses

All analyses were conducted using SAS software version 9·4 (SAS Institute Inc.). The appropriate sample weights were used to account for the complex sampling design. Differences in continuous and categorical variables were tested using independent samples t tests and Rao-Scott χ^2 tests, respectively. A P-value $< 0{\cdot}01$ was considered statistically significant.

The National Cancer Institute (NCI) method (amount only model) was used to assess usual intake for dietary fibre across subgroups of interest[26]. In short, the NCI method involves a two-part model using the MIXTRAN and DISTRIB macros created by the NCI. First, it assesses the probability of consumption on a given day while controlling for covariates. Second, it assesses the amount of food on the consumption day(s) on a transformed scale while controlling for covariates (e.g. dietary recall sequence, weekend recall, etc.). Usual intake is the probability of consumption multiplied by the amount consumed. Next, the BRR_PVALUE_CI macro is employed to calculate

Table 1. Characteristics of USA adults stratified across diabetes categories

	No Diabetes (*n* 8221)		Prediabetes (*n* 3865)		T2D (*n* 2554)		
	Mean	SE	Mean	SE	Mean	SE	*P* value[a]
Age, years	43·3	0·3*	54·6	0·4†	59·9	0·4‡	
Gender, %							< 0·001
Female	51·2	0·7	53·4	0·8	47·9	1·7	
Race/Ethnicity, %[b]							< 0·001
Mexican American	8·5	0·9	9·4	1·9	8·5	0·9	
Other Hispanic	5·9	0·6	6·9	0·6	5·9	0·6	
Non-Hispanic White	67·1	1·9	58·9	2·0	67·1	1·9	
Non-Hispanic Black	9·5	0·9	14·5	1·3	9·5	0·9	
Non-Hispanic Asian	5·4	0·6	6·1	0·7	5·4	0·6	
Education, %							< 0·001
Less than 9th grade	3·1	0·3	5·2	0·5	8·3	0·8	
9–11th grade	7·9	0·5	8·7	0·7	11·0	1·1	
High school graduate/GED or equivalent	23·0	0·9	25·0	1·2	25·0	1·0	
Some college	32·0	0·8	31·0	1·2	33·0	1·6	
College graduate or above	33·0	1·5	29·0	1·9	21·0	1·6	
Income-to-poverty ratio	3·0	0·06*	3·0	0·07*,†	2·8	0·06†	
BMI, kg/m^2	28·0	0·1*	30·9	0·1†	33·3	0·2‡	
BMI category, %							< 0·001
Underweight	1·9	0·1	0·8	0·2	0·1	0·0	
Normal weight	33·0	0·9	17·0	0·9	9·4	0·8	
Overweight	32·0	0·7	33·0	1·0	25·0	1·2	
Obese	31·0	1·0	48·0	1·0	64·0	1·5	
Waist circumference, cm	96·3	0·4*	104·0	0·3†	112·0	0·5‡	
Smoking status, %							< 0·001
Current	18·0	0·7	18·0	0·9	14·0	1·2	
Former	21·0	0·7	27·0	0·9	35·0	1·6	
Never	59·0	0·9	53·0	0·8	50·0	1·6	
Alcohol consumption, %[c]							< 0·001
None	23·0	1·1	33·0	1·2	40·0	1·7	
Moderate	39·0	0·7	33·0	1·0	33·0	2·0	
Excessive	37·0	0·8	33·0	1·0	25·0	1·7	

T2D, type 2 diabetes; GED, General Educational Development.
Values are mean (SE) from individuals with at least one day of reliable intake data from NHANES 2013–2018. Diabetes category was determined through either self-report of physician diagnosis or HbA1c values. Similar symbols indicate significant differences. aGroups were compared using independent samples *t* tests and Rao-Scott χ^2 tests for continuous and categorical variables, respectively. Pairwise differences in continuous variables are indicated by different capital letters.
bThe proportions do not sum to 100 % given that the 'Other' race/ethnicity category is not represented.
cModerate and excessive alcohol consumption for women was defined as consuming 1–2 drinks/d and 3 or more drinks/d, respectively, and 1–3 drinks/d and 4 or more drinks/d for men, respectively.

standard error using Balanced Repeated Replication variance estimation. For nutrients consumed daily, part 1 is not necessary for analysis; this is called the amount-only model.

To test for the relationship between dietary fibre intake and glycaemic outcomes, we used regression models calibrated for measurement error using the NCI method[27]. We ran the models separately for each subgroup of interest (no diabetes, prediabetes and T2D). For each outcome, we ran three models with varying levels of covariates:

Model 1: Age, race/ethnicity, gender, education, family income:poverty ratio, statin use, survey cycle

Model 2: Model 1 covariates + BMI, waist circumference, hypertension

Model 3: Model 2 covariates + smoking status, physical activity and alcohol use

For those with T2D, age at diabetes diagnosis and diabetes medication use were included as covariates for all models. We described the effect of dietary fibre intake on glycaemic outcomes as the slope of the regression (β) and as the differences in the glycaemic outcomes between the 75th and 25th percentile of dietary fibre consumption.

Results

Sample population

Characteristics of the sample can be found in Table 1. The sample size included 14 640 USA adults (51·3 % female), mostly non-Hispanic white (> 58 % for each category) with a mean age of 43·3 (0·3) years, 54·6 (0·4) years, 59·9 (0·4) years in the no diabetes, prediabetes and T2D groups, respectively. Adults with T2D were less likely to be college graduates, have a lower income-to-poverty ratio, more likely to have obesity, have a higher waist circumference, be a former smoker and less likely to consume alcohol compared with adults with no diabetes and prediabetes.

More than half of the sample were classified as having no diabetes (56·2 %), while 26·4 % had prediabetes and 17·4 % had T2D. The prevalence of T2D increased among the age groups. For example, for adults with T2D, 93·7 % were 40 years and older. In the prediabetes category, 44·0 % were ≥60 years, 37·9 % were 40–59 years and 18·1 % were 20–39 years of age. On the contrary, most adults with no diabetes (78·2 %) were less than 60 years.

Table 2. Usual daily total fibre intake in USA adults

		Mean fibre g/1000 kcal		% ≥ AI		Percentiles					
						25		50		75	
	n	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
All adults	14 640	8·4	0·08	4·0	0·43	6·3	0·07	8·0	0·08	10·1	0·11
Male	7136	7·9	0·1*	2·6	0·38	5·9	0·08	7·6	0·10	9·5	0·13
Female	7504	8·8	0·09*	5·3	0·54	6·7	0·09	8·5	0·09	10·6	0·12

AI, adequate intake.
Values are mean (SE) from individuals with at least one day of reliable intake data from NHANES 2013–2018. Total dietary fibre does not include fibre supplements.
* $P < 0·001$ between-sex groups.

Table 3. Usual daily total fibre intake in USA adults across sex and diabetes category

		Mean fibre g/1000 kcal		% Meeting AI		Percentiles					
						25		50		75	
	n	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Male											
No diabetes	3961	7·7	0·11*,†	2·3	0·40	5·8	0·09	7·4	0·11	9·4	0·14
Prediabetes	1842	7·9	0·10*,‡	2·5	0·40	5·9	0·10	7·6	0·11	9·6	0·15
T2D	1333	8·5	0·12†,‡	4·2	0·50	6·4	0·11	8·2	0·11	10·2	0·14
Female											
No diabetes	4260	8·7	0·11*,†	4·8	0·50	6·6	0·09	8·4	0·10	10·4	0·14
Prediabetes	2023	8·8	0·10*,‡	5·3	0·60	6·7	0·10	8·5	0·10	10·6	0·13
T2D	1221	9·5	0·13†,‡	8·1	0·90	7·2	0·12	9·2	0·13	11·3	0·16

AI, adequate intake; T2D, type 2 diabetes.
Values are mean (SE) from individuals with at least one day of reliable intake data from NHANES 2013–2018. Total dietary fibre does not include fibre supplements. Similar symbols indicate $P < 0·01$ across diabetes category within the same-sex group.

Usual daily total fibre intake in all adults and by sex

The usual daily total fibre intake overall and by sex can be found in Table 2. Overall, the mean fibre intake was 8·4 g/1000 kcal/d with only 4·0 % of USA adults meeting the AI for dietary fibre. Adult females had higher fibre intake (8·8 g/1000 kcal/d) than males (7·9 g/1000 kcal/d; $P < 0·001$) with only 5·3 % of females and 2·6 % of males meeting the AI.

Usual daily total fibre intake across sex, age and diabetes category

In contrast to our hypothesis, adults with T2D had the highest dietary fibre intake (9·5 g/1000 kcal/d for females; 8·5 g/1000 kcal/d for males) compared with those with no diabetes and prediabetes ($P < 0·01$ across diabetes category within sex group) as shown in Table 3. Although adults with T2D had the highest dietary fibre intake, only 8·1 % of females and 4·2 % of males met the AI for dietary fibre. Adults with prediabetes had the second highest dietary fibre intake (8·8 g and 7·9 g/1000 kcal/d for females and males, respectively); only 5·3 % of females and 2·5 % of males with prediabetes met the AI. The lowest dietary fibre intake was reported among adults with no diabetes (8·7 g and 7·7 g/1000 kcal/d for females and males, respectively) and only 4·8 % of females and 2·3 % of males met the AI.

Dietary fibre intake differed with age across diabetes categories and within the same sex. Older adults (≥ 60 years) reported the highest dietary fibre intake across each diabetes category within the same sex ($P < 0·01$; Table 4). The fibre intake for older adults ranged from 9·3–9·8 g/1000 kcal/d for females to 8·5–8·9 g/1000 kcal/d for males. Dietary fibre intake ranged 8·4–9·1 g/1000 kcal/d for females and 7·7–8·1 g/1000 kcal/d for males between 40 and 59 y. Adults 20–39 years had fibre intake that ranged between 8·2–8·6 g/1000 kcal/d for females and 7·3–7·7 g/1000 kcal/d for males.

Association between usual daily total fibre intake and glycaemic outcomes across diabetes category

Dietary fibre intake was associated with lower fasting insulin ($\beta = -0·80$, $P < 0·01$), fasting glucose ($\beta = -1·35$, $P < 0·01$) and Homeostatic Model Assessment for Insulin Resistance ($\beta = -26·96$, $P < 0·01$) in adults with no diabetes (Table 5). These associations were only found in Model 1. No associations between glycaemic outcomes and dietary fibre intake were observed in adults with prediabetes or T2D.

Discussion

We examined data from the NHANES cycles 2013–2018 to estimate usual total dietary fibre intake among USA adults according to diabetes category. Current study findings are concerning as overall dietary fibre intake was well below recommendations

Table 4. Usual daily total fibre intake in USA adults by sex, diabetes and age categories

		Mean fibre g/1000 kcal		% ≥ AI		Percentiles					
						25		50		75	
	N	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Male											
No diabetes											
20–39 years	1914	7·4	0·11*,†	1·6	0·30	5·5	0·09	7·1	0·11	9·0	0·14
40–59 years	1164	7·8	0·14*,‡	2·4	0·50	5·8	0·12	7·5	0·14	9·5	0·18
≥ 60 years	883	8·5	0·13†,‡	4·0	0·60	6·5	0·11	8·2	0·13	10·2	0·17
Prediabetes											
20–39 years	349	7·3	0·13*,†	1·4	0·30	5·5	0·11	7·1	0·13	8·9	0·17
40–59 years	713	7·7	0·15*,‡	2·0	0·40	5·8	0·12	7·4	0·14	9·3	0·19
≥ 60 years	780	8·4	0·12†,‡	3·6	0·60	6·4	0·13	8·1	0·12	10·1	0·14
T2D											
20–39 years	64	7·7	0·17*,†	2·0	0·60	5·8	0·17	7·4	0·19	9·3	0·22
40–59 years	413	8·1	0·15*,‡	3·0	0·60	6·1	0·14	7·8	0·15	9·8	0·17
≥ 60 years	856	8·9	0·13†,‡	5·5	0·70	6·8	0·12	8·6	0·13	10·6	0·16
Female											
No diabetes											
20–39 years	1930	8·3	0·11*,†	4·6	0·50	6·3	0·10	8·0	0·11	10·0	0·14
40–59 years	1420	8·7	0·13*,‡	4·7	0·60	6·6	0·12	8·4	0·14	10·5	0·17
≥ 60 years	910	9·5	0·14†,‡	7·9	0·90	7·3	0·12	9·1	0·14	11·3	0·18
Prediabetes											
20–39 years	351	8·2	0·14*,†	3·1	0·60	6·2	0·12	7·9	0·14	9·9	0·17
40–59 years	753	8·5	0·14*,‡	4·2	0·70	6·5	0·12	8·3	0·14	10·3	0·17
≥ 60 years	919	9·3	0·11†,‡	7·4	0·80	7·2	0·10	9·0	0·11	11·2	0·14
T2D											
20–39 years	98	8·6	0·18*,†	4·7	0·80	6·6	0·17	8·4	0·19	10·4	0·22
40–59 years	409	9·1	0·14*,‡	6·1	0·80	6·9	0·14	8·8	0·14	10·9	0·19
≥ 60 years	714	9·8	0·15†,‡	9·8	1·10	7·6	0·14	9·5	0·15	11·7	0·20

AI, adequate intake; T2D, type 2 diabetes.
Values are mean (SE) from individuals with at least one day of reliable intake data from NHANES 2013–2018. Total fibre does not include supplements. Similar symbols indicate $P < 0·01$ across age groups within the same diabetes and sex category.

across all diabetes categories. Although dietary fibre intake was highest among adults with T2D and lowest in adults with no diabetes, no group met the current AI recommendation of 14 kcal/1000 g/d. In addition, no relationship was observed between dietary fibre intake and glycaemic outcomes in adults with prediabetes and T2D, possibly due to inadequate intake. In contrast, lower fasting glucose and insulin concentrations were associated with higher dietary fibre intake in adults with no diabetes.

The characteristics of adults with T2D in our sample are similar to other reports. Here, we show that adults with T2D are older, less likely to be a college graduate, have a lower income-to-poverty ratio and have higher rates of obesity. Data from the Centers for Disease Control and Prevention exhibit 26·8 % of adults ≥ 65 years have T2D compared with 17·5 % of 45–65 years and 4·2 % of 18–44 years[28]. Low socio-economic status, assessed here using education attainment and income: poverty ratio, is associated with T2D. In the same Centers for Disease Control and Prevention report, adults with a lower income:poverty ratio of < 100 % (14·1 %) and less than high school education (13·3 %) were more likely to have a T2D diagnosis[28]. Both variables are indicators of socio-economic status. In addition, 89·0 % of adults with T2D had a BMI ≥ 25 kg/m^2 and were more likely to be a former smoker (36·4 %),[28] which is similar to our sample where 89·0 % were overweight or obese and 35·0 % were former smokers.

The low intake of fibre reported among this sample is not surprising. According to earlier NHANES data (2009–2010), the USA population consumes an average of 16·2 g of fibre per day[21]. After controlling for energy, fibre density by sex was similarly low (8–10 g/1000 kcal/d for females and 7–9 g/1000 kcal/d for males)[21]. We observed similar results where dietary fibre intake ranged from 8·7–9·5 g/1000 kcal/d in females to 7·7–8·5 g/1000 kcal/d for males across diabetes categories. Clear associations between low intake of fibre-rich foods such as fruits, vegetables, and whole grains and poor overall diet quality have been well established as indicated by the 2015-Healthy Eating Index score of 57·7 out of 100[29]. In addition, our results found that older adults (> 60 years) consume more fibre than the other age groups. Similarly, others have shown increased dietary fibre and improved diet quality (Healthy Eating Index score of 64) among ≥ 70 years old adults compared with the youngest age group (Healthy Eating Index score of 53)[30]. Shifts in dietary patterns that include higher quality nutrient-dense foods may partially explain why older adults consume the most fibre.

Despite numerous accounts of dietary fibre's health benefits, overall intake among this USA sample was suboptimal. It is unclear why dietary fibre intake is so poor, but plausible explanations include inadequate knowledge of fibre-rich foods, high processed food intake, limited financial resources or following diet trends or fads that are known to be low in fibre such as low-carbohydrate or ketogenic diets[31,32]. We also found that adults with T2D diagnosis reported the greatest fibre intake. While this finding is contrary to our hypothesis, it is possible that a chronic disease diagnosis prompts dietary change. Stretliz et al.

Table 5. Association between dietary fibre intake (g/d) and glycaemic outcomes in USA adults across diabetes category

	No Diabetes						Prediabetes						T2D					
			95 % CI						95 % CI						95 % CI			
	B	SE	LCLM, UCLM	DIFF	SE	*P*	*B*	SE	LCLM, UCLM	DIFF	SE	*P*	*B*	SE	LCLM, UCLM	DIFF	SE	*P*
HbAlc, %																		
Model 1*	0·01	0·01	–0·01, 0·03	0·01	0·01	0·3492	0·01	0·01	–0·02, 0·04	0·01	0·02	0·6549	–0·06	0·13	–0·31, 0·19	–0·05	0·1	0·628
Model 2†	0·02	0·01	–0·01, 0·04	0·01	0·01	0·1718	0·01	0·02	–0·02, 0·04	0·01	0·02	0·6081	–0·12	0·13	–0·38, 0·14	–0·1	0·11	0·3663
Model 3‡	0·02	0·01	0, 0·04	0·02	0·01	0·1108	0·01	0·01	–0·02, 0·03	0·01	0·02	0·622	–0·13	0·14	–0·4, 0·14	–0·11	0·11	0·3482
Fasting insulin, μU/ml																		
Model 1	–0·8	0·31	–1·4, –0·2	–0·65	0·25	0·0087*	–1·1	1·01	–3·08, 0·87	–1·56	1·42	0·2722	–0·92	3·67	–8·11, 6·27	–0·75	3	0·8019
Model 2	–0·13	0·3	–0·71, 0·45	–0·1	0·24	0·6685	–0·75	0·82	–2·35, 0·85	–1·05	1·15	0·3609	1·61	3·9	–6·04, 9·26	1·28	3·11	0·6806
Model 3	–0·15	0·29	–0·71, 0·4	–0·13	0·23	0·5878	–0·57	0·85	–2·23, 1·09	–0·8	1·19	0·502	1·19	3·92	–6·49, 8·87	0·95	3·12	0·7608
Fasting glucose, mg/dl																		
Model 1	–0·73	0·54	–1·79, 0·34	–0·59	0·44	0·1824	–0·03	1·05	–2·1, 2·04	–0·04	1·53	0·9772	6·33	8·95	–11·21, 12·87	5·05	7·13	0·4791
Model 2	–0·35	0·5	–1·34, 0·63	–0·29	0·41	0·4827	0·41	1·24	–2·03, 2·84	0·57	1·76	0·7448	1·98	8·19	–14·07, 18·03	1·62	6·71	0·8088
Model 3	–0·33	0·49	–1·28, 0·63	–0·27	0·4	0·4992	0·35	1·15	–1·91, 2·61	0·5	1·63	0·7601	0·27	7·54	–14·51, 15·05	0·22	6·18	0·9712
Glucose, mg/dl																		
Model 1	–1·35	0·47	–2·28, –0·43	–1·1	0·38	0·0042*	–0·74	0·85	–2·41, 0·92	–1·05	1·2	0·3822	3·9	6·22	–8·29, 16·09	3·29	5·24	0·5303
Model 2	–0·9	0·46	–1·79, 0	–0·73	0·37	0·0497	–0·61	0·87	–2·32, 1·09	–0·89	1·26	0·4789	0·03	6·2	–12·12, 12·18	0·03	4·94	0·9957
Model 3	–0·92	0·46	–1·82, –0·02	–0·75	0·38	0·0451	–0·57	0·89	–2·31, 1·18	–0·8	1·26	0·5235	–0·59	6·18	–12·69, 11·52	–0·47	4·92	0·924
HOMA-IR																		
Model 1	–0·22	0·08	–0·38, –0·06	–0·18	0·07	0·0067*	–0·3	0·28	–0·85, 0·26	–0·43	0·41	0·2961	–0·43	1·91	–4·18, 3·31	–0·35	1·56	0·8206
Model 2	–0·04	0·08	–0·19, 0·11	–0·03	0·06	0·5942	–0·19	0·24	–0·65, 0·27	–0·28	0·34	0·4232	0·2	1·98	–3·67, 4·08	0·17	1·62	0·9185
Model 3	–0·05	0·07	–0·19, 0·09	–0·04	0·06	0·4992	–0·15	0·25	–0·65, 0·35	–0·21	0·36	0·5527	–0·1	2	–4·02, 3·82	–0·08	1·59	0·96
HOMA-β																		
Model 1	–26·96	19·92	–66, 12·08	–22	16·26	0·1759	–10·53	7·55	–25·33, 4·27	–15·3	10·97	0·163	–112·41	106·36	–320·87, 96·06	–92·08	87·12	0·2906
Model 2	–21·16	19·73	–59·83, 17·51	–17·27	16·1	0·2834	–8·74	6·37	–21·22, 3·75	–12·7	9·26	0·1704	5·74	20·34	–34·13, 45·6	4·57	16·21	0·7779
Model 3	–19·07	17·76	–53·88, 15·74	–15·56	14·5	0·283	–6·92	6·54	–19·74, 5·9	–9·78	9·23	0·2898	8·83	20·3	–30·95, 48·61	7·04	16·18	0·6636

B, regression coefficient; DIFF, difference in outcome of interest between the 25th and 75th percentile of fibre intake; HOMA-IR, Homeostatic Model Assessment for Insulin Resistance; HOMA-β, Homeostasis Model Assessment of β-cell Function; LCLM, lower confidence limit for the mean; T2D, type 2 diabetes; UCLM, upper confidence limit for the mean.
Linear regression was used to identify relationships among fibre intake and glycaemic outcomes. Dietary fibre did not include fibre from supplements.
Age at diabetes diagnosis and diabetes medication use were included as covariates for all three models for those with T2D only.
* Model 1 covariates: statin use, age, race/ethnicity, gender, education, income:poverty ratio and survey cycle.
† Model 2 covariates: model 1 covariates plus BMI, waist circumference and hypertension diagnosis.
‡ Model 3 covariates: model 2 covariates plus smoking status, physical activity and alcohol use.

reported that following T2D diagnosis, adults make healthy dietary changes including decreasing energy and fat intake and increasing dietary fibre intake[33]. In addition, a recent study found that adults diagnosed with T2D consumed more higher quality carbohydrates, plant and animal proteins, unsaturated fatty acids and less low-quality carbohydrates than those with undiagnosed diabetes[34]. Diabetes prevention and management strategies highlight behavioural changes necessary to prevent or delay T2D. In fact, the National Diabetes Prevention Program, a Center for Disease Control and Prevention-led lifestyle change program, promotes eating well and instructs participants on increasing dietary fibre and making food selections based on dietary fibre content[35].

Contrary to earlier reports and our hypothesis, we did not discern a relationship between dietary fibre and glycaemic outcomes in adults with prediabetes or T2D. It is plausible that this absence of a relationship is due to low dietary fibre intake in our population. Other studies have reported associations with glycaemic outcomes when dietary fibre intake is met or exceeded. For example, in normal weight adult males with T2D who consumed 65 g plant fibre/d for 2 weeks had reduced or eliminated insulin requirements, and most had decreased fasting and postprandial glucose concentrations, compared with a control diet[36]. Another study found that adults with T2D consuming a high fibre (36·3 g/d) vegan diet decreased HbA1c concentrations and body weight more than those randomised to a standard American Diabetes Association diet providing 19·0 g dietary fibre/d at 22 weeks[37]. In addition, 43 % of participants in the vegan diet group had reduced reliance on glucose-lowering medications compared with 26 % in the American Diabetes Association group[37]. These studies included dietary fibre that met or exceeded the current recommendations, as well as the average amounts observed in this analysis, may have led to major improvements in glycaemic outcomes.

Associations among dietary fibre, diabetes status and glycaemic outcomes have been explored in other countries. Finnish adults without diabetes who consumed greater dietary fibre intake (> 15·55 g/d) had a reduced risk for diabetes development following a Diabetes Prevention Program compared with those with lower fibre intake (< 10·85 g/d)[38]. Chinese adults who consumed ≥ 7·2 g fibre/d had no change in HbA1c,[39] and Italian adults with and without diabetes consumed similar amounts of fibre albeit intake was below recommendations[40]. Still, dietary fibre intake outside the USA is suboptimal, but higher intake has been associated with a reduced risk of developing diabetes in some studies.

This study has several strengths. We estimated usual total dietary fibre, the long-term evaluation of daily intake, according to the NCI method. The validity of the NCI method has been previously recognised as a tool to mitigate the effects of measurement error to provide unbiased estimates of usual intake[26]. Our sample consisted of a large, representative group of USA adults. Also, diabetes category was determined using data from the personal interview as well as biomarkers. The inclusion of blood biomarkers enabled us to assess for relationships between dietary fibre intake and glycaemic outcomes.

The NHANES is an established and on-going nationally represented dataset, but limitations for secondary data analysis exist and must be acknowledged. The dietary analyses do not include fibre supplements, and as such, outcomes may not be representative of usual intake. Fibre supplements are an isolated fibre source that can conveniently promote increased fibre intake. One meta-analysis did show improved glycaemic outcomes in adults with T2D after consuming a soluble fibre supplement[41], and perhaps including fibre supplements along with dietary fibre intake would have elicited different glycaemic outcomes. Fibre viscosity and fermentability, which possess unique physiological effects, were not distinguished and limit our understanding on fibre classification and glycaemic outcomes[42]. Though trained interviewers collect the 24-h diet recall using the automated multiple pass method[24,25], we recognise that the data re self-reported and prone to recall bias. Lastly, although we did not find associations among glycaemic outcomes in adults with prediabetes or T2D, adequate dietary fibre has been shown to improve other T2D risk factors, such as elevated blood lipids[37,43], overweight and obesity[44] and incidence of CVD and mortality[33]. These outcomes were not assessed in the present study.

In conclusion, older adults and adults diagnosed with T2D consumed more dietary fibre than adults with no diabetes or prediabetes. However, no group consumed the recommended AI for dietary fibre. Although higher fibre intake was associated with lower fasting glucose and insulin in adults with no diabetes, these associations were not found in adults with prediabetes or T2D, which may be related to suboptimal dietary fibre intake. Moreover, the observed associations were attenuated when BMI, waist circumference and hypertension status were included as covariates. Future studies should focus on glycaemic, as well as CVD risk, outcomes across diabetes status where the AI for fibre is met or exceeded. Given the protective health benefits of dietary fibre, it is imperative that we implement strategies to support increased intake of dietary fibre in the USA diet.

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