Dietary Fiber Reduces the Concentrations of Certain Aldehydes in Serum

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Abstract

Aldehydes have been shown to be potentially carcinogenic, mutagenic, and cardiotoxic to humans. Dietary fiber reduces exposure to certain environmental pollutants and has been widely used to improve various metabolic disorders. However, the effects of dietary fiber on serum concentrations of aldehydes remain unexplored. We collected data from the National Health and Nutrition Examination Survey (NHANES) 2013–2014. Generalized linear regression and restricted cubic spline models were performed to elucidate the association of dietary fiber intake with the serum concentration of aldehydes. After fully adjusting for age, sex, education level, race, smoking status, alcohol use, diabetes, hypertension, body mass index, energy intake, poverty-income ratio and physical activity, dietary fiber intake had a strong negative association with serum levels of isopentanaldehyde and propanaldehyde and a positive association with serum levels of benzaldehyde. The estimated increases in the mean log₂-unit (ng/mL) of aldehydes for each fold increase in dietary fiber ranged from – 0.155 (95% confidence intervals [CI]: -0.210 to -0.101) for isopentanaldehyde to -0.053 (95% CI: -0.094 to -0.011) for propanaldehyde and 0.156 (95% CI: 0.091 to 0.222) for benzaldehyde. No significant association was observed between dietary fiber intake and the concentration of any other aldehydes. These results demonstrate that dietary fiber reduces the concentration of certain aldehydes in serum.

Introduction

Exposuromics has revealed the interrelated interactions of physicochemical, human toxicity, ecotoxicological and exposure data (Fan et al. 2016; Jeliaskova et al. 2021). Aldehydes are common organic compounds produced from a variety of sources, such as e-cigarettes and tobacco smoke, environmental exposure, dietary intake and endogenous intermediary metabolism, to which organisms are frequently exposed (O'Brien et al. 2005; Silva et al. 2021). Studies have linked aldehydes to various human diseases (Uchida 2000) due to their cytotoxicity (Xie et al. 2016). Our previous studies have shown that serum isopentanaldehyde is associated with obesity (Liao et al. 2020), and that benzaldehyde and isopentanaldehyde are associated with CVD (Liao et al. 2020), and these findings have also been verified by another study (Xu et al. 2020).

Dietary fiber is widely recognized as a beneficial component derived from vegetables, fruits, legumes, nuts and various grains in plant-based foods. Evidence indicates that an increased proportion of energy-adjusted dietary fiber can improve glucose metabolic disorders (Lin et al. 2015; Sekgala et al. 2018), decrease visceral fat (Bajerska et al. 2018) and may protect against coronary artery disease (Basu et al. 2021). Additional evidence comes from recent studies showing that high dietary fiber can reduce the risk of intestinal diseases, such as colorectal cancer (Dahm et al. 2010) and Crohn's disease (Ananthakrishnan et al. 2013). In renal diseases, a high-fiber diet has also been shown to improve kidney function, reduce inflammation and lower the risk of mortality (Xu et al. 2014).

However, there are few data evaluating dietary fiber in regulating potentially harmful organic compounds. A large population-based study proved that exposure to environmental tobacco smoke (ETS) under workplace conditions was associated with low intake of fruits and vegetables (Emmons et al. 1995). Although ETS is a significant source of aldehydes, the direct relationship between the two has not been further investigated. The emerging field of precise nutrition can provide effective strategies for public health through high-dimensional data analysis (Wang and Hu 2018). Therefore, based on the established data, we should explore the role of precise regulation of nutrition to eliminate harmful components. Therefore, using national health examination surveys conducted in 2013–2014, we evaluated the effect of the energy-adjusted dietary fiber available in daily life on serum aldehyde concentration.

Materials And Methods

Study population

The National Health and Nutrition Examination Survey (NHANES) was designed and conducted to continuously monitor the nutritional status and health of American noninstitutionalized civilians by the National Centers for Disease Control and Prevention (CDC). The population was collected from the NHANES surveys in 2013–2014, which were provided online (<https://www.cdc.gov/nchs/nhanes/index.htm>). We included 10175 participants in total, while 7849 were excluded for missing serum aldehyde data. Participants without dietary fiber data (n = 5), aged under 18 (n = 224), and pregnant individuals (n = 18) were further excluded, leaving a total of 1877 people available for the final analysis (Fig. 1).

Aldehydes measurements

The CDC has developed an automated analytical method using solid phase microextraction (SPME) gas chromatography (GC) and high-resolution mass spectrometry (HRMS) with selected ion mass detection and isotope-dilution techniques to quantify the content of aldehydes in serum. Each sample was measured twice to reduce measurement errors in the laboratory. We selected aldehydes that were detected in > 80% of participants to explore their relationship between dietary fiber intake and the serum concentrations of aldehydes, including isopentanaldehyde, butyraldehyde, hexanaldehyde, heptanaldehyde, propanaldehyde, and benzaldehyde.

Dietary fiber measurements

As one part of the NHANES survey, all participants were required to complete two 24 h dietary recall interviews. The first interview was administered by trained personnel in the mobile examination center, and the second interview was conducted by telephone 3 to 10 days later. Dietary fiber intake was calculated by the US Department of Agriculture (USDA) Food and Nutrient Databases for Dietary Studies (FNDDS) (<https://www.cdc.gov/nchs/tutorials/dietary/SurveyOrientation/ResourceDietaryAnalysis/intro.htm>). Daily dietary fiber intake was averaged based on the two 24 h recall data and adjusted by the total energy intake.

Covariates

Covariates included age, sex, education level (< 9th grade, 9–11th grade, high school graduate, college degree, college graduate or above), race (Mexican American, other Hispanic American, non-Hispanic black, non-Hispanic white, and others), hypertension (yes or no) and diabetes (yes or no), body mass index (BMI, kg/m²), past smoking (at least 100 cigarettes in life or not) or alcohol use (at least 12 alcohol drinks per year or not), daily energy intake, physical activity and poverty-income ratio. Total daily energy intake was calculated by averaging the energy intake of diet and dietary supplements. Daily physical activity time was multiplied by the corresponding metabolic equivalent (MET) score to assess physical activity level. The poverty-income ratios were defined as the ratio of household income to the threshold adjusted by inflation and household size.

Statistical methods

Continuous variables are expressed as the mean (standard deviation, SD) and were compared using a t-test (normal distribution). Categorical variables presented as numbers (frequencies, %) were analyzed by the chi-squared test. Log₂ transformation was used because of the skewed distribution of the energy-adjusted dietary fiber and all aldehydes. The energy-adjusted dietary fiber intake was calculated as grams per day according to the regression residuals of fiber on total energy intake. A generalized linear model and restricted cubic spline (3 knots located at the 10th, 50th, 90th) were performed to assess the associations of dietary fiber (both in quantiles and continuously) with the serum concentrations of aldehydes after adjusting for confounding factors, including age, sex, education level, race, smoking status, alcohol use, diabetes, hypertension, body mass index, energy intake, poverty-income ratio and physical activity. All statistical analyses were performed with R software version 3.6.0. $P < 0.05$ was considered as significant.

Results

Baseline characteristics

The demographic characteristics are displayed in Table 1. Age, educational level, race, hypertension, BMI, smoking, alcohol consumption, physical activity and poverty-income ratio (all $P < 0.01$) showed significant differences in the groups with different levels of energy-adjusted dietary fiber intake. Participants with higher dietary fiber intake were older, had lower BMIs, had a higher poverty-income ratio, and had a lower likelihood of smoking, drinking and vigorous physical activity.

Association between dietary fiber intake and the serum concentrations of aldehydes

After fully adjusting for confounding factors, including age, sex, education level, race, smoking, alcohol use, diabetes, hypertension, body mass index, energy intake, poverty-income ratio and physical activity, compared with the lowest quantile of dietary fiber, a high level of dietary fiber (>75th percentile) was associated with lower serum concentrations of isopentanaldehyde ($\beta = -0.361$, 95% confidence interval [CI]: -0.475 to -0.248) and propionaldehyde ($\beta = -0.139$, 95% CI -0.225 to -0.053) and higher serum concentrations of benzaldehyde ($\beta = 0.334$, 95% CI 0.198 to 0.470) (Table 2). The estimated increases in the mean log₂-unit (ng/mL) of aldehydes for each 1-fold increase in dietary fiber ranged from -0.155 (95% confidence interval [CI]: -0.210 to -0.101) for isopentanaldehyde to -0.053 (95% CI: -0.094 to -0.011) for propanaldehyde and 0.156 (95% CI: 0.091 to 0.222) for benzaldehyde. There was no significant association between dietary fiber intake and the concentration of any other aldehydes.

The restricted cubic spline plots indicated that there was a linear and positive association between dietary fiber and benzaldehyde (P for nonlinearity = 0.635, Fig. 2A) and a linear and negative association between dietary fiber and isopentanaldehyde (P for nonlinearity = 0.561, Fig. 2B). There was also a nonlinear and negative association between dietary fiber and propanaldehyde (P for nonlinearity = 0.043, Fig. 2C). No linear or nonlinear association was found between dietary fiber intake and the concentration of any other aldehydes.

Discussion

To the best of our knowledge, we were the first to observe significant correlations between energy-adjusted dietary fiber and various serum aldehyde exposures. Dietary fiber was negatively associated with isopentanaldehyde and propanaldehyde but positively associated with benzaldehyde. Nonetheless, in the other 3 aldehydes, there was no significant trend toward an association with dietary fiber.

Previous studies have mainly focused on the involvement of aldehydes in human disease. Nonetheless, no experimental research has shown an effective approach to regulating these 6 aldehyde concentrations in the human body. According to a recent study, no dietary variables were associated with serum isopentanaldehyde and propanaldehyde concentrations (Silva et al. 2021). Our findings seem to contradict this. However, the study provided strict food consumption information from different sources, such as vegetable, fruit, legume, nut, and seed grain products. In contrast, our study provides a holistic analysis of dietary fiber and serum aldehyde. Therefore, this regulatory effect may be related to the increase in the diversity of dietary fiber intake sources, further suggesting a combination of dietary fiber from multiple sources to modulate serum aldehyde. In addition, our study supplemented the effect of dietary fiber on serum benzaldehyde that was not present in the abovementioned study.

The mechanisms by which dietary fiber affects the serum concentration of aldehydes may include the following aspects. First, dietary fiber reduces oxidative stress and inflammation by regulating beneficial metabolites and toxic molecules and increasing the metabolism of aldehyde substances. A previous study showed that dietary fiber reduces the accumulation of protein-bound uremia toxin (PBUT) in children with multiple chronic kidney diseases as renal function deteriorates, and a dose-effect relationship was observed between the potential benefitor and dietary fiber (El Amouri et al. 2021). A randomized controlled trial also verified that dietary fiber increased the plasma concentrations of total alkylresorcinol (AR) (Donin et al. 2021), which has potential antioxidant effects, reduced the risk of hyperglycemia, and exerted neuroprotective effects on hippocampal neurons (Fan et al. 2020; Tryggvadottir et al. 2021). Previous studies have also shown that aldehydes are associated with tissue and cell damage caused by oxidative stress (Kuntic et al. 2020; Lin et al. 2021; Shafie et al. 2021; Vivarelli et al. 2021; Yusuf et al. 2020). Additionally, studies at the animal and human levels have shown that dietary fiber exerts an anti-inflammatory effect

by presenting fiber-specific changes in their microbiomes, regulating the composition of the gut microbiome and increasing the production of microbiome-derived metabolites (Delannoy-Bruno et al. 2021; Tian et al. 2021).

Isopentanaldehyde is a methyl butyraldehyde formed by replacing the methyl group at the third position of butyraldehyde. According to the Human Metabolome Database, it has been shown to be associated with a substantial number of digestive disorders, such as ulcerative colitis, nonalcoholic fatty liver disease, and Crohn's disease (<http://www.hmdb.ca/metabolites/HMDB0006478>). These diseases have been shown to be ameliorated by adding dietary fiber intake (Ananthakrishnan et al. 2013; Zhao et al. 2020). Therefore, this reflects that digestive disease conditions may be regulated by reduced dietary fiber, which may in turn reduce the absorption of isopentanaldehyde. Moreover, the specific mechanism has not been studied and is worth further exploration.

Propanaldehyde is commonly used in the manufacture of plastics and synthetic rubber chemicals and as a disinfectant and preservative. It can be absorbed into the body by inhaling its vapor and ingestion. Propanaldehyde, as a perinatal air poison, was positively associated with autism spectrum disorder (ASD) in high-risk families (Kalkbrenner et al. 2018). Environmental propanaldehyde is usually biodegraded to propionic acid, which is then further degraded to carbon dioxide and water (Urano and Kato 1986). Considering its unknown degradation pathway and harm in vivo, this study provides evidence for high-risk patients to increase dietary fiber intake.

The increased concentration of benzaldehyde with dietary fiber intake may be because benzaldehyde, as the second most useful flavoring agent in foods, is used in the postprocessing of dietary fiber (Duff and Murray 1989). The second reason is that the microbial biocatalyst can produce benzaldehyde (Jain et al.). *Pichia pastoris* can effectively convert benzyl alcohol to benzaldehyde through biotransformation (Duff and Murray 1989). Benzaldehyde can also be catalyzed to form phenylalanine in the presence of a cell extract of *Lactobacillus plantarum* (Nierop Groot and de Bont 1998); however, the conversion rate of benzaldehyde to benzyl alcohol is reduced in *Escherichia coli* expressing recombinant carboxylate reductase (Kunjapur et al. 2014). These possible paths may lead to a positive association between benzaldehyde and dietary fiber intake.

The limitations of this study include the following aspects. First, this cross-sectional study was designed to describe the association; hence, it cannot conclude and further explain causality. Second, given that this population is an American population, dietary habits exert regional differences. Moreover, due to the lack of potential bowel disturbances, we could not include it as one possible intermediate link. Further research is needed to determine whether these results can be extrapolated to other regions or other ethnicities.

Conclusions

Our study results demonstrated that dietary fiber intake was negatively correlated with serum concentrations of isopentanaldehyde and propanaldehyde. Further research is needed to elucidate the underlying mechanisms between dietary fiber intake and aldehyde metabolism.

Declarations

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Contributions

Yanli Zhou conceptualized the research. Shengen Liao conducted the data analysis. Shi Shi and Qingqing Zhu wrote and edited the original draft of the paper. Xu Zhu and Xiaosu Tang took responsibility for the integrity of the data and the accuracy of the data analysis. All authors contributed to the interpretation of the results and critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript.

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Ethics declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable. There is no individual level data in our publication.

Availability of data and materials

The datasets used and analyzed during the current study are available from https://www.cdc.gov/nchs/nhanes/nhanes_questionnaires.htm.

Competing interests

The authors declare that they have no competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tables

Table 1 Demographic characteristics of study population according to quartile of Energy adjusted dietary fiber

Variable	Overall (N =1877)	Energy adjusted dietary fiber (g/day)				<i>P</i> value
		≤10.1 (n=471)	10.2-13.9 (n=468)	14.0-19.2 (n=469)	≥19.3 (n=469)	
Age, years	46.5 (17.5)	42.9 (16.4)	44.7 (18.0)	48.6 (18.0)	49.6 (16.6)	<0.001
Male, %	924 (49.2%)	248 (52.7%)	224 (47.9%)	226 (48.2%)	226 (48.2%)	0.397
Education level, %						<0.001
<9th grade	139 (7.4%)	23 (4.9%)	21 (4.5%)	28 (6.0%)	67 (14.3%)	
9–11th grade	269 (14.3%)	100 (21.2%)	77 (16.5%)	50 (10.7%)	42 (9.0%)	
High school	447 (23.8%)	137 (29.1%)	123 (26.3%)	111 (23.7%)	76 (16.2%)	
College	614 (32.7%)	166 (35.2%)	175 (37.4%)	150 (32.0%)	123 (26.2%)	
Graduate	408 (21.7%)	45 (9.6%)	72 (15.4%)	130 (27.7%)	161 (34.3%)	
Race/ethnicity, %						<0.001
Mexican American	251 (13.4%)	33 (7.0%)	42 (9.0%)	71 (15.1%)	105 (22.4%)	
Other Hispanic	152 (8.1%)	30 (6.4%)	29 (6.2%)	38 (8.1%)	55 (11.7%)	
Non-Hispanic White	926 (49.3%)	253 (53.7%)	248 (53.0%)	236 (50.3%)	189 (40.3%)	
Non-Hispanic Black	329 (17.5%)	116 (24.6%)	104 (22.2%)	65 (13.9%)	44 (9.4%)	
Other race	219 (11.7%)	39 (8.3%)	45 (9.6%)	59 (12.6%)	76 (16.2%)	
Hypertension, %	649 (34.6%)	145 (30.8%)	190 (40.6%)	163 (34.8%)	151 (32.2%)	0.009
Diabetes	198 (10.5%)	44 (9.3%)	49 (10.5%)	46 (9.8%)	59 (12.6%)	0.383
Body mass index, kg/m ²	29.0 (7.1)	29.4 (7.5)	29.7 (7.5)	28.7 (6.7)	28.2 (6.7)	0.009
Smoker, %	1045 (55.7%)	345 (73.2%)	294 (62.8%)	230 (49.0%)	176 (37.5%)	<0.001
Alcohol user, %	1428 (76.1%)	377 (80.0%)	371 (79.3%)	357 (76.1%)	323 (68.9%)	<0.001
Energy intake, kcal/day	2080 (918)	2090 (1230)	2100 (899)	2110 (760)	2030 (681)	0.459
Physical activity						<0.001
Never	1120 (59.7%)	269 (57.1%)	261 (55.8%)	287 (61.2%)	303 (64.6%)	
Moderate	356 (19.0%)	69 (14.6%)	94 (20.1%)	105 (22.4%)	88 (18.8%)	
Vigorous	401 (21.4%)	133 (28.2%)	113 (24.1%)	77 (16.4%)	78 (16.6%)	
Poverty-income ratio	2.15 (1.55)	1.69 (1.31)	1.94 (1.46)	2.31 (1.57)	2.66 (1.67)	<0.001

Data are presented as mean (standard deviation, SD) or n (%).

Table 2 Association between energy adjusted dietary fiber and serum concentration of several aldehydes.

	Benzaldehyde	Isopentanaldehyde	Propanaldehyde	Butyraldehyde	Hexanaldehyde
Fiber	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)
Q1	Ref.	Ref.	Ref.	Ref.	Ref.
Q2	0.107(-0.016 to 0.231)	-0.153(-0.256 to -0.050)	-0.166(-0.2444 to -0.088) ***	-0.091(-0.186 to 0.004)	-0.002(-0.083 to 0.079)
Q3	0.179(0.05 to 0.308) **	-0.23(-0.337 to -0.122) ***	-0.118(-0.199 to -0.037) **	0.054(-0.045 to 0.152)	-0.045(-0.13 to 0.039)
Q4	0.334(0.198 to 0.470) ***	-0.361(-0.475 to -0.248) ***	-0.139(-0.225 to -0.053) **	-0.063(-0.168 to 0.041)	-0.034(-0.123 to 0.054)
Continuously	0.156(0.091 to 0.222) ***	-0.155(-0.210 to -0.101) ***	-0.053(-0.094 to -0.011) **	-0.006(-0.045 to 0.056)	-0.023(-0.065 to 0.020)
<i>P-trend</i>	<0.001	<0.001	0.006	0.740	0.320

Analyses were adjusted for age, sex, education level, race, smoker, alcohol user, diabetes, hypertension, body mass index, energy intake, poverty-income ratio and physical activity. Energy adjusted dietary fiber and all aldehydes were log2-transformed to fit the regression model. Q, quantile. ** $p < 0.01$, *** $p < 0.001$.

Figures

Figure 1

Figure 2

The restricted cubic spline plot of the association between energy adjusted dietary fiber and serum concentrations of (A) Benzaldehyde; (B) Isopentanaldehyde; (C) Propanaldehyde; (D) Butyraldehyde; (E) Hexanaldehyde; and (F) Heptanaldehyde. Energy adjusted dietary fiber is log2 transformed. The association was adjusted for age, sex, education level, race, smoking status, alcohol use, diabetes, hypertension, body mass index, energy intake, poverty-income ratio and physical activity.