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Total, Insoluble, and Soluble Dietary Fiber Intake and Insulin Resistance and Blood Pressure in Adolescents

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Abstract

Background/Objectives: To evaluate sex and race differences in fiber intakes, which are understudied in adolescents, and to investigate whether low insoluble and soluble fiber intakes would be associated with higher risk for insulin resistance and blood pressure (BP).

Subjects/Methods: A total of 754 black and white adolescents, 14 to 18 years old (49.2% blacks; 50.3% female) were previously recruited in Augusta, Georgia, the US between 2001 to 2005. Diet was assessed with four to seven independent 24-hour dietary recalls.

Results: The average daily consumption of total, insoluble, and soluble fiber were 10.9, 6.7, and 4.0g, respectively. Only two adolescents met their daily fiber intake recommendation. Adjusted multiple linear regressions revealed that increasing dietary fiber intake from current averages to recommendation levels (12g to 38g in the male and 9.9g to 25g in the female), were associated with predicted decreases of 5.4 and 3.0 mg/dL fasting glucose, 7.0 and 5.0 mg/dL fasting insulin, 1.6 and 1.1 HOMA-IR, 6.3 and 3.7 mmHg SBP, and 5.2 and 3.0 mmHg DBP in the males and females, respectively (all $p < 0.05$). Furthermore, both insoluble and soluble fiber intakes were inversely associated with fasting insulin and HOMA-IR ($p < 0.05$); whereas only soluble fiber intake was found to be associated with BP ($p < 0.05$).

Conclusions: Fiber consumption in adolescents is far below daily-recommended levels across all sex and race groups. Lower fiber intake of all types is associated with higher insulin level. Fiber Intake at recommendation levels may be associated with significant cardiometabolic benefits.

Keywords

dietary fiber; soluble fiber; insoluble fiber; insulin resistance; blood pressure; adolescents

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Conflict of Interest

The authors of this manuscript have no conflicts of interest to disclose.

Introduction

The prevalence of type 2 diabetes and hypertension has been increasing in children and adolescents (1). Childhood diabetes and hypertension track into adulthood (2). Therefore, identification of risk factors during early years is important for early intervention.

Low fiber intake plays a role in cardiometabolic diseases in adults, and major organizations support increasing fiber intake as part of a healthy lifestyle promotion. However, recent meta-analyses of adolescent diet and health conclude that the relationships between fiber intake and cardiometabolic risks are not well studied and more in-depth studies are needed (3–5). Dietary fiber can be subcategorized by its solubility into water-insoluble and soluble fiber (6). The effect of fiber type (i.e. soluble and insoluble) on cardiometabolic disease is also not well understood; only two observational studies in adults, and none in adolescents have been conducted to date (6, 7).

We have shown that total dietary fiber consumption was negatively correlated to adiposity and inflammation in adolescents (8). In this paper, we first examined sex and race differences in total, insoluble, and soluble fiber consumption among adolescents. We then tested the hypothesis that lower total fiber, and insoluble or soluble fiber intakes were associated with higher risks of insulin resistance and BP.

Methods

Participants

We conducted a cross-sectional study in a cohort of apparently healthy black and white adolescents, 14 to 18 years of age (n = 754, 49.2% blacks; 50.3% girls) (9). Student participants were from Augusta, Georgia area. Students were asked to self-report their ethnicity. Self-identified whites and blacks were then enrolled. Participants were excluded when taking medications, or diagnosed with chronic health conditions. All recruitments and measurements were performed between 2001 and 2005. This study was approved by the Institutional Review Board at the Augusta University (Augusta, GA, USA, protocol #622505). Parental or guardian of the adolescents provided informed consent

Anthropometry and body composition

Height was measured using a wall-mounted stadiometer (Tanita Corporation of American, Arlington Heights, IL), and weight was obtained using calibrated electronic scale (model CN2OL; Cardinal Detecto, Webb City, MO). BMI was calculated as weight (kg) divided by height (m^2). A trained research assistant measured resting supine blood pressure after 10 minutes of quiet rest with a Dinamap monitor (Critikon, Tampa, FL); five readings were made at 1-minute intervals, and the last three were averaged.

Biochemical Measurements

Fasting glucose (FG) was measured using an EKtachem DT system (Johnson and Johnson Clinical Diagnostics) and run in duplicate, with intra- and inter-assay CV of 0.6 and 1.5%, respectively. Fasting insulin was assayed in duplicate 100-μL aliquots of sera by specific radioimmunoassay (Linco Research, St. Charles, MO). Assay sensitivity was 3.41 μU/mL.

The intra-assay CV was 3.7%. HOMA-IR, a surrogate marker of insulin resistance, was computed using the function: fasting insulin (μU/L) × fasting glucose (mg/dL)/405 (8). A five stage of sexual development ranging from prepubertal to fully mature defined by Tanner (8) was measured using a sex-specific questionnaire as previously described (9).

Physical Activity

MTI Actigraph monitors (model 7164; MTI Health Services, Fort Walton Beach, FL) measured subjects' daily duration of moderate and vigorous physical activities (PA) for seven continuous days with only removal during bathing, sleeping, or any activity that may damage the monitor or injure other. The detail information was described elsewhere (9). PA records from the first day and the last day were excluded because a full day of information was not available. Mean daily minutes spent in moderate (3–6 metabolic equivalents) and vigorous (>6 metabolic equivalents) PA were calculated based on movement counts by the program came with the monitor.

Dietary intake

Seven 24-h dietary non-consecutive recalls, which covered the period from midnight of the previous day to midnight for next day, were collected using the Nutrition Data System for Research (NDS-R 2006) (University of Minnesota, Minneapolis, MN). The first two recalls were obtained via face-to-face within 1 week of testing, and the following interviews were performed by telephone every week for a total of 12 weeks, with all 7 recalls completed within that period. We sought to obtain 7 recalls, one for each day of the week. To minimize the potential for under-eating during the time frame for 24-h recalls, subjects were blinded to the telephone recall schedule. Ninety-five percent of adolescents provided above 4 days dietary recalls. Total dietary fiber intake was the sum of insoluble fiber and soluble fiber intakes.

Statistical Analysis

Descriptive statistics for variables are presented as mean (standard deviation). Prior to analysis, homogeneity of variances for all variables was checked using Levene's test for equality of variances. Race and sex differences were checked for the characteristics assessed, using one-way ANOVA. Pearson Chi-squared test was used to analyze for significant associations between sex and race. ANCOVA, adjusted for energy intake (EI), age, Tanner stage, and BMI, was used to estimate the differences in fiber intakes (total, insoluble, soluble) among sex and race.

Multiple linear regression models were performed to investigate the associations of fiber consumption and insulin-related dependent variables, (FG, fasting insulin, HOMA-IR), SBP and DBP. FG, fasting insulin and HOMA-IR were log-transformed for regression models. The model was adjusted for EI, age, sex, race, Tanner stage, BMI and PA.

All statistical analyses were performed via SPSS –IBM Software (version 24.0 SPSS Inc., Chicago, IL, USA) with the significance level set at $\alpha < 0.05$.

Results

Adolescent males exercised longer, black females had higher BMI and Tanner stage (all p<0.001). The males had higher FG, SBP, and consumed more calories than females (all p <0.05). Blacks had higher Tanner Stage, BMI, fasting insulin, HOMA-IR, SBP, DBP (Table 1), and consumed fewer calories than whites (all p <0.05) (Table 2).

Overall, our adolescents consumed on average 10.9g/d total dietary fiber (males 12.0g/d, females 9.9g/d), 6.7g/d insoluble fiber, and 4.0g/d soluble fiber per day. Black females consumed the least dietary fiber with an average of 8.8g/d total fiber, and white males consumed the most dietary fiber with an average of 13.2g/d total fiber (p <0.001). The average fiber consumption is below the recommended intake level for adolescent males and females, 38g/ d and 25g/d respectively (3, 10). The average intake in boys was less than one-third of the recommendation, while in girls it was less than half of the recommendation. Only two participants consumed at the recommended levels. Moreover, the fiber intake didn't vary significantly across seasons (p-value=0.432).

Regression models adjusted for energy intake showed that total fiber intake, insoluble fiber intake, and soluble fiber intake were significantly associated with all dependent variables. Models were then further adjusted for age, sex, race, BMI, Tanner Stage, and PA. Increasing dietary fiber intakes from current averages to the recommended levels (12g to 38g in the male and 9.9g to 25g in the female), were associated with predicted decreases of 5.4 and 3.0 mg/dL FG, 7.0 and 5.0 mg/dL fasting insulin, 1.6 and 1.1 HOMA-IR, 6.3 and 3.7 mmHg SBP, and 5.2 and 3.0 mmHg DBP in the males and females, respectively (all p < 0.05, Table 3, Figure 1, Supplementary Table S1). No significant sex or race interactions were identified.

Insoluble fiber intake was inversely associated with fasting insulin and HOMA-IR (all p-values < 0.001, Table 3). No associations between insoluble fiber and SBP/DBP were found. Soluble fiber intake was inversely associated with fasting insulin, HOMA-IR SBP and DBP (all p-values < 0.05, Table 3).

Discussions

Our study observed that fiber intakes in our adolescents were far below daily-recommended levels. There were sex and race differences in fiber intake levels, with black females consuming the least amount for all types of fiber. Less consumption of dietary fiber of all types was related to higher insulin level and HOMA-IR, independent of energy intake, BMI, and PA. Total and soluble fiber intakes were also inversely associated with SBP and DBP.

Our adolescent males and females on average consumed 12.0g and 9.9g total dietary fiber per day, respectively. Only 2 adolescents (<0.3%) met the recommended national guidelines for total fiber intakes, which is 38g per day for boys and 25g per day for girls (10). Other adolescent and adult studies, including Bogalusa, NHANES, and CARDIA, have reached similar conclusions (11, 12). In fact, 9 out of 10 youths were suggested to consume below the recommended fiber intake levels (3, 5). Few youth studies have examined the differences in fiber intakes among sex and race together (11). Our adolescents consumed similar level of soluble fiber to, but much lower level of insoluble fiber than those consumed by overweight

Latino teens (13). Comparing between sex and race groups revealed that black females consumed the least amount of fiber of any type. Furthermore, we provided evidence that blacks, in particular female blacks, consume lower amount of dietary fiber compared to white males and females.

Our study observed that lower consumption of total dietary fiber was associated with higher insulin levels and BP. Other studies in adults have found similar results (14). The CARDIA study concluded that intakes of fat, carbohydrates, and protein had contradictory or weak associations with cardiovascular markers, but lower intakes of fiber were associated with higher fasting insulin levels and BP (15).

Few human studies examined the relationships of both insoluble and soluble fiber intake with cardiometabolic health. Our finding that less consumption of insoluble fiber was associated with higher insulin levels was similar to the results found in adults from the INTERMAP, Aragon Worker's Health, and Botnia Dietary studies (7, 16). We also observed that lower soluble fiber intake was also associated with higher insulin levels and blood pressure, which was in agreement with the findings from the Botnia Dietary Study (16). The present study is the first to replicate the findings from adult studies in adolescents. Furthermore, randomized controlled clinical trials have demonstrated that soluble fiber supplementation decreases insulin resistance and BP in type 2 diabetes and hypercholesterolemic patients (17, 18). Moreover, cereal fiber improves whole-body insulin sensitivity in overweight and obese women (19).

The mechanisms through which dietary fiber regulates insulin resistance and BP are complex. Dietary insoluble fiber has low energy density and can improve postprandial satiety to reduce appetite (6). Appetite loss may reduce body weight, leading to reductions in BP, although the effects may be moderate (20, 21). Additionally, insoluble fibers have been shown to improve insulin resistance, as measured using euglycemic hyperinsulinemic clamps (22). Although insoluble fiber is not readily fermented in our gut, it may affect the digestion and absorption of dietary proteins, possibly delaying protein-induced mTOR/S6K1 signaling pathway. S6K1-knockout mice have been shown to be protected against diet-induced insulin resistance (22).

On the other hand, soluble fiber through its viscous properties forms gel-like substances in our gastrointestinal tract, which can entrap carbohydrates and nutrients from being absorbed efficiently and delay gastric emptying to reduce postprandial glycemic response (23). Its viscous properties can also catch bile acids and cholesterol to reduce insulin resistance and inflammation, consequently leading to decreased BP (24–26). Moreover, studies have suggested that soluble fiber can be fermented in our intestines and can improve the quality of our gut microbiome, increasing the production of short-chain fatty acids (SCFAs) (27–29). In fact, soluble fiber intake can correct the composition of SCFA-producing gut microbiome which were diminished in type 2 diabetes and colon cancer (27, 30). Additionally, SCFAs can regulate sympathetic and parasympathetic nervous systems, which then regulate glucose and cholesterol metabolism as well as insulin resistance (31, 32). Both insoluble and soluble fiber intakes can improve glycemic control, but recent evidence suggests that more benefits may be gained from fermentable fibers from gut microbial fermentation, including soluble

fibers, to improve our gut health, immunity, and energy metabolism (25, 33–35). Our study provides evidence to support the potential greater benefits of soluble fiber compared to insoluble fiber starting in youth.

Our study had several strengths. First, our adolescent population was relatively large and apparently healthy with nearly even distributions of males and females and of blacks and whites. Second as previously mentioned, the repeated assessments of 24-hour dietary recalls over a 12-week period provided relatively accurate dietary estimates of fiber intake patterns, by reducing measurement error and random error owing to within-person variability over time (36). Third, we observed sex and race differences in total, insoluble and soluble fiber intake and their relationships of different fiber types with cardiometabolic health in adolescents. A limitation of our study was its cross-sectional nature; thus the associations did not prove causality. Another limitation was that the data were collected 15 years ago, which may not represent the current fiber intake among adolescents. However, this study could set up historical benchmarks, and as references and justifications for studying current status of healthy eating among adolescents.

In conclusion, our adolescent study shows that (1) the vast majority of our adolescents do not consume sufficient dietary fiber, (2) there are sex and race differences in total, insoluble, and soluble fiber intakes with black females consuming the least; (3) lower dietary fiber intake is associated with higher risk for insulin resistance and BP, independent of energy intake, BMI, and physical activity. The possibility to reduce both insulin resistance and BP makes increasing dietary fiber intake an attractive component of prevention strategies, because these benefits can lead to substantial reductions in cardiometabolic risks among adolescents.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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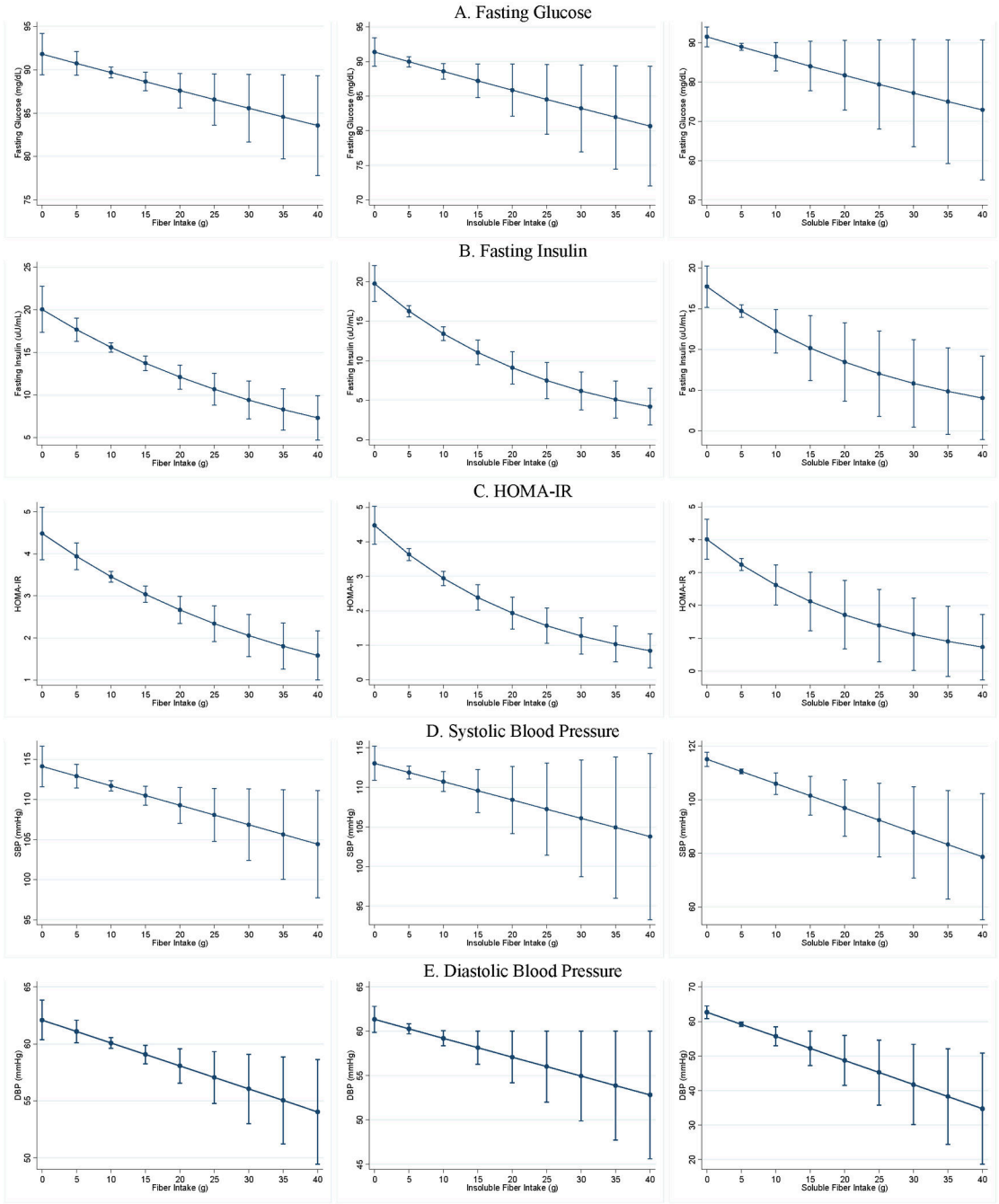

Figure 1. Predicted outcomes of dietary fiber intakes based on multiple linear regression models.
Linear regression models are adjusted for energy intake, age, sex, race, Tanner stage, BMI and physical activity.

Table 1.

Demographics by sex and race of 754 adolescents

Characteristics	White		Black		p-values
	Male (N=187)	Female (N=191)	Male (N=184)	Female (N=184)	
Age	16.2 (14.9, 17.5)	16.0 (14.9, 17.1)	16.1 (14.9, 17.3)	16.3 (15.1, 17.5)	0.124
BMI (kg/m^2)	22.3 (18.1, 26.5)	21.8 (17.8, 25.8)	23.6 (18.4, 28.8)	24.9 (18.9, 30.9)	<0.001
Physical Activity (METs)	1.6 (1.4, 1.8)	1.5 (1.4, 1.6)	1.6 (1.4, 1.8)	1.5 (1.4, 1.6)	<0.001
Tanner Stage	4.4 (3.7, 5.1)	4.2 (3.5, 4.9)	4.2 (3.4, 5.0)	4.6 (4.0, 5.2)	<0.001
Fasting Glucose (mg/dL)	91.7 (69.0, 105.0)	87.7 (68.2, 110.0)	91.7 (73.0, 126.0)	88.0 (71.0, 120.0)	<0.001
Fasting Insulin (uU/mL)	15.5 (2.2, 59.7)	14.4 (3.5, 67.3)	16.9 (2.3, 58.9)	18.8 (5.0, 61.7)	<0.001
HOMA-IR	3.6 (0.6, 13.9)	3.2 (0.6, 15.0)	3.9 (0.5, 14.2)	4.0 (0.9, 61.7)	<0.001
SBP (mmHg)	114.4 (92.0, 157.7)	104.5 (82.0, 126.0)	117.7 (94.0, 152.7)	108.8 (90.3, 140.0)	<0.001
DBP (mmHg)	57.7 (43.0, 75.0)	58.6 (43.3, 78.3)	61.0 (49.0, 84.7)	61.9 (38.3, 74.7)	<0.001

*Values presented as mean (95% CI).

Table 2.

Biochemical markers and dietary intakes by sex and race of 754 adolescents

Characteristics*	White		Black		p-values
	Male (N=187)	Female (N=191)	Male (N=184)	Female (N=184)	
Energy Intake (kJ/d)	2296.0 (932.1, 3760.5)	1754.8 (632.0, 3733.5)	2095.8 (913.1, 3742.3)	1677.2 (505.4, 3455.0)	<0.001
Total Fiber (g/d)	13.2 (3.8, 31.6)	11.0 (2.7, 28.7)	10.8 (2.7, 35.5)	8.8 (2.9, 26.9)	<0.001
Insoluble Fiber (g/d)	8.2 (2.2, 22.6)	6.8 (1.4, 17.7)	6.5 (1.4, 28.5)	5.3 (1.8, 19.2)	<0.001
Soluble Fiber (g/d)	4.7 (1.5, 12.6)	4.0 (1.2, 10.4)	4.1 (1.2, 9.3)	3.2 (1.0, 8.7)	<0.001

*Values presented as mean (95% CI).

Table 3.

Regressions for intakes of total, insoluble, and soluble dietary fiber with insulin markers and blood pressures

Dependent variables	Independent variables					
	Total Fiber (g/d) β (95% CI)		Insoluble Fiber (g/d) β (95% CI)		Soluble Fiber (g/d) β (95% CI)	
	Base Model[a]	Model 1[b]	Base Model[a]	Model 1[b]	Base Model[a]	Model 1[b]
Fasting glucose (log-transformed mg/dL)	−0.01** (−0.01, −0.00)	−0.0* (−0.01, −0.00)	−0.01** (−0.01, −0.00)	−0.01(−0.01, 0.00)	−0.01* (−0.01, −0.00)	−0.01(−0.01, 0.00)
Fasting insulin (log-transformed mg/dL)	−0.04** (−0.5, −0.02)	−0.02** (−0.04, −0.01)	−0.05** (−0.07, −0.03)	−0.04** (−0.05, −0.02)	−0.06** (−0.08, −0.03)	−0.03** (−0.06, −0.01)
HOMA-IR (log-transformed)	−0.04** (−0.05, −0.03)	−0.03** (−0.04, −0.01)	−0.06** (−0.07, −0.04)	−0.04** (−0.06, −0.02)	−0.06** (−0.09, −0.04)	−0.04* (−0.06, −0.01)
Systolic Blood Pressure (mmHg)	−0.59** (−0.82, −0.36)	−0.25* (−0.48, −0.03)	−0.70** (−1.02, −0.39)	−0.24(−0.54, 0.06)	−1.21** (−1.72, −0.70)	−0.48* (−0.96, −0.01)
Diastolic Blood Pressure (mmHg)	−0.28** (−0.42, −0.14)	−0.20* (−0.35, −0.05)	−0.33** (−0.52, −0.14)	−0.20(−0.41, 0.00)	−0.54** (−0.85, −0.24)	−0.44** (−0.76, −0.11)

[a] Effect size reported as unstandardized coefficients from regression models adjusted for energy intake

[b] Effect sizes reported as unstandardized coefficients from regression models adjusted for energy intake, age, sex, race, Tanner stage, BMI and physical activity.

** p-value < 0.001

* p-value < 0.05