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Reducing Consumption of Sugar-Sweetened Beverages Is Associated with Reduced Blood Pressure: A Prospective Study among U.S. Adults

Liwei Chen, MD, PhD

Program of Epidemiology, School of Public Health, Louisiana State University Health Science Center

Benjamin Caballero, MD, PhD

Center for Human Nutrition, Johns Hopkins Bloomberg School of Public Health

Diane C. Mitchell, MS, RD

Diet Assessment Center, Department of Nutritional Sciences, Pennsylvania State University

Catherine Loria, PhD

Division of Prevention and Population Sciences, National Heart, Lung, and Blood Institute

Pao-Hwa Lin, PhD

Department of Medicine, Duke University Medical Center

Catherine M. Champagne, PhD, RD

Pennington Biomedical Research Center

Patricia J. Elmer, PhD

Kaiser Permanente Center for Health Research

Jamy D. Ard, MD

Division of Clinical Nutrition & Dietetics, University of Alabama at Birmingham

Bryan C. Batch

Duke Hypertension Center, Duke University

Cheryl A. M. Anderson, PhD, MPH, MS

Center for Human Nutrition, Johns Hopkins Bloomberg School of Public Health

Welch Center for Prevention, Epidemiology and Clinical Research, Johns Hopkins Medical Institutions

Lawrence J. Appel, MD, MPH

Welch Center for Prevention, Epidemiology and Clinical Research, Johns Hopkins Medical Institutions

Corresponding author: Liwei Chen: Program of Epidemiology, School of Public Health, Louisiana State University Health Science Center, 1615 Poydras Street Suite 1400, New Orleans, LA 70112, lchen@lsuhsc.edu.

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Abstract

Background—Increased consumption of sugar-sweetened beverages (SSB) has been associated with an elevated risk of obesity, metabolic syndrome, and type 2 diabetes. However, the effects of SSB consumption on blood pressure (BP) are uncertain. The objective of this study was to determine the relationship between changes in SSB consumption and changes in BP among adults.

Methods and Results—Prospective analysis of 810 adults who participated in the PREMIER Study (an 18-month behavioral intervention trial). BP and dietary intake (by two 24-h recalls) were measured at baseline, 6-month, and 18-month. Mixed effects models were applied to estimate the changes in BP in responding to changes in SSB consumption. At baseline, mean SSB intake was 0.9 ± 1.0 servings/day (10.5 ± 11.9 fl oz/day), and mean SBP/DBP was $134.9 \pm 9.6/84.8 \pm 4.2$ mmHg. After controlling for potential confounders, a reduction in SSB of 1 serving/day was associated with a 1.8 mmHg (95% CI: 1.2 to 2.4 mmHg) reduction in SBP and 1.1 mmHg (95% CI: 0.7 to 1.4 mmHg) reduction in DBP over 18 months. After additional adjustment for weight change over the same period, a reduction in SSB intake was still significantly associated with reductions in SBP and DBP ($P < 0.05$). Reduced intake of sugars was also significantly associated with reduced BP. No association was found for diet beverage consumption or caffeine intake and BP. These findings suggest that sugars may be the nutrients that contribute to the observed association between SSB and BP.

Conclusions—Reduced consumption of SSB and sugars were significantly associated with reduced BP. Reducing SSB and sugar consumption may be an important dietary strategy to lower BP.

Keywords

Blood pressure; Hypertension; Glucose; Nutrition; Follow-up studies

INTRODUCTION

Elevated blood pressure (BP) continues to be one of the most common and important health problems in the United States (U.S.). In 2004, 72 million (35%) U. S. adults had hypertension [defined as systolic BP (SBP) ≥ 140 mmHg and/or diastolic blood pressure (DBP) ≥ 90 mmHg, or use of antihypertensive medication] and another 59 million (29%) had prehypertension [defined as SBP from 120 to 140 mmHg, or DBP from 80 mmHg to 90 mmHg]¹. Elevated BP is an established risk factor for cardiovascular disease, stroke, kidney disease, all-cause mortality, and shortened life expectancy².

Sugar-sweetened beverages (SSB) are the most commonly consumed caloric beverage and the leading source of added sugars in the U.S.³. Mean SSB consumption was 28 ± 1 oz/day (2.3 servings/day) for U.S. adults (> 20 y) as reported from the National Health and Nutritional Examination Survey (NHANES) 1999–2004⁴. An emerging body of evidence from prospective studies documented that increased SSB consumption is associated with a higher risk of obesity^{5–7}, type II diabetes^{7–9}, and coronary heart disease¹⁰. Experimental studies^{11–14} found that high consumption of sugary drinks can induce hypertension in animal models. Whether long-term consumption of SSB has a direct effect on BP in humans has not been well investigated. Up to date, three human studies have provided limited data that suggest there may be a positive association between habitual SSB consumption and BP^{15–17}. However, these studies are either cross-sectional¹⁶, did not have direct measure of BP¹⁷, or failed to show the association was statistically significant¹⁵. In addition, it is not clear whether both high consumption of the SSB and diet beverages (sweetened by artificial sweetener, no calories) may increase the risk of high BP.

A relationship between consumption of SSB or diet beverages and BP could have substantial public health implications, given the high prevalence of elevated BP and widespread consumption of these beverages. Therefore, the primary objective of this study is to prospectively examine the relationship between changes in SSB consumption and BP among U.S. adults. Additionally, we evaluate whether change in consumption of diet beverages is associated with BP.

METHODS

Study population

Study participants are from the PREMIER study. PREMIER is a completed, 18-month multicenter randomized trial designed to test the BP-lowering effects of two multi-component behavioral interventions in adults with SBP of 120 to 159 mmHg and DBP of 80 to 95 mmHg¹⁸. The study consisted of 810 men and women, aged 25–79, recruited from 4 study centers in the U.S. (Baltimore, MD; Baton Rouge, LA; Durham, NC; and Portland, OR). Information on study design, participant recruitment, and data collection has been previously published¹⁹.

Eligible participants were randomly assigned to one of three groups: (A) an “Advice Only” comparison group that received information but no behavioral counseling on weight loss, physical activity, sodium intake, or the DASH (Dietary Approaches to Stop Hypertension) dietary pattern; (B) a behavioral intervention, termed “Established”, that received counseling on how to lose weight, increase physical activity and reduce sodium intake; or (C) a behavioral intervention, termed “Established Plus DASH”, that received counseling on the same lifestyle goals as “Established” along with counseling on the DASH dietary pattern. The weight loss approaches in the Established group focused on increased physical activity and reduced energy intake. By contrast, the weight loss approach in Established Plus DASH group focused on increased physical activity, reduced energy intake, and substitution of high-fat, high-calorie foods with fruits and vegetables. All 810 study participants enrolled at baseline were included in this analysis.

Measurement of BP

BP was measured manually by trained, certified observers at baseline, 3, 6, 12, and 18 months using a standard protocol. After participants sat quietly for 5 minutes, the observer measured BP in the right arm with an appropriately sized cuff. For this analysis, the values of SBP and DBP were calculated by taking the mean of all available measurements at baseline (4 visits), 6 months (3 visits) or 18 months (3 visits). At each visit, a set of 2 BP measurements was obtained. BPs taken in participants who reported using antihypertensive medication within the preceding month were censored; along with missing values, these cases received imputed values by using the BP measured at the preceding visit (last observation carried forward method, LOCF), or using BP values from similar participants in the advice group (single imputation Hot-Deck procedure). Overall, 9% of the BP at 6 months (5% due to antihypertensive medication use and 4% due to loss to follow-up; 3% were imputed using LOCF method) and 17% at 18 months (13% due to antihypertensive medication use and 4% due to loss to follow-up; 5% were imputed using LOCF method) were imputed. Hypertension was defined as an average SBP \geq 140 mmHg, a DBP \geq 90 mmHg, or use of antihypertensive medication.

Measurement of dietary and beverage intake

Dietary intake was measured by unannounced 24-hour dietary recalls conducted by telephone interviews. Two recalls (one on a week day and one on a weekend) per participant were obtained at baseline, 6, and 18 months. A multiple-pass technique and portion size estimation aids (2

Dimensions Food Portion Visual, Nutrition Consulting Enterprises, Framingham, MA) were used during the phone interview. Intakes of total energy, nutrients (e.g. sugar and caffeine) and food groups (e.g. dairy foods and fruits & vegetables) were calculated using the Nutrition Data System for Research (Version NDS-R 1998, University of Minnesota, Minneapolis, MN). For this analysis, participants' daily nutrient, energy, and beverage intake were calculated by taking the average from two 24-hour dietary recalls. SSB was defined as carbonated or uncarbonated drinks that were sweetened with sugars (sucrose or high-fructose corn syrup). These included regular soft drinks, fruit drinks, lemonade, fruit punch, and other sweetened beverages, but excluded diet drinks. Diet beverages were defined as carbonated or uncarbonated drinks that were sweetened with artificial sweeteners (non-calorically sweeteners).

Measurement of covariates

Weight and height were measured with subjects wearing light clothing and no shoes using a calibrated scale and a wall-mounted stadiometer. Fitness was assessed using a 2-stage 10-minute sub-maximal treadmill stress test and defined as the heart rate (beats/minute) at a fixed work load (Stage 2). Physical activity (PA) and estimated energy expenditure (kcal/kg/day) was assessed using a 7-day recall questionnaire²⁰. Urinary excretion of sodium and potassium were obtained from 24-hour urinary collection at baseline, 6 months, and 18 months. Participants' characteristics such as age, sex, race/ethnicity, income, education, employment and marriage status, and smoking habits were collected at baseline. Because the DASH diet includes several dietary components, we used a single index, DASH Index, to measure overall adherence to the DASH diet. The DASH Index is an average of three subindices measuring daily intake of dairy products, fruits and vegetables servings, and percentage of calories from saturated fat. A score of 0–1 indicates that the intake is in the target range of the DASH diet, while scores <0 indicate worse than target and scores >1 indicated better than target. The computational details of the DASH Index have been described previously²¹.

Statistical analysis

Descriptive data on SSB consumption and BP at each visit were expressed as mean \pm standard deviation if not mentioned otherwise. Student's T-test and χ^2 test were applied to compare continuous variables and categorical variables, respectively. For the primary analysis, we applied mixed effects models to account for the correlation between repeated measurements, and to incorporate between-individual variability to estimate the overall effect. The main exposure was the change in SSB consumption from baseline to follow-up visits (continuous: Δ = follow-up - baseline). In this way, the regression coefficient of change in SSB consumption represents the longitudinal association between SSB and BP (the average change in BP on the concurrent average change in SSB consumption). Potential confounding factors that were adjusted for included gender, race, baseline age, alcohol intake, randomization assignment, study sites, baseline PA and change in PA, baseline fitness and change in fitness, baseline SSB consumption, baseline dietary intakes of selected foods and nutrients and their changes during follow-up, and baseline body mass index (BMI) and change in weight. The primary analyses were conducted by combining all participants and adding intervention assignment as a covariate in all models. Stratified analyses were performed to evaluate whether the associations of SSB and BP were modified by race (white vs. black), gender (male vs. female) and hypertension status (hypertensive vs. non-hypertension). All statistical analyses were performed using STATA version 9.0 (Stata Corp. College Station, Texas). Statistical significance was set at $P \leq 0.05$ (two-tailed).

RESULTS

Baseline characteristics and SSB consumption

At baseline, mean SSB intake in PREMIER participants was 0.9 ± 1.0 servings/day (equal to 10.5 ± 11.9 fl oz/day) and mean diet beverages intake was 0.9 ± 1.2 servings/day (11.2 ± 14.0 fl oz/day). The mean SBP/DBP was $134.9 \pm 9.6/84.8 \pm 4.2$ mmHg. Table 1 displays the sociodemographic characteristics, anthropometric measurements, PA, fitness, dietary intakes of selected foods and nutrients, adherence to DASH Index, urinary sodium and potassium excretions across the baseline SSB consumption quartiles and in the entire study population. Compared with persons in the lowest (1st) quartile, individuals in the higher quartiles were on average younger, less fit, had lower annual household incomes, and drank less alcohol. African Americans drank more SSB than Whites (difference = 4.3 fl oz/day, $P < 0.0001$) and men drank more than women (difference = 3.7 fl oz/day, $P < 0.0001$). Participants in the higher quartiles of SSB consumption also had greater body weights, BMIs, and waist circumferences compared with those in the 1st quartile ($P < 0.0001$ for trend). For dietary intake, there was a trend of higher consumption of total calories, total carbohydrates, glucose, fructose, sucrose, combined sugar (sum of monosaccharide and disaccharide), and lower consumption of protein, dairy foods, fruit and vegetables, dietary fiber, caffeine, calcium, and magnesium with higher SSB intake. Across quartiles of SSB consumption, a slightly significant increase was observed in DBP, but not in SBP or prevalence of hypertension.

At 18-months, 94% of study participants had at least one BP measurement and 90% had at least one dietary recall. For all participants, mean SBP declined 9.8 ± 9.4 mmHg at 6 months and 8.2 ± 9.9 mmHg at 18 months, each net of baseline. For DBP, corresponding declines were 5.4 ± 6.5 mmHg and 5.6 ± 6.8 mmHg, respectively. Compared to baseline, the mean reduction in SSB consumption was 0.5 ± 1.1 servings/day (6.0 ± 13.0 fl oz/day) at 6 months, and 0.2 ± 1.0 servings/day (2.8 ± 12.0 fl oz/day) at 18 months. The consumption of diet beverages was reduced by 0.2 ± 1.1 servings/day (2.3 ± 13.6 fl oz/day) at 6 months but increased by 0.1 ± 1.2 servings/day (1.5 ± 14.0 fl oz/day) at 18 months.

Association between change in SSB consumption and change in BP

Change in SSB consumption was strongly and positively associated with SBP and DBP in both age-adjusted and multivariate-adjusted models (Table 2). In a multivariate-adjusted model that did not include weight change (model 1), a reduction of 1 serving/day (12 fl oz) in SSB consumption was associated with reduced SBP ($\beta = 1.8$; 95% CI: 1.2 to 2.4 mmHg) and DBP ($\beta = 1.1$; 95% CI: 0.7 to 1.5 mmHg). With additional adjustment for concurrent change in weight (model 2), the associations between SSB intake and BPs were attenuated, but still statistically significant with a reduction of 1 serving/day in SSB consumption being associated with a decrease of 0.7 mmHg in SBP (95% CI: 0.12 to 1.25 mmHg) and 0.4 mmHg (95% CI: 0.02 to 0.75 mmHg) in DBP. Results were similar in sensitivity analyses that adjusted for change in total energy instead of change in weight (data not shown). These results suggest that change in SSB consumption is positively associated with BP, independent of weight change and other risk factors for BP. In a sensitivity analysis using non-imputed BP, the results were virtually unchanged, even slightly stronger: a reduction of 1 serving/day in SSB consumption was associated with reduced SBP of 2.0 mmHg (95% CI: 1.4 to 2.6 mmHg) and DBP of 1.2 mmHg (95% CI: 0.9 to 1.6 mmHg) in model 2.

A similar pattern was evident in subgroups (Table 2) defined by baseline hypertension status (hypertensive/non-hypertensive), race (blacks/whites), and gender (female/male). While the pattern of subgroup analyses was similar to that of the overall analyses, not all results were statistically significant, likely because of reduced sample size. Test for interactions showed

that the association between BP and change in SSB consumption was not modified by baseline hypertension status, race, or gender (each P for interaction > 0.05).

To examine the dose-response relationship, we divided participants into tertiles based on their 18-month change in SSB consumption. Table 3 shows the baseline sociodemographic characteristics and changes in selected variables across the tertiles of 18-month change in SSB consumption. There is a linear trend in weight loss and reductions in intakes of total energy, glucose, fructose, sucrose, and combined sugars across the tertiles.

We calculated the model adjusted mean changes in SBP and DBP as well as the proportion of participants who moved from hypertensive at baseline to non-hypertensive at 18 months by tertile of 18-month change in SSB consumption (Figure 1). The mean change in SSB consumption across the tertiles was 9.5 ± 7.4 , -0.9 ± 1.6 , and -15.3 ± 9.9 fl oz/day (persons in the 3rd tertile had the greatest reduction in SSB consumption). Adjustment variables were the same as those in model 2 in the Table 2. At 18 months, participants in the 3rd tertile had a significantly greater reduction in SBP as compared with individuals in the 1st and 2nd tertiles: the mean reduction in SBP across the tertiles was 7.2 ± 4.3 , 8.0 ± 4.3 , and 9.5 ± 4.3 mmHg, respectively (P for trend < 0.001). There was also a statistically significant decline in DBP across tertiles (-5.2 ± 1.8 , -5.3 ± 2.3 , -6.3 ± 2.9 mmHg, respectively; P for trend = 0.001). A trend of increase in the proportion of individuals who moved from the hypertensive at baseline to non-hypertensive at 18 months across tertiles was also observed (17.0%, 18.5%, 23.5%, respectively; P for trend < 0.001).

Association between change in diet beverages consumption and change in BP

We also examine the relationship between consumption of diet beverages and BP. Change in consumption of diet beverages was not associated with either SBP or DBP in both age-adjusted and multivariate-adjusted models (Table 4).

Association between changes in sugar or caffeine consumption and change in BP

In order to investigate which specific nutrients might be responsible for the observed association between SSB and BP, we examined the associations of change in consumption of sugars (glucose, fructose, sucrose, or combined sugar from all foods and beverages) or caffeine (from all foods and beverages) with change in BP (Table 5). In model 1, without weight change as a covariate, change in BP was significantly and positively associated with changes in glucose, fructose, sucrose, and combined sugars. A 10 g/day reduction in glucose, fructose, sucrose, or combined sugar was associated with reductions in SBP of 0.6 mmHg (95% CI: 0.2 to 1.0), 0.5 mmHg (95% CI: 0.1 to 0.8), 0.4 mmHg (95% CI: 0.2 to 0.6), and 0.3 mmHg (95% CI: 0.1 to 0.5). Corresponding data for DBP were 0.5 mmHg (95% CI: 0.3 to 0.8), 0.4 mmHg (95% CI: 0.2 to 0.6), 0.3 mmHg (95% CI: 0.2 to 0.5); 0.3 mmHg (95% CI: 0.2 to 0.3), respectively. Further adjustment for weight loss attenuated these associations; however, in most instances, they were still statistically significant (Table 5). There was no significant relationship between change in caffeine consumption and change in BP.

DISCUSSION

In this prospective study of 810 men and women with prehypertension and stage I hypertension, there was a positive association between change in SSB consumption and change in BP. After controlling for potential confounders, an average reduction in SSB intake by 1 serving (12 fl oz) per day was associated with a 1.8 mmHg (95% CI: 1.2 to 2.4 mmHg) reduction in SBP and 1.1 mmHg (95% CI: 0.7 to 1.5 mmHg) reduction in DBP over 18 months. This association was partially mediated through weight change. Specifically, after controlling for weight change over the same period, the association between SSB intake and BP was attenuated by

approximately 61% (0.7 mmHg/per serving for SBP and 0.4 mmHg/serving for DBP), but still statistically significant ($P < 0.05$, each), suggesting that reducing SSB intake has a BP lowering effect which is independent of weight loss. We also observed significant, positive associations of BP with change in consumption of sugars (glucose, fructose, sucrose, and combined sugar), but not with change in consumption of caffeine. No association was found for diet beverage consumption and BP. These data suggest that sugars may be the nutrients in SSB that contribute to the observed association between SSB and BP.

Our results are supported by data from two large prospective studies and one cross-sectional study suggesting a positive association between SSB consumption and the risk of hypertension. Data from the Nurses' Health Study¹⁷ showed a strong positive association between cola beverage intake and hypertension risk (P for trend < 0.001). Additionally, an analysis of data from the Framingham Offspring Study¹⁵ also found that consumption of soft drinks (regular and diet soda combined) was associated with an increased risk of high BP, although not statistically significant. In addition, cross-sectional findings from NHANES (1999–2004) data among adolescents (12–18 years) indicated a positive association between SSB consumption and directly measured BP¹⁶.

Our results provide additional evidence supporting a relationship between higher SSB consumption and elevated BP. First, the data show that SSB affects BP in part via mechanisms that are independent of weight change. Second, the relationship is evident in both non-hypertensive and hypertensive, suggesting reduced SSB should have a role in both preventing and treating hypertension. In contrast with the above-mentioned two studies which observed an increased hypertension risk associated with both SSB and diet soft drinks^{15, 17}, we found no association between diet beverages and BP in present study (Table 4).

The mechanism by which higher intake of SSB may increase BP is uncertain. It is well documented that ingestion of caffeine has an acute pressor effect^{22, 23}. However, tolerance to the caffeine-induced pressor effect develops within days²³. We found no association between 18-month change in caffeine intake and BP in present study. Studies in a variety of animal models, including rats, dogs, and primates^{11–14}, have shown that diets high in glucose, fructose, or sucrose can induce hypertension. There are few similar studies in humans, and one study has reported that a diet high in sucrose, consumed for 6 weeks, causes a significant elevation in BP²⁴.

A possible mechanism for the pressor effect of sugars may be enhanced sympathetic nervous system activity. An acute increase in catecholamine secretion has been shown after ingestion of sugar during euglycemic clamp studies²⁵. Another mechanism may be a reduction in sodium excretion, as documented in animal and human studies²⁶. Recent evidence suggests that fructose consumption might increase BP by raising serum uric acid^{16, 27}, which can decrease endothelial nitric oxide and/or activate the renin-angiotensin system²⁸.

Our study has several strengths. First, both diet and BP were measured frequently by trained, certified staff. Second, our study had precise, objective measurements of potential confounders including weight, urinary sodium excretion, physical activity, fitness, and other covariates. Third, the follow-up rate was high and missing data were uncommon. Furthermore, the BP status of our study population is comparable to the BP of two-thirds of the U.S. population. Our study is limited in that it included few Hispanics and Asians. Additionally, given the observational nature of our study, it cannot prove causality or completely rule out residual confounding. Randomized controlled trials are needed to confirm the observation and to determine whether interventions that target SSB or sugar consumption can lower BP among adults.

Our study has important public health implications. In view of the direct, progressive relationship of BP with CVD, even small reductions in BP are projected to have substantial health benefits. For example, it has been estimated that a 3 mmHg reduction in systolic BP should reduce stroke mortality by 8% and CHD mortality by 5%²⁹. Such reductions in SBP would be anticipated by reducing SSB consumption by an average of 2 servings per day. Currently, the average intake of SSB is 2.3 servings per day for U.S. adults. In our study, one third of participants reduced SSB consumption on average of 1.3 servings/day over the 18 months and had an average of 1.5 mmHg more reduction in SBP compared with participants who did not change their SSB consumption, suggesting such reduction in SSB consumption should be achievable and could be beneficial.

In summary, findings from this prospective study suggest a positive association between SSB consumption and BP. These findings warrant future studies, particularly randomized controlled trials, to establish the causal relationship.

Clinical Summary

Consumption of sugar-sweetened beverages (SSB) has increased dramatically in the United States (U.S.). While high SSB consumption has been linked with excess calorie intake and overweight/obesity, SSB may have other adverse effects. In a prospective study of 810 U.S. adults with prehypertension and stage I hypertension, we found that reducing SSB consumption was associated with significant reductions in blood pressures (BP). On average, a reduction in SSB intake of 1 serving/day (12 ounces/day) was associated with a 1.8 mmHg reduction in SBP and 1.1 mmHg reduction in DBP over 18 months. A positive association was also found for dietary sugar intake and BP. No association was found for diet beverage consumption or caffeine intake and BP. These findings have important clinical and public health implications. It has been estimated that a 3 mmHg reduction in SBP should reduce stroke mortality by 8% and CHD mortality by 5%. Such reductions in SBP would be anticipated by reducing SSB consumption by an average of 2 servings per day. Currently, the average intake of SSB is 2.3 servings per day for U.S. adults. National wide, 72 million (35%) U. S. adults have hypertension and another 59 million (29%) have prehypertension. Given the high prevalence of both SSB consumption and hypertension in the U.S. and throughout much of the world, even small reductions in the SSB consumption should have a beneficial public health impact. In conclusion, our data suggest that reducing SSB and sugar consumption may be an important dietary strategy to lower BP.

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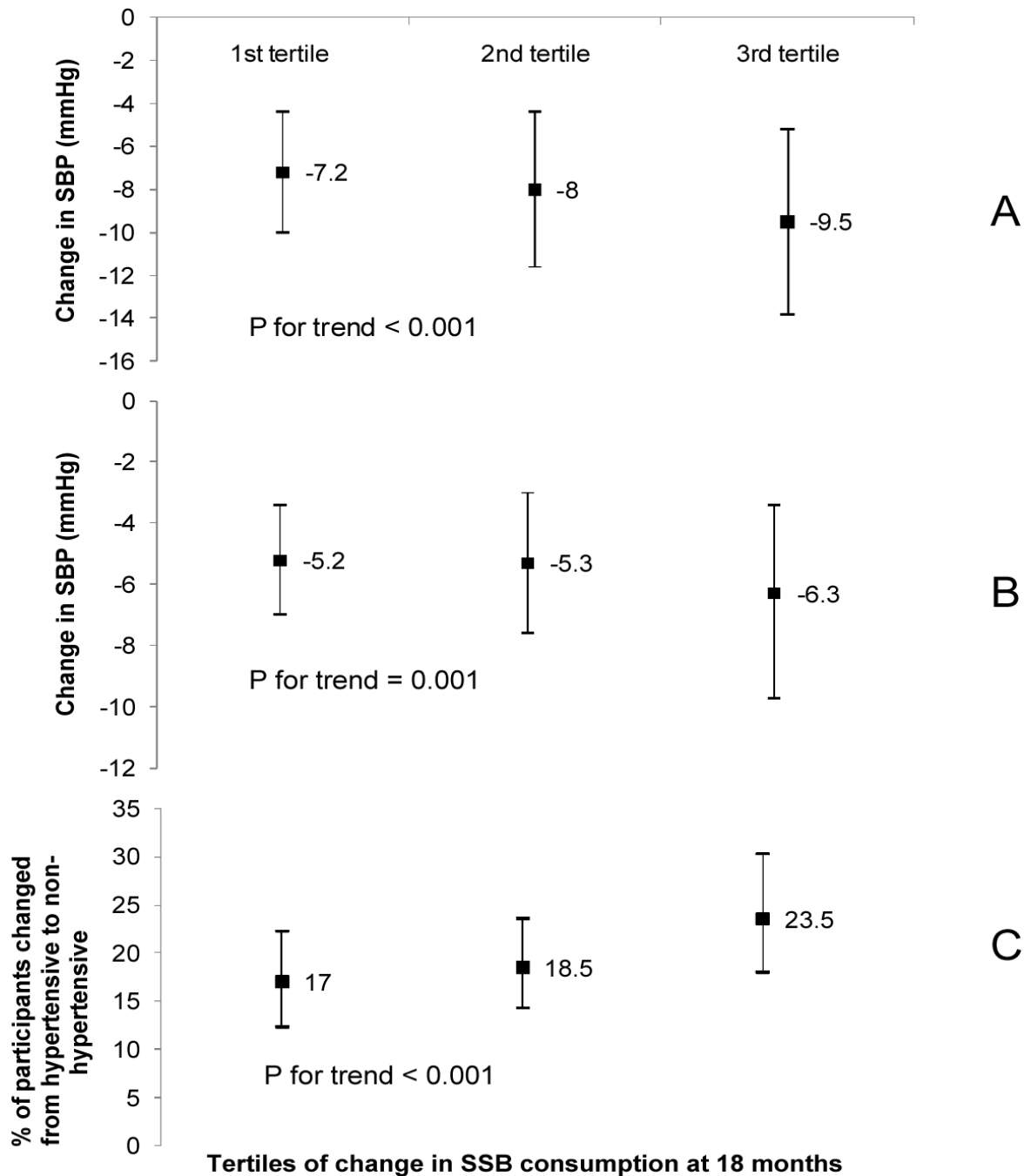


Figure 1.

Model adjusted mean blood pressure changes (Panel A: SBP; Panel B: DBP) and proportion of participants (%) who moved from hypertensive at baseline to non-hypertensive at 18 months (Panel C) by tertiles of change in sugar-sweetened beverage (SSB) consumption (fl oz/day) from baseline to 18 months (18-mo – baseline). The mean change in SSB consumption across the tertiles was 9.5 ± 7.4 , -0.9 ± 1.6 , and -15.3 ± 9.9 fl oz/day (persons in the 3rd tertile had the greatest reduction in SSB). Covariates in the model included gender, race, family history of hypertension, randomization assignment, site, baseline age, alcohol drinking, and BMI, baseline SSB intake, baseline fitness and change in fitness, baseline physical activity and change in physical activity, baseline urinary sodium excretion and change in urinary sodium

excretion, baseline DASH Index and change in DASH Index, and change in body weight from baseline to 18 months.

Table 1
Baseline characteristics of PREMIER study participants by quartile of sugar-sweetened beverages consumption

Variables	Sugar-Sweetened Beverage Consumption Quartiles				P for trend	All Participants
	1 st	2 nd	3 rd	4 th		
SSB intake, fl oz/day						
Mean (SD)	0	6.3 (2.3)	12.0 (1.8)	27.0 (10.7)		10.5 (11.9)
Median (range)	0 (0–0)	6.3 (0.2–8.5)	12.4 (8.6–16.4)	25.0 (16.5–75.4)		8.5 (0–75.4)
Age, year	52.2 (8.4)	50.3 (9.3)	49.4 (8.9)	47.1 (8.5)	<0.001	50.0 (8.9)
Female, %	63.3	72.0	64.5	50.5	0.01	61.5
Africa American, %	19.0	34.0	44.7	46.5	<0.001	34.0
Education (have college degree or above), %	59.4	65.0	57.4	50.0	0.06	57.2
Annual household income (above \$45,000/year), %	76.4	65.0	65.5	67.0	0.01	70.0
Marriage status (married), %	69.2	65.0	62.9	65.0	0.50	66.1
Current smoking (yes), %	4.4	3.0	4.1	7.1	0.50	4.8
Current alcohol intake (yes), %	58.4	56.0	42.1	34.5	<0.001	48.1
Physical activity (time spent on moderate or hard activity), min/week [†]	210	180	145	175	0.19	173.5
Fitness, mean (SD): heart beats/min	129.0 (13.6)	130.3 (14.6)	130.0 (14.4)	133.2 (15.7)	0.009	130.5 (14.5)
Anthropometric measurements, mean (SD)						
Weight, lbs	204.3 (40.1)	193.9 (40.0)	211.3 (39.4)	224.7 (42.7)	<0.001	209.8 (41.5)
BMI, kg/m ²	32.4 (5.7)	31.2 (5.2)	33.5 (5.8)	34.5 (5.9)	<0.001	33.1 (5.8)
Waist Circumference, cm	106.7 (14.8)	102.5 (14.6)	107.9 (15.2)	111.3 (15.5)	<0.001	107.6 (15.2)
Dietary intake, mean (SD)						
Total energy, kcal/day	1785.8 (567.2)	1755.2 (509.8)	1988.4 (611.3)	2180.0 (683.5)	<0.001	1904.5 (625.2)
Total protein, % of TEI	17.3 (4.5)	16.0 (3.6)	15.2 (3.4)	14.4 (3.1)	<0.001	15.9 (4.0)
Total fat, % of TEI	33.9 (8.5)	32.1 (7.7)	32.8 (7.0)	32.7 (6.7)	0.13	33.1 (7.6)
Saturated fat, % of TEI	11.2 (3.5)	10.9 (3.0)	10.7 (3.0)	10.7 (2.8)	0.35	10.9 (3.2)
Monounsaturated fat, % of TEI	13.4 (4.1)	12.6 (3.5)	12.8 (3.3)	12.9 (3.2)	0.17	13.2 (3.6)
Polyunsaturated fat, % of TEI	7.2 (2.8)	6.5 (2.5)	7.1 (2.4)	7.0 (2.4)	0.75	7.0 (2.6)
Trans fat, % of TEI	2.3 (1.2)	2.3 (1.1)	2.4 (1.1)	2.3 (1.2)	0.96	2.3 (1.2)
Total carbohydrate, % of TEI	48.6 (10.3)	52.1 (8.9)	52.4 (9.2)	53.7 (8.3)	<0.001	51.3 (9.6)
Glucose, g/day	18.3 (10.2)	24.0 (11.0)	29.2 (11.7)	42.1 (17.4)	<0.001	27.5 (15.8)
Fructose, g/day	16.0 (10.8)	20.1 (9.0)	28.1 (11.6)	42.1 (17.6)	<0.001	25.9 (16.5)

Variables	Sugar-Sweetened Beverage Consumption Quartiles					P for trend	All Participants
	1 st	2 nd	3 rd	4 th			
Sucrose, g/day	42.6 (28.1)	44.5 (23.1)	49.8 (29.1)	59.0 (31.9)	<0.001	48.7 (29.5)	
Total sugar, g/day	92.3 (42.7)	104.6 (41.2)	122.1 (44.3)	156.8 (52.2)	<0.001	116.9 (52.4)	
Dairy foods, serving/day [†]	1.5	1.5	1.4	1.3	0.01	1.4	
Fruit and vegetable, serving/day	4.7 (2.3)	4.5 (2.3)	4.5 (2.3)	4.2 (2.4)	0.003	4.5 (2.3)	
Dietary fiber, g/day	18.0 (7.7)	16.4 (7.8)	16.3 (7.5)	16.0 (7.7)	0.001	16.9 (7.7)	
Caffeine, mg/day [†]	157.8	110.9	79.1	101.4	<0.001	111.2	
Calcium, mg/day [†]	711.4	633.5	666.2	651.1	0.049	672.5	
Magnesium, mg/day	287.2 (98.1)	261.7 (102.7)	265.9 (105.5)	261.2 (114.6)	0.001	272.0 (105.3)	
Folate, ug/day	346.2 (157.2)	333.1 (148.0)	332.5 (165.2)	332.2 (162.8)	0.70	337.6 (158.4)	
DASH Index	-3.2 (2.3)	-3.3 (2.2)	-3.2 (2.1)	-3.4 (1.9)	0.68	-3.3 (2.1)	
Urinary excretion, mean (SD)							
Sodium, mmol/24h	174.7 (72.4)	155.7 (55.9)	169.4 (71.2)	189.1 (80.4)	0.21	174.5 (72.7)	
Potassium, g/24h	70.1 (25.0)	65.7 (23.9)	63.8 (24.8)	65.2 (29.6)	0.002	66.6 (26.0)	
Blood pressure, mean (SD)							
SBP, mmHg	135.2 (9.5)	135.7 (10.0)	135.6 (9.7)	133.2 (9.6)	0.57	134.9 (9.6)	
DBP, mmHg	84.2 (3.8)	84.9 (4.0)	85.4 (4.6)	85.0 (4.2)	0.01	84.8 (4.2)	
Prevalence of hypertension, %	35.4	41.0	41.2	34.0	0.31	37.5	

P for trend by Wilcoxon rank-sum test

TEI: total energy intake

[†]Median was shown instead of mean because of the highly skewed distribution of that variable

Table 2

Associations of blood pressure with change in sugar-sweetened beverage among PREMIER participants: results from mixed effects models

	Systolic Blood Pressure			Diastolic Blood Pressure		
	β	95% C	P	β	95% C	P
All participants						
Age-adjusted model	1.99	1.46, 2.52	<0.001	1.12	0.78, 1.45	<0.001
Multivariate model 1	1.76	1.17, 2.35	<0.001	1.08	0.69, 1.47	<0.001
Multivariate model 2	0.70	0.15, 1.25	0.01	0.38	0.02, 0.75	0.04
Hypertensive status at baseline						
<i>Hypertensive</i>						
Age-adjusted model	2.26	1.32, 3.21	<0.001	1.33	0.75, 1.90	<0.001
Multivariate model 1	1.94	0.82, 3.06	0.001	1.42	0.71, 2.14	<0.001
Multivariate model 2	0.76	-0.30, 1.82	0.16	0.62	-0.05, 1.29	0.07
<i>Non-hypertensive</i>						
Age-adjusted model	1.61	1.05, 2.17	<0.001	0.91	0.53, 1.31	<0.001
Multivariate model 1	1.60	0.94, 2.20	<0.001	0.88	0.43, 1.33	<0.001
Multivariate model 2	0.58	-0.02, 1.17	0.06	0.19	-0.24, 0.61	0.34
Race						
<i>White</i>						
Age-adjusted model	2.29	1.62, 2.95	<0.001	1.29	0.87, 1.70	<0.001
Multivariate model 1	1.76	1.17, 2.35	<0.001	1.08	0.69, 1.47	<0.001
Multivariate model 2	0.70	0.15, 1.25	0.01	0.38	0.02, 0.75	0.04
<i>Black</i>						
Age-adjusted model	1.38	0.48, 2.29	0.003	0.72	0.14, 1.31	0.016
Multivariate model 1	1.54	0.52, 2.56	0.003	0.92	0.23, 1.62	0.009
Multivariate model 2	0.60	-0.42, 1.63	0.25	0.15	0.53, 0.83	0.67
Gender						
<i>Male</i>						
Age-adjusted model	2.01	1.33, 2.68	<0.001	1.29	0.84, 1.74	<0.001
Multivariate model 1	1.75	0.98, 1.52	<0.001	1.14	0.60, 1.67	<0.001
Multivariate model 2	0.78	0.09, 1.47	0.03	0.50	0.01, 1.00	0.05
<i>Female</i>						

	Systolic Blood Pressure			Diastolic Blood Pressure		
	β	95% C	P	β	95% C	P
Age-adjusted model	1.84	1.01, 2.68	<0.001	0.96	0.46, 1.62	<0.001
Multivariate model 1	1.84	0.93, 1.75	<0.001	1.04	0.46, 1.61	<0.001
Multivariate model 2	0.61	-0.27, 1.48	0.01	0.21	-0.34, 0.76	0.45

β : change in mmHg per change in servings/day

Multivariate model 1: Adjusted for gender, race, family history of hypertension, randomization assignment, site, baseline age, alcohol drinking, and BMI, baseline SSB intake, baseline fitness and change in fitness, baseline physical activity and change in physical activity, baseline urinary sodium excretion and change in urinary sodium excretion, baseline DASH index and change in DASH index.

Multivariate model 2: Model 1 plus change in body weight.

Table 3

Baseline characteristics and changes in selected variables from baseline to 18 month according to the tertiles of change in SSB intake at 18 months

	Tertiles of change in SSB intake at 18 months			
	1 st	2 nd	3 rd	P for trend
Baseline Characteristics				
Age, years	49.3 (8.6)	51.4 (8.8)	49.8 (9.0)	0.5
Female, %	59.6	63.5	58.7	0.8
African Americans, %	33.8	28.9	37.2	0.3
Education, (have college degree or above), %	57.6	58.3	58.3	0.8
Annual household income (> \$45,000/year), %	66.7	75.1	66.1	0.8
Marriage status (married), %	62.1	69.1	66.5	0.4
Changes (18 months - baseline)				
SSB intake, fl oz/day	9.5 (7.4)	-0.9 (1.6)	-15.3 (9.9)	<0.001
Total energy intake, kcal/day	-81.2 (534.1)	-199.8 (563.0)	-350.6 (615.4)	<0.001
DASH Index	1.1 (2.6)	1.2 (2.6)	1.4 (2.7)	0.3
Glucose intake, g/day	7.4 (13.9)	0.9 (13.6)	-7.5 (18.7)	<0.001
Fructose intake, g/day	9.3 (15.9)	1.4 (13.5)	-8.2 (19.6)	<0.001
Sucrose intake, g/day	-1.6 (33.4)	-6.1 (30.9)	-9.5 (34.2)	0.001
Combined sugars intake, g/day	14.4 (50.0)	-3.3 (49.7)	-23.4 (55.9)	<0.001
Urinary excretion of sodium, mmol/24h	-10.1 (80.4)	-17.4 (76.8)	-18.2(101.1)	0.2
Urinary excretion of potassium, g/24h	2.1 (28.6)	0.5 (28.7)	4.7 (31.7)	0.3
Physical activity (time spent on moderate or hard activity), min/week [†]	0	0	-10.0	0.2
Body weight, lbs	-3.9 (9.2)	-6.4 (12.7)	-10.9 (16.4)	<0.001

Data are shown in mean (SD) if not mentioned otherwise

[†]Median was shown instead of mean because of the highly skewed distribution of that variable

Associations of blood pressure with change in diet beverages among PREMIER participants: results from mixed effects models

Table 4

	Systolic Blood Pressure		Diastolic Blood Pressure	
	β	95% C	β	95% C
All participants				
Age-adjusted model	0.14	-0.35, 0.64	0.57	-0.18 -0.49, 0.14
Multivariate model 1	-0.20	-0.41, 0.89	0.73	-0.34 -0.69, 0.01
Multivariate model 2	0.25	-0.24, 0.74	0.99	-0.05 -0.38, 0.27

β : change in mmHg per change in servings/day

Multivariate model 1: Adjusted for gender, race, family history of hypertension, randomization assignment, site, baseline age, alcohol drinking, and BMI, baseline SSB intake, baseline fitness and change in fitness, baseline physical activity and change in physical activity, baseline urinary sodium excretion and change in urinary sodium excretion, baseline DASH index and change in DASH index.

Multivariate model 2: Model 1 plus change in body weight.

Table 5

Associations of blood pressure with change in sugars or caffeine among PREMIER participants: results from mixed effects models

	Systolic Blood Pressure			Diastolic Blood Pressure		
	β	95% C	P	β	95% C	P
Sugars						
Glucose (per 10 g/day)						
Multivariate model 1	0.62	0.24, 1.00	0.001	0.54	0.29, 0.78	<0.001
Multivariate model 2	0.32	-0.02, 0.67	0.07	0.33	0.10, 0.56	0.005
Fructose (per 10 g/day)						
Multivariate model 1	0.46	0.01, 0.83	0.01	0.40	0.16, 0.64	0.001
Multivariate model 2	0.15	-0.19, 0.48	0.39	0.18	-0.04, 0.40	0.11
Sucrose (per 10 g/day)						
Multivariate model 1	0.43	0.23, 0.62	<0.001	0.32	0.19, 0.45	<0.001
Multivariate model 2	0.29	0.11, 0.47	0.002	0.22	0.11, 0.34	<0.001
Combined Sugars (per 10 g/day)						
Multivariate model 1	0.30	0.17, 0.42	<0.001	0.24	0.16, 0.32	<0.001
Multivariate model 2	0.17	0.06, 0.28	0.003	0.15	0.08, 0.23	<0.001
Caffeine (per 100 mg/day)						
Multivariate model 1	0.35	-0.09, 0.80	0.12	0.06	-0.23, 0.34	0.70
Multivariate model 2	0.36	-0.04, 0.76	0.08	0.08	-0.18, 0.34	0.56

 β : mmHg per unit of exposure

Multivariate model 1: Adjusted for gender, race, family history of hypertension, randomization assignment, site, baseline age, alcohol drinking, and BMI, baseline SSB intake, baseline fitness and change in fitness, baseline physical activity and change in physical activity, baseline urinary sodium excretion and change in urinary sodium excretion, baseline DASH index and change in DASH index.

Multivariate model 2: Model 1 plus change in body weight.