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Original Paper

Associations of Usual 24-Hour Sodium and Potassium Intakes with Blood Pressure and Risk of Hypertension among Adults in China's Shandong and Jiangsu Provinces

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Key Words
Sodium • Potassium • Blood pressure • Hypertension • 24-hour urine

Abstract
Background/Aims: High sodium intake and low intake of potassium can increase blood pressure (BP) and risk of developing hypertension. Few studies have examined the association between 24-h urinary sodium and potassium excretion and BP or risk of hypertension in China, and most used only a single 24-h urinary sample. ***Methods:*** We analyzed data on 2281 participants aged 18-69 years by using two 24-h urinary sodium and potassium excretions from the supplemental baseline survey of the Shandong- Ministry of Health Action on Salt Reduction and Hypertension (SMASH) project. We used measurement error models to estimate usual intakes, multivariable linear regression to assess their association with BP, and logistic regression to estimate the risk of hypertension. ***Results:*** The average usual intakes of sodium and potassium, and the mean sodium-potassium ratio, were 166.9 mmol/day, 25.3 mmol/day, and 6.8, respectively. All three measures were significantly associated with systolic BP (SBP) and diastolic BP (DBP), with an increase of 1.39 mmHg (95% confidence interval [CI] 0.44—2.34) in SBP and 0.94 mmHg (95% CI 0.34—1.55) in DBP for a 1-standard deviation (SD) (25.6mmol/day) increase in sodium intake, a decrease of 1.42 mmHg (95% CI -2.37— -0.47) in SBP and 0.91 mmHg (95% CI -1.52— -0.30) in DBP for a 1-SD (3.4 mmol/day) increase in potassium intake, and an increase of 0.97 mmHg (95% CI 0.36—1.58) in SBP and of 0.65 mmHg (95% CI 0.26—1.04) in DBP per unit increase in the sodium-to-potassium ratio. The adjusted odds ratios comparing the risk of hypertension among adults in the highest with those in the lowest quintile differ significantly for potassium (0.51; 95% CI 0.29—0.88) and sodium-

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to-potassium ratio (1.40; 95% CI 1.01—1.94). ***Conclusions****:* Our results suggested that higher sodium and lower potassium intakes are associated with increased BP and risk of hypertension in the Shandong and Jiangsu adults.

Introduction

Cardiovascular disease (CVD) is the leading cause of death in China, and hypertension is the key modifiable risk factor for this problem [1, 2]. Hypertension accounts for about 40% of all deaths [3] and 23% of the health care costs in China [4], indicating that control of high blood pressure (HBP) must be given high priority in this country. According to estimates obtained in 2014, roughly 270 million Chinese adults have HBP [5]. Various studies have suggested that high sodium and low potassium are among the key risk factors for hypertension [6-10]. In 2010, the mean salt intake of Chinese adults was estimated to be 9.1g/day in urban areas and 11.5g/day in rural areas [3], both amounts significantly higher than the 6.0g/day recommended by the Chinese Nutritional Society [4]. Studies suggest that reducing salt intake is one of the easiest, most efficient and cost-effective ways to reduce the burden of CVD [1, 11-12].

Although the exact mechanisms by which sodium and potassium levels affect blood pressure are not well understood, evidence suggest that the altered sodium and potassium homeostasis play a key role in pathogenesis of hypertension [6]. However, population-based studies of the associations between sodium and potassium intakes or the sodium-to-potassium ratio and BP or the risk of hypertension among Chinese adults are limited. Most previous studies used just one 24-h urinary sample, thereby not accounting for within-individual variation in dietary intakes. This lack of adjustment for day-to-day variability increases measurement error and may result in biasing the estimates of the associations toward the null.

In the present study, we estimated the usual sodium and potassium intakes, and the sodium-potassium ratio, in Chinese adults using two 24-h urine collections, and examined their relationships with BP and risk of hypertension.

Materials and Methods

Study participants

Our data came from the supplemental baseline survey of the Shandong-Ministry of Health Action on Salt Reduction and Hypertension (SMASH) project, which was conducted at four sites in the Shandong and Jiangsu provinces in 2013. The Gaomi and Fushan sites are in Shandong Province, while the Xinyi and Ganyu sites are located in Jiangsu Province. The 9600 participants, all aged 18-69 y, completed a face-to-face interview to provide sociodemographic and lifestyle information and underwent a physical examination, and a subsample of 2408 participants (25.1% of total participants) underwent 24-h urine collections. All of these participants provided a first 24-h urine, and 1445 (60.0%) provided a second 24-h urine. We excluded, sequentially, 15 participants with missing data on BP or the physical examination and 112 participants with incomplete urine collection, leaving 2281 participants for the present analysis. Our study was conducted according to the Declaration of Helsinki guidelines, and any procedures involving human subjects were approved by the ethics committee of the Chinese Center for Disease Control and Prevention. All participants provided written informed consent.

24-h urine collection

Following the INTERSALT method [13], we collected two 24-h urines one day apart, i.e., the first collection day was followed by a day without collection and then a second collection day. Participants were given a standard plastic container that contained boric acid (around 1.0 g) as a preservative and were provided both written and verbal instructions for the urine collection. The first urine of the day was discarded, and then all urine over the remainder of the 24-h period was collected. The supervising health

professional recorded the beginning and ending time for each urine collection and the total hours between the first and last void collected. A standard questionnaire was orally administered to each participant at the end of the 24-h period to assess the completeness of urine collection. Total volume of the collection was measured, and urine aliquots were stored at −20°C before being transported frozen to a certified laboratory (ADICON Clinical Laboratory Inc., Jinan, China). In accordance with the standard procedure, urinary sodium and potassium were measured with the ion-selective electrode method using the Olympus AU 680 autoanalyzer (the coefficient of variation [CV] was 1.5% for sodium and 2.5% for potassium). Creatinine was measured with the picric acid method using the Olympus AU 640 analyzer (the CV was 3.0%). An incomplete urine collection was defined as either a 24-h urinary volume less than 500 ml or a 24-h urinary creatinine volume that was ±2 standard deviations (SD) outside of the sex-specific mean.

Estimating usual intakes of sodium and potassium

Of the 2281 participants eligible for analysis, 1356 (59%) provided a reliable second 24-h urine. We used PC-SIDE software (Software for Intake Distribution Estimation for the Windows OS, Version 1.0, Iowa State University) to estimate the usual intake of sodium, potassium, and their ratio [14]; this method requires that at least some participants have multiple days of intake values. We estimated the usual intake while adjusting for the period of the week when the 24-h urine was collected and for the covariates listed below, and estimated the best linear unbiased predictors of usual sodium and potassium intake and their ratio for association study.

Outcome measures

BP was measured three times using an electronic sphygmomanometer (HEM-7071, Omron Corporation, Japan), with the average of the three measures used for analyses. Hypertension was defined per the Chinese guidelines on preventing and controlling hypertension and the United States Seventh Report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure (JNC-7) as the presence of one or more of the following characteristics: an average SBP≥140 mmHg, average DBP≥90 mmHg, a prior diagnosis of hypertension, or taking antihypertensive medication [15-16].

Covariates

The covariates included age, sex, study site, educational attainment, occupation, smoking status, drinking status (alcoholic beverages), physical activity, body mass index (BMI), and use of antihypertensive medication. There were four study sites, two each in Shandong and Jiangsu provinces; educational attainment was classified in years as <6, 6-9, and >9; occupations: farmers, workers, household workers, and other; drinking status as: nondrinker and drinker; physical activity was defined by leisure-time exercise and classified as either active or inactive; smoking status as: none or current smoker. The BMI was calculated as weight in kilograms divided by height in meters squared (kg/m^2). Normal weight was defined as a BMI<24, while overweight was defined as a BMI 24 to <28, and BMI≥28 as obese [16].

Statistical analysis

We calculated the mean, standard deviation (SD) and standard error (SE), percentages, and 95% confidence intervals (CIs) for the intake of sodium and potassium, the sodium-potassium ratio, and selected covariates. We used multivariable linear regression to examine the associations with SBP and DBP of usual sodium intake, usual potassium intake, and their ratio. We estimated the adjusted β-coefficients of changes in SBP or DBP associated with a 1-standard deviation (SD) increase in urinary sodium or potassium and a 1-unit change in the sodium-potassium ratio.

In fitting a restricted cubic spline function [17] while adjusting for covariates to examine the dose-response relationship between (a) values for urinary sodium and potassium as well as the sodium-potassium ratio and (b) BP and risk of hypertension, we found no evidence of a significant departure from linearity for the three intake variables of interest. Thus, we calculated the 10^{th}-, 30^{th}-, 50^{th}-, 70^{th}-, and 90^{th}-percentile distributions of the estimated usual intakes and, using the parameters from the linear regression models, estimated the adjusted mean SBP and DBP for these five distributions. These adjusted means can be interpreted as the middle value of each quintile (Q1, Q2, Q3, Q4, and Q5). For risk of hypertension, we used multivariable logistic regression analysis to estimate adjusted odds ratios (AORs) comparing Q5, Q4, Q3, and Q2 to the lowest quintile (Q1) using an approach similar to that used in the linear regression models. In both our linear and logistic regression analyses, we developed three covariate-adjusted models. In model

1, we adjusted for age, sex, and study site; in model 2, in addition to the covariates in model 1, we adjusted for educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication; in model 3, we further adjusted for BMI as a continuous variable. We adjusted for sodium intake in the regression models for potassium and for potassium intake in the regression models for sodium; we did not make these adjustments in the regression models for the sodium-to-potassium ratio. We tested the interaction between the estimated usual intakes and covariates by including the interaction terms in the regression models while accounting for the multiple comparisons. We found no evidence of significant interaction.

We conducted several sensitivity analyses. First, we repeated the analysis using the World Health Organization (WHO) criterion (ratio of urinary creatinine [mg/d] to body weight [kg] of <10.8 or >25.2) [18] and the Reinivuo criterion (urinary creatinine level <6 mmol/d plus a total urine volume <1000 ml/d or with a urinary excretion <5 mmol/d as having incomplete urine) [19] for incompleteness of urine collection based on excretion of urinary creatinine and other variables (see Tables 5-8). Second, we repeated our analysis by excluding the participants who were taking an antihypertensive medication. Awareness of their hypertension status might have changed their intake of sodium, and some BP-lowering medications could affect values for sodium or potassium excretion (see Table 9, 10). Statistical analyses were performed with SAS 9.3 (SAS Institute Inc.); all tests were 2-sided, and a p value < 0.05 was considered significant.

Results

The mean age of the 2281 participants was 42.1 years (SD=13.4). More than half of the participants (56.9%) were overweight or obese, and 37.0% (95% CI 35.0—38.9%) had hypertension (Table 1). Overall, the participants' average estimated usual intakes of sodium and potassium and the sodium-to-potassium ratio were 166.9 mmol/day, 25.3 mmol/day, and 6.8, respectively, and none of these values differed by BMI or hypertension status (Table 2). Mean sodium intake was higher among participants <50 years of age, Ganyu study site, with 6-9 years of education, current smokers and drinking alcohol, physically inactive and obesity (Table 2).

After adjustment for potential confounders (Table 3, Model 3), intake of sodium, potassium, and their ratio were all significantly associated with SBP, with an increase of 1.39 mmHg (95% CI 0.44—2.34) for a 1-SD increase (SD=25.6 mmol) in sodium intake and a decrease of 1.42 mmHg (95% CI -2.37 — -0.47) for a 1-SD (SD=3.4 mmol) increase in potassium intake. There was an increase of 0.97 mmHg (95% CI 0.36-1.58) for a 1-unit increase in the sodium-to-potassium ratio. For DBP, a 1-SD increase in sodium intake was associated with a 0.94 mmHg (95% CI 0.34—1.55) increase in that value, and a 1-SD increase in potassium intake was associated with a decrease of 0.91 mmHg (95% CI -1.52 — -0.30). Finally, there was an increase of 0.65 mmHg in DBP (95% CI 0.26—1.04) with a 1-unit increase in the sodium-to-potassium ratio.

The adjusted average SBP among the participants ranged from 128.9 mmHg (95% CI 127.1—130.6) among those in the lowest to 134.3 mmHg (95% CI 132.3—136.4) among those in the highest quintile (Fig. 1A); from 134.0 mmHg (95% CI 132.2—135.9) among those in the lowest to 128.5 mmHg (95% CI 126.5—130.5) among those in the highest quintile of potassium intake (Fig. 1B); and from 129.8 mmHg (95% CI 128.6—131.0) among those in the lowest to 133.3 mmHg (95% CI 131.9—134.6) among those in the highest quintile of sodium-to-potassium ratio (Fig. 1C).

The adjusted ORs comparing the prevalence of hypertension among adults in the highest quintile with those in the lowest quintile did not reveal significant differences for sodium intake (1.57; 95% CI 0.89—2.75), but significant difference for potassium intake (0.51; 95% CI 0.29—0.88), or the sodium-potassium ratio (1.40; 95% CI 1.01—1.94) (Table 4).

In sensitivity analyses, we repeated our analyses using two alternative measures of incompleteness of urine collection (the WHO and Reinivuo criteria). Overall, the patterns of the associations remained largely unchanged (see Table 5-8), although the adjusted OR comparing the prevalence of hypertension among adults in the highest vs. those in the lowest quintile was significant (AOR 1.95; 95% CI 1.02—3.71) for sodium intake using the WHO

Table 1. Characteristics of participants in 2013 supplemental survey of the SMASH project

Characteristic	All participants		Male		Female	
	N	Mean (SD) or % (95% CI)	N	Mean (SD) or % (95% CI)	N	Mean (SD) or % (95% CI)
Age (years)	2281	42.1(13.4)	1135	42.2(13.5)	1146	41.9(13.4)
region						
Fushan	551	24.2(21.8-26.7)	295	26.0(23.4- 28.5)	256	22.3(19.9-24.8)
Gaomi	568	24.9(22.4-27.3)	294	25.9(23.4-28.5)	274	23.9(21.4-26.4)
Xinyi	598	26.2(23.1-29.6)	272	24.0(21.5-26.5)	326	28.5(25.8-31.1)
Ganyu	564	24.7(22.3-27.1)	274	24.1(21.7-26.6)	290	25.3(22.8-27.8)
Years of education						
0-6	822	36.0(34.1- 38.1)	304	26.7(24.2- 29.4)	518	45.2(42.3-48.1)
6-9	917	40.2(38.2-42.3)	509	44.9(42.0- 47.7)	408	35.6(32.8-38.4)
>9	542	23.8(22.0-25.6)	322	28.4(25.8- 31.0)	220	19.2(16.9-21.5)
Occupation						
Farmer	869	38.1(36.1-40.1)	443	39.0(36.2- 41.9)	426	37.2(34.4-40.0)
Worker	569	25.0 (23.1-26.8)	374	33.0(30.2- 35.7)	195	17.0(14.8-19.2)
Household worker	368	16.1(13.4-19.4)	34	3.0(2.0- 4.0)	334	29.1(26.5-31.8)
Other	475	20.8(5.8-10.5)	284	25.0(22.5- 27.5)	191	16.7(14.5-18.8)
Smoking						
No	1614	70.8(68.9-72.6)	491	43.3(40.4- 46.1)	1123	98.0(97.2-98.8)
Yes	667	29.2(27.4-31.1)	644	56.7(53.9- 59.6)	23	2.0(1.2-2.8)
Drinking status						
Nondrinker	1682	73.7(71.9-75.6)	561	49.4(46.5- 52.3)	1121	97.8(97.0-99.0)
Drinker	599	26.3(24.5-28.1)	574	50.6(47.7- 53.5)	25	2.2(1.3-3.0)
Physical activity						
Inactive	1810	79.4(77.7-81.0)	899	79.2(76.9-81.6)	911	79.5(77.2-81.8)
Active	471	20.6(19.0-22.3)	236	20.8(18.4-23.2)	235	20.5(18.2-22.8)
BMI						
Normal	982	43.1(41.0-45.1)	480	42.3(39.4-45.2)	502	43.8(40.9-46.7)
Overweight	860	37.7(35.7-39.7)	458	40.4(37.5-43.2)	402	35.1(32.3-37.8)
Obese	439	19.2(17.6-20.9)	197	17.3(15.2-19.6)	242	21.1(18.8-23.5)
SBP	2281	131.4(19.9)	1135	134.6(18.0)	1146	128.2(21.1)
DBP	2281	83.6(11.9)	1135	85.9(11.9)	1146	81.3(11.5)
Hypertension						
No	1438	63.0(61.1-65.0)	634	55.9(53.0-58.8)	804	70.2(67.5-72.8)
Yes	843	37.0(35.0-38.9)	501	44.1(41.3-47.0)	342	29.8(27.2-32.5)

criterion (Table 6). We also repeated the analysis by excluding the participants who were on antihypertensive medications, with the results remaining largely unchanged (Table 9, 10).

Discussion

In this study, we found that usual sodium intake and the sodium-potassium ratio were positively associated with both SBP and DBP, and potassium intake negatively associated with both measures. For risk of hypertension, only potassium intake (a negative association) and the sodium-potassium ratio (positive) had a significant association, but the association with sodium intake became significant (positive) after we employed the WHO criterion for completeness of urine collection (Table 6).

Our finding of a positive association between sodium intake and BP is consistent with results from animal experiments, epidemiological studies, and clinical trials [20-24]. In addition, a recent meta-analysis of 34 trials reported that a reduction of 75 mmol per 24-h in urinary sodium excretion reduced SBP by an average of 4.18 mmHg (95% CI -5.18—-3.18) and DBP by an average of 2.06 mmHg (95% CI -2.67— -1.45) [13], findings similar to ours. In our study, the slope of the overall relationship between usual sodium intake and BP (equivalent to an increase of 2.36 mmHg in SBP and 1.60 mmHg in DBP per g increase in sodium intake)

is more steeper than the results of the INTERSALT study (increment of 2.2 mmHg in SBP and 0.1 mmHg in DBP per 100 mmol/d sodium) [25] and PURE study (increment of 2.11 mmHg in SBP and 0.78 mmHg in DBP per g of sodium [26].

Unlike the INTERSALT and PURE studies, however, we estimated the associations of BP with usual sodium intake while accounting for within-individual variation in such intake. The significant inverse relationship we found between potassium excretion and BP (equivalent to a decrease of 10.7 mmHg in SBP and 6.86 mmHg in DBP per g) is substantially steeper than that reported in the INTERSALT study (decrements of 0.65 mmHg in SBP and 0.42 mmHg in DBP per g) and PURE study (decrements of 0.75 mmHg in SBP and 0.06 mmHg in DBP per g). The reason for the steep association between potassium and BP in this study is probably the very low potassium intake, which makes this population very sensitive to an increased intake in potassium. The PURE study also found a stronger inverse relationship between potassium excretion and BP in China than in other geographic regions in that study. A recent meta-analysis, however, reported that an increased potassium intake had no statistically significant effect on BP [28]. And yet, other meta-analyses reported that an increased potassium intake lowered BP in patients both with and without hypertension [8, 29-30]. A WHO-sponsored

Table 2. Usual intakes of sodium and potassium and sodium-potassium ratio by characteristics

Characteristics	24-h sodium excretion (mmol)	24-h potassium excretion (mmol)	Sodium-potassium ratio
	Mean(SD)	Mean(SD)	Mean(SD)
All	166.9 (25.6)	25.3 (3.4)	6.8 (1.5)
Sex			
Male	172.4 (29.0)	25.3 (3.6)	7.0 (1.6)
Female	161.6 (22.0)	25.3 (3.0)	6.5 (1.4)
Age, years			
<50	169.7 (26.9)	24.9 (3.6)	7.0 (1.6)
≥50	160.7 (20.3)	26.3 (3.3)	6.3 (1.3)
p-value[a]	<0.001	<0.001	<0.001
Region			
Fushan (1)	170.4 (36.8)	23.8 (4.3)	7.4 (1.9)
Gaomi (2)	138.7 (23.5)	23.0 (2.8)	6.2 (1.4)
Xinyi (3)	178.8 (18.3)	26.2 (2.2)	6.9 (1.1)
Ganyu (4)	180.8 (21.3)	28.2 (2.8)	6.6 (1.3)
p-value (1) vs. (2)	<0.001	<0.001	<0.001
p-value (1) vs. (3)	<0.001	<0.001	<0.001
p-value (1) vs. (4)	<0.001	<0.001	<0.001
Educational attainment			
0 ~6	164.3 (21.9)	25.8 (2.8)	6.5 (1.3)
6~9	174.1 (21.5)	26.7 (3.1)	6.7 (1.4)
>9	159.1 (35.2)	22.4 (3.5)	7.3 (1.8)
p-value for trend[a]	<0.001	<0.001	<0.001
Occupation			
Peasant (1)	163.4 (20.0)	25.5 (3.0)	6.5 (1.4)
Worker (2)	170.2 (30.3)	24.8 (3.5)	7.0 (1.4)
Household (3)[b]	164.2 (18.2)	26.5 (2.2)	6.3 (1.2)
Others (4)	171.2 (35.4)	24.5 (3.3)	7.1 (1.7)
p-value (1) vs. (2)	0.01	0.001	<0.001
p-value (1) vs. (3)	0.66	0.002	0.06
p-value (1) vs. (4)	0.03	<0.001	<0.001
Smoking status			
Yes[b]	172.6 (26.8)	25.3 (3.4)	7.1 (1.5)
No	164.6 (24.5)	25.3 (3.4)	6.7 (1.5)
p-value[a]	<0.001	1.00	<0.001
Drinking status			
Drinker[b]	175.6 (28.4)	25.8 (3.6)	7.0 (1.4)
Nondrinker	163.9 (24.5)	25.2 (3.2)	6.7 (1.5)
p-value[a]	<0.001	0.02	<0.001
Physical activity			
Inactive	168.4 (23.6)	25.7 (3.5)	6.7 (1.4)
Active	161.6 (31.3)	24.0 (3.2)	6.9 (1.8)
p-value[a]	<0.001	<0.001	0.01
BMI			
Normal	160.3 (24.6)	24.2 (3.4)	6.8 (1.6)
Overweight	170.3 (26.9)	26.0 (3.3)	6.7 (1.4)
Obesity	175.2 (20.9)	26.5 (3.0)	6.8 (1.4)
p-value for trend[a]	<0.001	<0.001	0.25

All participants (n=2281). [a] For categorical variable with two categories, P value based on T-test; for categories of the continuous variables in nature (e.g., years of education and body mass index), P value for difference across the categories; for categorical variables (e.g., study sites), we presented pairwise P values. All tests were 2-tailed. [b] "-":sample size is too small to estimate the usual intake.

Table 3. Adjusted associations between usual intake of sodium, potassium, and sodium-potassium ratio and systolic and diastolic blood pressure

	Systolic Blood Pressure		Diastolic Blood Pressure	
	β-coefficient (95% CI)[a]	*p*-Value	β-coefficient (95% CI)[a]	*p*-Value
Sodium				
Model 1[b]	1.85(0.86 - 2.83)	0.0003	1.29 (0.64 - 1.93)	<0.0001
Model 2[c]	1.70 (0.71 - 2.69)	0.0008	1.19 (0.55 - 1.83)	0.0003
Model 3[d]	1.39 (0.44 - 2.34)	0.0042	0.94 (0.34 - 1.55)	0.0023
Potassium				
Model 1[b]	-1.22 (-2.21- -0.23)	0.0158	-0.70 (-1.34 - -0.06)	0.0324
Model 2[c]	-1.07 (-2.06 - -0.08)	0.0348	-0.64 (-1.28 - 0.01)	0.0524
Model 3[d]	-1.42 (-2.37 - -0.47)	0.0033	-0.91 (-1.52 - -0.30)	0.0033
Sodium-potassium ratio				
Model 1[b]	1.08 (0.46 - 1.70)	0.0006	0.70 (0.30 - 1.11)	0.0007
Model 2[c]	1.02 (0.39 - 1.66)	0.0016	0.69 (0.28 - 1.10)	0.0011
Model 3[d]	0.97 (0.36 -1.58)	0.0019	0.65 (0.26 - 1.04)	0.0011

[a]β-coefficients for the usual intake of sodium and potassium are presented as per 1 standard deviation (SD) of intake; the estimated population SD for 24-h sodium and 24-h potassium was 25.6 mmol and 3.4 mmol, respectively. The β-coefficient for the sodium-potassium ratio is presented as per 1 unit of change. [b]Model 1 adjusted for age, sex, and study site. In addition, potassium intake was included in the model for sodium and sodium intake in the model for potassium. [c]Model 2 adjusted for all factors in Model 1 plus educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable.

Table 4. Adjusted odds ratios for risk of hypertension by estimated usual sodium and potassium intakes and sodium-potassium ratio

▽

	Odds Ratio (95% CI)[a]					*p*-Value
	Q1	Q2	Q3	Q4	Q5	
Sodium						
Mid-value*	117	143	163	184	218	
Model 1[b]	1.00	1.20 (1.05 -1.36)	1.37 (1.09 - 1.73)	1.59 (1.14 - 2.22)	2.01 (1.21 - 3.34)	0.0070
Model 2[c]	1.00	1.18 (1.03 - 1.35)	1.34 (1.06 - 1.70)	1.53 (1.09 - 2.16)	1.90 (1.14 - 3.19)	0.0146
Model 3[d]	1.00	1.12 (0.97 - 1.30)	1.23 (0.95 - 1.59)	1.35 (0.93 -1.96)	1.57 (0.89 - 2.75)	0.1166
Potassium						
Mid-value*	18.8	22.4	25.0	27.8	32.1	
Model 1[b]	1.00	0.87 (0.76 - 0.99)	0.79 (0.63 - 0.98)	0.70 (0.51 - 0.98)	0.60 (0.37 - 0.96)	0.0348
Model 2[c]	1.00	0.88 (0.77 -1.01)	0.80 (0.64 - 1.02)	0.73 (0.52 - 1.03)	0.63 (0.38 - 1.04)	0.0698
Model 3[d]	1.00	0.83 (0.72 - 0.97)	0.73 (0.57 - 0.94)	0.63 (0.44 - 0.92)	0.51 (0.29 - 0.88)	0.0151
Sodium-potassium ratio						
Mid-value**	4.99	5.90	6.59	7.35	8.60	
Model1[b]	1.00	1.11 (1.03 -1.20)	1.20 (1.05 -1.37)	1.30 (1.07 - 1.59)	1.50 (1.11 - 2.03)	0.0090
Model 2[c]	1.00	1.10 (1.02 - 1.19)	1.18 (1.03 - 1.36)	1.28 (1.04 - 1.57)	1.46 (1.07 - 1.99)	0.0172
Model 3[d]	1.00	1.09 (1.00 - 1.18)	1.16 (1.00 - 1.34)	1.25 (1.01- 1.54)	1.40 (1.01 - 1.94)	0.0440

*Mid-value of quintile (mmol); **Mid-value of quintile; [a]For usual intake of sodium and potassium, the odds ratios (ORs) are per 1 standard deviation (SD) increase in excretion. For the sodium-potassium ratio, the ORs are per unit of change. [b]Model 1 adjusted for age, sex, and study site. In addition, potassium intake was included in the model for sodium and sodium in the model for potassium. [c]Model 2 adjusted for all the factors in Model 1 plus educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable.

study [31] showed an added complexity of the relationship between potassium and BP, as it found that potassium intake was negatively associated with both SBP and DBP in Tibetan participants but was positively associated with SBP and DBP in Han participants (Han is the majority ethnicity in China). The WHO study focused on people aged 48-56 years and had a limited sample size (n = 800) [31].

We found that the sodium-to-potassium ratio was significantly associated with SBP, DBP, and risk of hypertension, with increments of 0.97 mmHg in SBP and 0.65 mmHg in DBP per a 1-unit increase in the ratio. These results are consistent with previous studies [32].

The PURE study found that a 1-SD increment in the estimated sodium-to-potassium ratio (SD=3.26) was associated with increments of 2.3 mmHg in SBP and 0.78 mmHg in DBP. The 2005-2010 NHANES study [31] found that the sodium-to-potassium ratio was associated with SBP, with an increase of 1.05 mmHg (95%CI 0.12—1.98) for every 0.5-unit increase in this ratio. The China Health and Nutrition Survey cohort study found that a high sodium-to-potassium ratio had a strong independent dose-response association with incident hypertension. The findings there suggested that the sodium-to-potassium ratio might be a better measurement than either sodium or potassium alone in the evaluation of BP outcomes and incident hypertension [33]. In addition, a recent meta-analysis found that among the randomized controlled trials reviewed, the sodium-to-potassium ratio appeared to be more strongly associated with BP than either sodium or potassium intake alone in the hypertensive adult population [32].

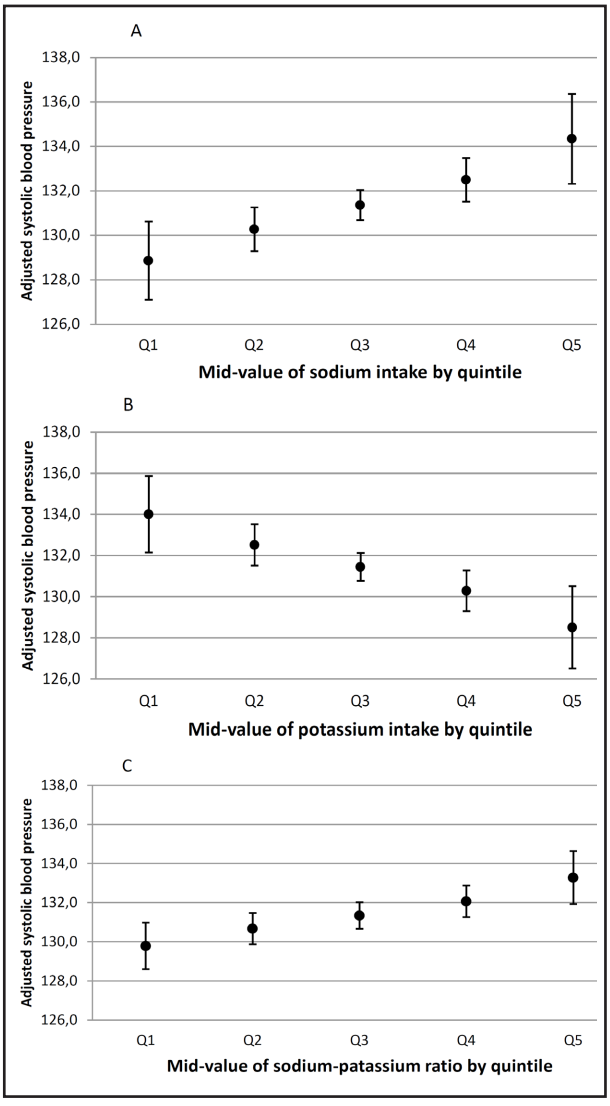

Fig. 1. Adjusted systolic blood pressure (with 95% confidence interval) by mid-value of quintile of usual sodium intake (panel A), potassium intake (panel B), and sodium-potassium ratio (panel C).

Our study found that both potassium intake and the sodium-to-potassium ratio were significantly associated with risk of hypertension. The 2005-2010 NHANES found that the AORs for comparisons of the prevalence of hypertension among adults in the highest quartile of intake vs. the lowest quartile were 1.40 (95% CI 1.07—1.83) for sodium and 0.72 (95% CI 0.53—0.97) for potassium, while the AOR for the sodium-to-potassium ratio using this comparison was 1.30 (95% CI 1.05—1.61 [27]. Elsewhere, the China Health and Nutrition Survey cohort study, which compared intake in the highest against the lowest quintile, the AOR for incident hypertension was 1.84 (95% CI 1.56—2.16) for sodium, 0.66 (95% CI 0.56—0.78) for potassium, and 2.14 (95% CI 1.79—2.55) for their ratio [33]. Our results were similar to these two studies, but we found an insignificant association between sodium intake and hypertension after we adjusted for covariates. However, the association became significant after we used the WHO criterion for completeness of urine collection (Table 6).

Our study had several major strengths. First, to our knowledge, this is the first study to assess the association between usual intakes of salt and potassium and both BP and risk of hypertension using two 24-h collections of urine in a relatively large sample of Chinese adults. Having two urine collections rather than just one should have accounted for, at least partly, the between- and within-individual variation in sodium and potassium intakes.

Table 5. Adjusted associations between usual intakes of sodium and potassium and the sodium-potassium ratio and systolic and diastolic blood pressure using the WHO criterion

	Systolic Blood Pressure		Diastolic Blood Pressure	
	β-coefficient (95% CI)[a]	*p*-Value	β-coefficient (95% CI)[a]	*p*-Value
Sodium				
Model 1[b]	1.80(0.69 - 2.91)	0.0016	1.27 (0.55 - 2.00)	0.0006
Model 2[c]	1.68 (0.56 - 2.79)	0.0032	1.21 (0.48 - 1.93)	0.0012
Model 3[d]	1.24 (0.18 - 2.29)	0.0216	0.86 (0.19 - 1.54)	0.0125
Potassium				
Model 1[b]	-1.21 (-2.32 - -0.10)	0.0330	-0.29 (-1.01 - 0.44)	0.4372
Model 2[c]	-1.10 (-2.22 - -0.01)	0.0522	-0.30 (-1.03 - 0.42)	0.4150
Model 3[d]	-1.94 (-2.99 - -0.88)	0.0003	-0.99 (-1.66 - -0.31)	0.0044
Sodium-potassium ratio				
Model 1[b]	1.38 (0.58 - 2.18)	0.0007	0.79 (0.27 - 1.31)	0.0031
Model 2[c]	1.32 (0.50 - 2.15)	0.0017	0.80 (0.26 - 1.34)	0.0035
Model 3[d]	1.30 (0.50 - 2.10)	0.0014	0.79 (0.27 - 1.30)	0.0026

[a]β-coefficients for the usual intake of sodium and potassium are presented as per 1 standard deviation (SD); the estimated population SD for 24-h sodium and 24-h potassium was 23.5 mmol and 3.0 mmol, respectively. The β-coefficient for the sodium-potassium ratio is presented as per 1 unit of change in that ratio. [b]Model 1 adjusted for age, sex, and study site. In addition, potassium was included in the model for sodium and sodium in the model for potassium. [c]Model 2 adjusted for all factors in Model 1 plus educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable.

Table 6. Adjusted odds ratios for hypertension by estimated usual sodium and potassium intake and sodium-potassium ratio using the WHO criterion

▽

	Odds Ratio (95% CI)[a]					*p*-Value
	Q1	Q2	Q3	Q4	Q5	
Sodium excretion						
Mid-value*	151	175	194	214	245	
Model 1[b]	1.00	1.24 (1.08 - 1.43)	1.48 (1.14 - 1.91)	1.77 (1.22 - 2.58)	2.35 (1.34 - 4.10)	0.0028
Model 2[c]	1.00	1.23 (1.07 - 1.42)	1.45 (1.12 - 1.89)	1.73 (1.18 - 2.53)	2.26 (1.28 - 4.00)	0.0049
Model 3[d]	1.00	1.19 (1.01 - 1.40)	1.36 (1.01 - 1.82)	1.56 (1.02 - 2.41)	1.95 (1.02 - 3.71)	0.0424
Potassium excretion						
Mid-value*	23.7	26.9	29.3	31.8	35.6	
Model 1[b]	1.00	0.87 (0.76 - 1.01)	0.79 (0.61 - 1.01)	0.71 (0.49 - 1.02)	0.60 (0.36 - 1.02)	0.0609
Model 2[c]	1.00	0.88 (0.76 - 1.02)	0.80 (0.61 - 1.03)	0.72 (0.49 - 1.05)	0.62 (0.35 - 1.07)	0.0862
Model 3[d]	1.00	0.74 (0.62 - 0.88)	0.59 (0.43 - 0.80)	0.47 (0.30 - 0.72)	0.33 (0.17 - 0.62)	0.0007
Sodium-potassium ratio						
Mid-value**	5.14	6.04	6.70	7.41	8.54	
Model 1[b]	1.00	1.18 (1.07 - 1.30)	1.33 (1.12 - 1.57)	1.51 (1.17 - 1.93)	1.85 (1.27 - 2.69)	0.0014
Model 2[c]	1.00	1.17 (1.06 - 1.30)	1.32 (1.10 - 1.57)	1.49 (1.15 - 1.93)	1.82 (1.23 - 2.69)	0.0027
Model 3[d]	1.00	1.18 (1.06 -1.31)	1.33 (1.10 - 1.61)	1.52 (1.15 - 1.99)	1.86 (1.24 - 2.81)	0.0030

*Mid-value of quintile (mmol); **Mid-value of quintile; [a]For usual intake of sodium and potassium, ORs are per 1 standard deviation (SD) increase in excretion. For the sodium-potassium ratio, ORs are per 1 unit of change. [b]Model 1 adjusted for age, sex, and study site. In addition, potassium was included in the model for sodium and sodium in the model for potassium. [c]Model 2 adjusted for all factors in Model 1 plus educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable.

Second, we used a measurement error model to estimate the usual intakes of sodium and potassium and their ratio for the association analysis.

One potential limitation of our study was the method we chose to assess the completeness of urine collection. We did not have an objective biomarker of completeness such as para-aminobenzoic acid (PABA) [34-35]; rather, we employed sensitivity analyses, and used urinary creatinine, urine volume, and body weight to assess the completeness of collection, but our approach might have led to the inclusion of some incomplete urine samples or the exclusion of some complete urine samples, either approach introducing an additional source of variability. Second, in our study, covariates were based on self-reports and thus subject

Table 7. Adjusted association between usual intake of sodium, potassium, and sodium-potassium ratio and systolic and diastolic blood pressure using the Reinivuo criterion

	Systolic Blood Pressure		Diastolic Blood Pressure	
	β-coefficient (95% CI)[a]	*p*-Value	β-coefficient (95% CI)[a]	*p*-Value
Sodium excretion				
Model 1[b]	2.12(1.14 - 3.11)	<.0001	1.31 (0.67 - 1.96)	<.0001
Model 2[c]	1.99 (1.00 - 2.98)	<.0001	1.27 (0.63 - 1.92)	0.0001
Model 3[d]	1.77 (0.83 - 2.73)	0.0002	1.10 (0.49 - 1.71)	0.0004
Potassium excretion				
Model 1[b]	-1.64 (-2.63 - -0.65)	0.0011	-0.77 (-1.42 - -0.13)	0.0189
Model 2[c]	-1.48 (-2.47 - -0.49)	0.0033	-0.76 (-1.41 - -0.12)	0.0205
Model 3[d]	-1.85 (-2.80 - -0.90)	0.0001	-1.05 (-1.67 - -0.45)	0.0007
Sodium-potassium ratio				
Model 1[b]	1.32 (0.71 - 1.94)	<.0001	0.77 (0.37 - 1.17)	0.0002
Model 2[c]	1.28 (0.65 - 1.91)	<.0001	0.77 (0.36 - 1.18)	0.0003
Model 3[d]	1.27 (0.66 - 1.87)	<.0001	0.76 (0.37 - 1.15)	0.0001

[a]β-coefficients for the usual intake of sodium and potassium are presented as per 1 standard deviation (SD); the estimated population SD for 24-hour sodium and 24-hour potassium was 30.5 mmol and 3.9 mmol, respectively. β-coefficient for the sodium-potassium ratio is presented as per 1 unit of change. [b]Model 1 adjusted for age, sex, and study site. Potassium intake was included in the model for sodium and sodium intake in the model for potassium. [c]Model 2 adjusted for all factors in Model 1 plus educational attainment, smoking status, occupation, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable.

Table 8. Adjusted odds ratios for hypertension by estimated usual sodium and potassium intake and sodium-potassium ratio using the Reinivuo criterion

▽

	Odds Ratio (95% CI)[a]					*p*-Value
	Q1	Q2	Q3	Q4	Q5	
Sodium						
Mid-value*	126	155	177	201	239	
Model 1[b]	1.00	1.17 (1.03 - 1.33)	1.32 (1.06 - 1.65)	1.51 (1.09 - 2.09)	1.86 (1.14 - 3.04)	0.0137
Model 2[c]	1.00	1.16 (1.02 - 1.32)	1.30 (1.04 - 1.63)	1.48 (1.06 - 2.06)	1.80 (1.09 - 2.96)	0.0211
Model 3[d]	1.00	1.11 (0.97 - 1.28)	1.21 (0.94 - 1.54)	1.32 (0.92 - 1.89)	1.52 (0.88 - 2.62)	0.1330
Potassium excretion						
Mid-value *	20.3	24.2	27.0	30.1	34.9	
Model 1[b]	1.00	0.85 (0.75 - 0.97)	0.76 (0.61 - 0.95)	0.67 (0.48 - 0.93)	0.55 (0.34 - 0.89)	0.0155
Model 2[c]	1.00	0.86 (0.75 - 0.98)	0.77 (0.61 - 0.97)	0.68 (0.48 - 0.95)	0.56 (0.34 - 0.93)	0.0244
Model 3[d]	1.00	0.80 (0.69 - 0.93)	0.69 (0.53 - 0.88)	0.58 (0.40 - 0.84)	0.44 (0.25 - 0.76)	0.0035
Sodium-potassium ratio						
Mid-value**	5.02	5.94	6.65	7.41	8.67	
Model 1[b]	1.00	1.11 (1.03 - 1.20)	1.21 (1.05 - 1.38)	1.32 (1.07 - 1.61)	1.52 (1.12 - 2.07)	0.0079
Model 2[c]	1.00	1.11 (1.02 - 1.20)	1.20 (1.04 - 1.38)	1.30 (1.06 - 1.60)	1.50 (1.09 - 2.06)	0.0128
Model 3[d]	1.00	1.10 (1.01 - 1.20)	1.19 (1.02 - 1.38)	1.28 (1.03 - 1.60)	1.47 (1.05 - 2.05)	0.0260

*Mid-value of quintile (mmol); **Mid-value of quintile; [a]For usual intake of sodium and potassium, ORs are per 1 standard deviation (SD) increase in excretion. For sodium-potassium ratio, the OR is 1 per unit of change. [b]Model 1 adjusted for age, sex, and study site. In addition, potassium was included in the model for sodium and sodium in the model for potassium. [c]Model 2 adjusted for all factors in Model 1 plus educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable.

to reporting error. For example, we did not obtain information on the intensity of physical activity or the amount and frequency of alcoholic beverages the participants consumed. Further, some potential confounding factors, such as total energy intake, were not included as covariates. Finally, this study was cross-sectional, and thus the observed associations should be interpreted with caution.

Table 9. Adjusted associations with systolic and diastolic blood pressure by usual intake of sodium, potassium, and the sodium-potassium ratio while excluding persons taking an antihypertensive medication

	Systolic Blood Pressure		Diastolic Blood Pressure	
	β-coefficient (95% CI)[a]	*p*-Value	β-coefficient (95% CI)[b]	*p*-Value
Sodium				
Model 1[b]	1.72 (0.74 - 2.68)	0.0005	1.18 (0.54 - 1.82)	0.0003
Model 2[c]	1.56 (0.58 - 2.53)	0.0017	1.10 (0.46 - 1.74)	0.0008
Model 3[d]	1.27 (0.33 - 2.20)	0.0080	0.85 (0.25 - 1.46)	0.0059
Potassium				
Model 1[b]	-1.03 (-2.63 - -0.65)	0.0369	-0.58 (-1.22 - 0.06)	0.0773
Model 2[c]	-0.91 (-1.88 - 0.06)	0.0657	-0.57 (-1.21 - 0.07)	0.0832
Model 3[d]	-1.25 (-2.19 - -0.31)	0.0089	-0.83 (-1.44 - -0.23)	0.0072
Sodium-potassium ratio				
Model 1[b]	0.98 (0.37 - 1.60)	0.0017	0.64 (0.23 - 1.05)	0.0020
Model 2[c]	0.91 (0.28 - 1.54)	0.0045	0.63 (0.21 - 1.04)	0.0032
Model 3[d]	0.86 (0.25 - 1.47)	0.0056	0.59 (0.19 - 0.98)	0.0038

[a]β-coefficients for usual intake of sodium and potassium are presented as per 1 standard deviation (SD); the estimated population SD for 24-h sodium and 24-h potassium was 24.6 mmol and 3.3 mmol, respectively. β-coefficient for the sodium-potassium ratio is presented as per 1 unit of change. [b]Model 1 adjusted for age, sex, and study site. In addition, the model adjusted for potassium in the sodium model and sodium in the potassium model. [c]Model 2 adjusted for all factors in Model 1 plus educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable.

Table 10. Adjusted odds ratios for hypertension by usual sodium and potassium intake and sodium-potassium ratio using the Reinivuo criterion while excluding persons taking an antihypertensive medication

▽

	Odds Ratio (95% CI)[a]					*p*-Value
	Q1	Q2	Q3	Q4	Q5	
Sodium						
Mid-value*	118	144	163	183	216	
Model 1[b]	1.00	1.23 (1.07 - 1.41)	1.43 (1.12 - 1.82)	1.67 (1.18 - 2.37)	2.16 (1.28 - 3.67)	0.0041
Model 2[c]	1.00	1.21 (1.05 - 1.40)	1.39 (1.08 - 1.78)	1.61 (1.12 - 2.30)	2.05 (1.19 - 3.51)	0.0093
Model 3[d]	1.00	1.15 (0.99 - 1.34)	1.28 (0.98 - 1.67)	1.42 (0.97 - 2.10)	1.70 (0.95 - 3.05)	0.0743
Potassium						
Mid-value*	18.8	22.3	24.9	27.6	31.9	
Model 1[b]	1.00	0.86 (0.75 - 0.99)	0.77 (0.61 - 0.98)	0.69 (0.49 - 0.97)	0.58 (0.35 - 0.96)	0.0323
Model 2[c]	1.00	0.87 (0.76 - 1.00)	0.78 (0.61 - 1.00)	0.70 (0.49 - 1.00)	0.59 (0.35 - 1.00)	0.0528
Model 3[d]	1.00	0.82 (0.70 - 0.96)	0.71 (0.54 - 0.92)	0.61 (0.41 - 0.89)	0.48 (0.27 - 0.84)	0.0108
Sodium-potassium ratio						
Mid-value**	5.02	5.92	6.62	7.38	8.61	
Model 1[b]	1.00	1.12 (1.03 - 1.21)	1.22 (1.06 - 1.40)	1.34 (1.09 - 1.65)	1.56 (1.14 - 2.13)	0.0057
Model 2[c]	1.00	1.11 (1.02 - 1.20)	1.20 (1.04 - 1.39)	1.32 (1.06 - 1.63)	1.52 (1.10 - 2.10)	0.0112
Model 3[d]	1.00	1.10 (1.01 - 1.20)	1.19 (1.02 - 1.38)	1.28 (1.03 - 1.60)	1.46 (1.04 - 2.05)	0.0272

*Mid-value of quintile (mmol); **Mid-value of quintile; [a]For usual intake of sodium and potassium, odds ratios (ORs) are per 1 standard deviation (SD) increase in excretion. For sodium-potassium ratio, the OR is per unit of change. [b]Model 1 adjusted for age, sex, and study site. Potassium was included in the model for sodium and sodium was included in the model for potassium. [c]Model 2 adjusted for all factors in Model 1 plus educational attainment, occupation, smoking status, drinking status, physical activity, and use of antihypertensive medication. [d]Model 3 adjusted for all factors in Model 2 plus BMI as a continuous variable

Conclusion

Our results indicate that sodium intake is positively associated with BP, that potassium intake is negatively associated with both BP and risk of hypertension, and that the sodium-to-potassium ratio is positively associated with both. These results are consistent with previous findings, and demonstrate the compelling importance of reducing sodium intake to

control BP. Our study suggested that reducing sodium and increasing potassium intake is a public health priority for these survey areas.

Disclosure Statement

The authors declare no conflict of interest.

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