Associations of Household Solid Fuel for Heating and Cooking With Hypertension in Chinese Adults

Zhiguang Liu
The Chinese University of Hong Kong
Perry Hystad
Oregon State University
Lu Yin
Chinese Academy of Medical Sciences & Peking Union Medical College Fuwai Hospital
Sumathy Rangarajan
Population Health Research Institute, Hamilton Health Sciences and McMaster University
Fanghong Lu
Shandong academy of medical Sciences
Bo Hu
Chinese Academy of Medical Sciences & Peking Union Medical College Fuwai Hospital
Yihong Zhou
Wujin Center for Disease Control and Prevention
Shrikant I Bangdiwala
Population Health Research Institute, Hamilton Health Sciences and McMaster University
Yindong Li
Shunyi district center for disease control and prevention
Yang Wang
Chinese Academy of Medical Sciences & Peking Union Medical College Fuwai Hospital
Salim Yusuf
Population Health Research Institute, Hamilton Health Sciences and McMaster University
Wei Li
Chinese Academy of Medical Sciences & Peking Union Medical College Fuwai Hospital
Lap Ah Tse (shelly@cuhk.edu.hk)
Chinese University of Hong Kong https://orcid.org/0000-0003-0355-6218

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Abstract

Background: Few studies have examined the association between indoor air pollution from household solid fuel use for heating and cooking with hypertension considering the influence of outdoor particles with aerodynamic diameter < 2.5 μm. The aim of this study is to investigate the association of household solid fuel for heating and cooking with hypertension prevalence in a large diverse Chinese population.

Methods: 44,007 individuals aged 35-70 years with complete information on fuels used for cooking and heating and PM2.5 air pollution levels for 279 urban and rural communities of 12 centers were recruited in this study. Generalized linear mixed models using community as the random effect were performed to estimate the association with hypertension prevalence and blood pressure after considering ambient PM2.5 and a comprehensive set of potential confounding factors at the individual and household level.

Results: 47.6% and 61.2% of participants used household solid fuel for heating and cooking, respectively. Solid fuel for heating was associated with statistically insignificant increase in hypertension prevalence (adjusted OR=1.08, 95% CI: 0.98, 1.20) or elevated systolic blood pressure (0.62mmHg, 95% CI: -0.24, 1.48). No association was found between solid fuel for cooking and hypertension or blood pressure, and no additional risk was observed among participants who had the combined exposure to both solid fuels for heating and cooking compared with those using household solid heating fuel only.

Conclusion: No statistical significant association between the use of solid fuel for cooking or heating with BP or prevalence of hypertension was found in this large and diverse Chinese population.

Introduction

Indoor air pollution resulting from burning fuels for heating and cooking has been a major public health problem in China and other developing countries for decades (1–3). Burning fuels for heating in winter or rainy season is especially common in many northern rural areas of China (4, 5), which generates large amounts of particulate matter (e.g., PM2.5, PM10), carbon monoxide nitrogen dioxide, sulfur dioxide, polycyclic aromatic hydrocarbons and/or other volatile organic compounds (6, 7). Many of these chemical substances are known to increase oxidative stress and systematic inflammation, and could potentially increase blood pressure (BP) and promote vascular atherosclerosis (7, 8).

Household solid fuel use for cooking and hypertension has been investigated by several epidemiological studies with mixed findings (9–16). A study examining 137,809 individuals from ten countries in the Prospective Urban and Rural Epidemiology (PURE) study observed no association between cooking with solid fuels and hypertension or blood pressure (9). However, this study did not examine solid fuel use for heating since many of the countries included did not have a high prevalence of heating. However, in China, solid fuel use for heating and cooking is high (4, 5), and heating may be more important to PM2.5 exposures than cooking (17). Until now, only two cross-sectional studies conducted in China have examined the association between using household solid fuels and hypertension prevalence and reported a positive association (15, 16), but both of them were not distinguish the effect of cooking from heating, or the combined effect of using solid fuels for heating and cooking. Recent evidence has shown that long-term exposure to ambient PM2.5 may harm blood vessels and increase blood pressure via increasing inflammatory factors and oxidative stress (18, 19), but more research is needed to determine if heating and cooking with solid fuels are a potential modifiable source of air pollution exposure that could decrease hypertension and blood pressure.

This study is the first to examine the association of household solid fuel use for both heating and cooking with hypertension and blood pressure among a large community-based population in China, after considering the influence of ambient PM2.5 exposure and a comprehensive set of potential confounding factors at the individual and household level.

Methods

Study design and participants

The Prospective Urban Rural Epidemiology (PURE) study is a large-scale epidemiological study that recruited 153,996 individuals aged 35-70 years from 600 communities in 17 countries around the world (20, 21). Here we use the baseline survey of the PURE study in China (PURE-China). Three-level cluster sampling (province, community and household) was used to enroll potential participants between 2005-2009 (22). For the PURE-China study, a total of 47,863 subjects aged 35 to 70 years were recruited from 279 communities in 12 centers (provinces), and the selection of communities was based on the feasibility for a long-term follow-up. A total of 3,563 participants were excluded due to incomplete information of age, sex or primary cooking and/or heating source, education, smoking and alcohol status, food intake and household wealth index. We further excluded 223 individuals who used kerosene as the main heating source because its emission characteristic differs from that of the solid fuels (23). Therefore, a total of 44,007 participants were retained in the current analyses.

Data collection

Trained research staff interviewed each participant according to standardized individual and household questionnaires to collect information on socio-demographic data, lifestyle behaviors (e.g., tobacco smoking, alcohol drinking, physical activity, and dietary habits), household fuels uses, and medical history (21). Physical activity was collected using the International Physical Activity Questionnaire and then evaluated in metabolic equivalents (24). Daily energy intake was assessed using a validated Food Frequency Questionnaire (25). Smoking and alcohol use were defined if an individual ever or current regularly used any tobacco/alcohol products, otherwise, the participant was referred to being a never smoker/alcohol drinker. Body mass index (BMI) was calculated by body weight (kilogram) divided by the square of the body height (meter) (26). We categorized BMI according to the guideline for the prevention and treatment of hypertension in China and defined participants as normal (BMI<24), overweight (28>BMI≥24) and obese (BMI≥28) (27). Household wealth index was developed based on household possessions from the PURE questionnaire and classified into three categories using the tertile value (28).

Definitions of outcomes

Blood pressure (BP) was measured twice separately on the right arm by trained personnel using standard digital BP measuring device and the mean value of two separate measurements was calculated for further analysis. Before BP was measured, each participant had at least 5 minutes for resting and stayed 30 minutes before the last smoking, exercising, eating or climbing stairs. Each measurement was recorded for both systolic blood pressure (SBP) and diastolic blood pressure (DBP) simultaneously. Hypertension was defined either using a self-reported physician diagnosed hypertension, receiving BP control drug within two weeks or the mean value of DBP≥90 mmHg or SBP≥140mmHg.

Measurement of household fuel uses for heating and cooking

Information on household fuel uses for heating and cooking were collected using the same protocol published elsewhere (29). In brief, the sources of fuels used for cooking and household heating during the cold or rainy season were collected by questionnaire at medical institute and validated by trained site monitor staff to response for quality control. As information on household fuel was recorded at the household level, we assumed all participants from the same household adopted the same source of the fuel from cooking and heating. We classified participants into the users of solid fuels for heating (coal open fire, wood open fire or agriculture/crop) and clean fuel (electricity, gas or central heating). As the socioeconomic background of people burning other types of fuel for heating or never using heating differed from those using solid fuel or clean fuel, they were classified into separate groups. We defined the primary cooking fuels as solid (charcoal, coal, wood, agriculture/crop, animal dung) and clean (electricity, gas or gobar gas) (29). As some participants used mixed fuel for heating and cooking, we grouped them into clean or solid fuel groups based on their primary fuel use and then conducted sensitivity analysis by their secondary fuel use.

Measurement of ambient PM2.5 air pollution

Detailed methodology of PM2.5 exposure assessment has been published elsewhere (30). Briefly, annual PM2.5 concentrations were estimates from satellite and fixed monitoring data using geographically weighted regression method at 1km*1km resolution. Multiple satellite products were used to estimate aerosol optical depth which was further combined with GEOS-Chem simulation based on sun photometer observation (30). We applied these estimates to predict the ground-level annual PM2.5 concentration for each PURE study community. All individuals living in a community were assigned the same PM2.5 concentration.

Statistical analysis

First, we present descriptive statistics of our study population characteristics and outcome measures. For normally distributed continuous variables we present the mean and standard deviation, for skewed continuous data the medium and Interval of Quantile Range (IQR), and for categorical data the frequency and proportion. Second, to assess the associations of household solid heating or cooking fuel with hypertension prevalence or blood pressure, we used generalized linear mixed model, with community as a random intercept variable (to account for the PURE-China study design and clustering of individuals within communities) to calculate adjusted odds ratio (AOR) and 95% confidence intervals (CIs). Fully adjusted models include: age, sex (male/female), location (rural or urban), smoking status (never and ever (former or current)), drinking status (never / ever (current and former)), education level, household wealth index (by tertile), BMI status, waist circumference status, physical activity (low/ middle or high), ambient PM2.5, energy intake and study center (19, 31, 32). We included study center to control for the unmeasured differences between centers, which may also be correlated with solid fuel use for heating and cooking.

Subgroup analyses for the association of household solid heating or cooking fuel and their specific types with hypertension prevalence and blood pressure were performed by selected socio-demographic characteristics, lifestyle factors and ambient PM2.5 levels. Associations with hypertension and blood pressure were also presented by each center using forest plot of meta-analysis approach in STATA (version 14) (33). Sensitivity analysis was also conducted according to participant's secondary choice of household solid fuel use. We used SAS® software, version 9.4 (SAS Institute Inc., Cary, NC, USA) to conduct all statistical tests using a two-sided significant level of 0.05.

Results

Of the 44,007 participants included in this analysis, 18,427 (41.9%) were males and 25,580 were females (58.1%), with a mean age of 51.1 ± 9.6 years. 20,935 participants (47.6%) used solid fuels for heating, 17,521 (39.8%) used clean fuel for heating and 5,551 (12.6%) reported never using heating. A total of 26,946 (61.2%) subjects used solid fuels for cooking and 17,061 (38.8%) adopted clean fuels for cooking. 12977 (33.7%) of individuals used solid fuels for both heating and cooking and 16136 (42.0%) of individuals using clean fuels for both heating and cooking. The annual median concentration of ambient PM2.5 was 45.8 ug/m^3 (IQR: 41.7 ug/m^3).

Table 1 summarizes study participants' characteristics according to the status of household solid fuel uses for heating and cooking. Compared with the clean heating fuel group, participants in the solid fuel group for heating group were younger, more like to be exposed to higher annual concentration of ambient PM2.5, had low education and lower household wealth index category, have a higher proportion of ever smokers, ever alcohol drinkers, and taking hypertensive medicine. Regarding status of cooking solid fuel use, a similar distribution to that of the heating solid fuel was observed except for ambient PM2.5, whose concentration was higher in the clean cooking fuel group. Participants who did not use heating, tended to have slightly higher education attainment and household wealth index than those using solid fuels for heating, but they were exposed to a relatively lower level of ambient PM2.5 than other fuel groups.

Table 1
Baseline individual and household characteristics among 44007 Chinese adults according to status of household solid fuel for heating and cooking

Characteristics	**All participants**	**Clean heating fuel ***	**Solid heating fuel ***	**No heating**	**Clean cooking fuel †**	**Solid cooking fuel†**
No. of participants (%)	44007	17521 (39.8)	20935 (47.6)	5551 (12.6)	17061 (38.8)	26946 (61.2)
Age (mean ± SD) [years]	51.1 (9.6)	52.6 (9.6)	49.9 (9.5)	50.7 (9.4)	51.7 (9.7)	50.1 (9.4)
Ambient $PM_{2.5}$ air pollution (median, IQR)[ug/m^3]	45.8 (41.7)	43.8 (26.7)	59.8 (44.6)	29.8 (24.5)	52.6 (41.5)	45.7 (37.2)
Sex (n, %)						
Male	25580 (58.1)	10547 (60.2)	11881 (56.8)	3152 (56.8)	15821 (58.7)	9759 (57.2)
Female	18427 (41.9)	6974 (39.8)	9054 (43.2)	2399 (43.2)	11125 (41.3)	7302 (42.8)
Location (n, %)						
Urban	21430 (48.7)	15010 (85.7)	4530 (21.6)	1890 (34.1)	20702 (76.8)	728 (4.3)
Rural	22577 (51.3)	2511 (14.3)	16405 (78.4)	3661 (65.9)	6244 (23.2)	16333 (95.7)
Education (n, %)						
None and primary school	14934 (34.0)	3408 (19.5)	9173 (43.8)	2353 (42.4)	6174 (22.9)	8760 (51.4)
Secondary school	22500 (51.1)	9980 (57.0)	9879 (47.2)	2641 (47.6)	14860 (55.2)	7640 (44.8)
Trade/college/university	6443 (14.6)	4073 (23.3)	1834 (8.8)	536 (9.6)	5833 (21.7)	610 (3.6)
Missing	130 (0.3)	60 (0.3)	49 (0.2)	21 (0.4)	79 (0.3)	51 (0.3)

* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop

† Clean household fuels for cooking include electricity, gas and gobar gas; Solid fuels for cooking include charcoal, coal, wood, agriculture, animal dung and shrub

Definition of abbreviations: SD = standard deviation; IQR = Interquartile range

Characteristics	All participants	Clean heating fuel *	Solid heating fuel *	No heating	Clean cooking fuel †	Solid cooking fuel†
Smoking status (n, %)						
Ever	11945 (27.1)	4403 (25.1)	5844 (27.9)	1698 (30.6)	7014 (26.0)	4931 (28.9)
Never	31289 (71.1)	12846 (73.3)	14793 (70.7)	3650 (65.7)	19524 (72.5)	11765 (69.0)
Missing	773 (1.8)	272 (1.6)	298 (1.4)	203 (3.7)	408 (1.5)	365 (2.1)
Alcohol status (n, %)						
Ever	10679 (24.3)	3797 (21.7)	5179 (24.7)	1703 (30.7)	6521 (24.2)	4158 (24.4)
Never	32768 (74.5)	13559 (77.4)	15521 (74.1)	3688 (66.4)	20159 (74.8)	12609 (73.9)
Missing	560 (1.3)	165 (0.9)	235 (1.1)	160 (2.9)	266 (1.0)	294 (1.7)
BMI status (kg/m^3)						
≥ 18.5 and < 24	20823 (47.3)	7766 (44.3)	9921 (47.4)	3136 (56.5)	11744 (43.6)	9079 (53.2)
≥ 24 and < 28	16270 (37.0)	6965 (39.8)	7467 (35.7)	1838 (33.1)	10595 (39.3)	5675 (33.3)
≥ 28	6914 (15.7)	2790 (15.9)	3547 (16.9)	577 (10.4)	4607 (17.1)	2307 (13.5)
Physical activity (n, %)						
Low	7289 (16.6)	2230 (13.3)	3895 (18.6)	1064 (19.2)	4141 (15.4)	3148 (18.5)
Middle and high	36718 (83.4)	15191 (86.7)	17040 (81.4)	4487 (80.8)	22805 (84.6)	13913 (81.5)
Energy intake (n, %)						

* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop

† Clean household fuels for cooking include electricity, gas and gobar gas; Solid fuels for cooking include charcoal, coal, wood, agriculture, animal dung and shrub

Definition of abbreviations: SD = standard deviation; IQR = Interquartile range

Characteristics	All participants	Clean heating fuel *	Solid heating fuel *	No heating	Clean cooking fuel †	Solid cooking fuel†
Low	15693 (35.7)	6880 (39.3)	7391 (35.3)	1422 (25.6)	9818 (36.4)	5875 (34.4)
Middle	14174 (32.2)	5651 (32.3)	6607 (31.6)	1916 (34.5)	8605 (31.9)	5569 (32.6)
High	14140 (32.1)	4990 (28.5)	6937 (33.1)	2213 (39.9)	8523 (31.6)	5617 (32.9)
Taking hypertension medicine (n, %)						
Yes	38119 (86.6)	14601 (83.3)	18565 (88.7)	4953 (89.2)	22757 (84.5)	15362 (90.0)
No	5888 (13.4)	2920 (16.7)	2370 (11.3)	598 (10.8)	4189 (15.6)	1699 (10.0)
Household wealth index (n, %)						
T1 (Lowest)	14713 (33.4)	1558 (8.9)	10843 (51.8)	2312 (41.7)	3916 (14.5)	10797 (63.3)
T2	14782 (33.6)	6442 (36.8)	6263 (29.9)	2077 (37.4)	10117 (37.6)	4665 (27.3)
T3	14511 (33.0)	9521 (54.3)	3829 (18.3)	1161 (20.9)	12913 (47.9)	1598 (9.4)
Missing	1 (0.0)	0 (0.0)	0 (0.0)	1 (0.0)	0 (0)	1 (0.0)
Season of blood pressure measurement (n, %)						
Winter	5334 (12.1)	1957 (11.1)	3035 (14.5)	342 (6.2)	3102 (11.5)	2232 (13.1)
Spring	7052 (16.0)	3491 (19.9)	2729 (13.0)	832 (15.0)	4689 (17.4)	2363 (13.8)
Summer	13326 (30.3)	5931 (33.9)	5319 (25.4)	2076 (37.4)	8198 (30.4)	5128 (30.1)

* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop

† Clean household fuels for cooking include electricity, gas and gobar gas; Solid fuels for cooking include charcoal, coal, wood, agriculture, animal dung and shrub

Definition of abbreviations: SD = standard deviation; IQR = Interquartile range

Characteristics	All participants	Clean heating fuel *	Solid heating fuel *	No heating	Clean cooking fuel †	Solid cooking fuel†
Autumn	18295 (41.6)	6142 (35.1)	9852 (47.1)	2301 (41.5)	10957 (40.7)	7338 (43.0)
* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop						
† Clean household fuels for cooking include electricity, gas and gobar gas; Solid fuels for cooking include charcoal, coal, wood, agriculture, animal dung and shrub						
Definition of abbreviations: SD = standard deviation; IQR = Interquartile range						

Associations between solid fuel use for heating, cooking and both heating/cooking are summarized in Table 2. The majority of participants in the group using solid fuel for heating used coal open fire (42.7%), with a small proportion of them using wood open fire (4.2%) and agriculture crop (0.6%). In the base model (Table S1), positive associations were observed between household heating with solid fuels and its subtypes with hypertension, but the associations were only statistically significant among agriculture/crop solid fuel users. Associations remained almost unchanged in the fully adjusted models for the association between household solid fuels for heating and hypertension prevalence (adjusted odds ratio, AOR = 1.08, 95% CI: 0.98, 1.20), and the association with agriculture crop (AOR = 1.49, 95% CI: 1.07, 2.06) and wood open fire (AOR = 1.15, 95% CI: 0.96, 1.38) was relatively higher than that for coal open fire (AOR = 1.06, 95% CI: 0.95, 1.18). For solid fuel use for cooking we observed no associations with hypertension.

Table 2

Associations of household fuels for heating and cooking with hypertension prevalence and blood pressure*

	No. of participants (%)	Hypertension (AOR, 95%CI)	Systolic blood pressure (mmHg, 95%CI)	Diastolic blood pressure (mmHg, 95%CI)
Fully Adjusted Model†				
Heating‡				
Clean fuels	15540 (38.4)	1.00	0.00	0.00
Solid fuels	19840 (49.0)	1.08 (0.98, 1.20)	0.62 (-0.24, 1.48)	0.24 (-0.32, 0.79)
Coal open fire	17815 (44.0)	1.06 (0.95, 1.18)	0.52 (-0.36, 1.40)	0.18 (-0.38, 0.75)
Wood open fire	1780 (4.4)	1.15 (0.96, 1.38)	1.22 (-0.21, 2.66)	0.62 (-0.30, 1.55)
Agriculture/crop	245 (0.6)	1.49 (1.07, 2.06)	1.41 (-1.18, 4.01)	-0.16 (-1.82, 1.51)
No heating	5134 (12.6)	0.91 (0.81, 1.03)	-0.73 (-1.67, 0.20)	-0.62 (-1.22, -0.02)
Cooking§				
Clean fuels	24104 (59.5)	1.00	0.00	0.00
Solid fuels	16410 (40.5)	0.94 (0.87, 1.03)	-0.06 (-0.74, 0.62)	-0.33 (-0.77, 0.10)
Charcoal	190 (0.5)	1.39 (0.96, 2.01)	1.73 (-1.26, 4.72)	0.25 (-1.68, 2.18)
Coal	8178 (20.2)	0.93 (0.84, 1.02)	-0.32 (-1.11, 0.46)	-0.27 (-0.77, 0.23)
Wood	2176 (5.4)	0.98 (0.81, 1.19)	0.13 (-1.36, 1.63)	-0.74 (-1.71, 0.22)
Agriculture	4448 (11.0)	0.96 (0.85, 1.09)	0.36 (-0.64, 1.36)	-0.45 (-1.10, 0.20)
Animal dung	281 (0.7)	0.93 (0.54, 1.58)	1.74 (-2.43, 5.91)	-0.16 (-2.86, 2.54)
Shrub	1137 (2.8)	0.92 (0.72, 1.16)	-0.19 (-2.13, 1.74)	0.28 (-0.97, 1.53)
Heating and cooking				

	No. of participants (%)	Hypertension (AOR, 95%CI)	Systolic blood pressure (mmHg, 95%CI)	Diastolic blood pressure (mmHg, 95%CI)
Clean Fuels for Cooking & Heating	14236 (40.2)	1.00	0.00	0.00
Solid Fuels for heating only	7283 (20.6)	1.12 (1.00, 1.26)	0.93 (0.00, 1.88)	0.23 (-0.38, 0.84)
Solid Fuels for cooking only	1304 (3.7)	1.02 (0.85, 1.23)	0.17 (-1.24, 1.57)	-0.26 (-1.17, 0.66)
Both Solid Fuels for Cooking & Heating	12557 (35.5)	1.04 (0.91, 1.19)	0.82 (-0.26, 1.90)	-0.13 (-0.83, 0.57)
* Adjusting for age, sex, location (rural or urban), random effect for community, fixed effect for center				
† Adjusting for age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, BMI status, physical activity, energy intake, season, random effect for community, fixed effect for center, outdoor PM2.5 for both cooking and heating. Include primary cooking source or primary heating source as well.				
‡ Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop				
§ Clean household fuels for cooking include electricity, gas and gobar gas; Solid household fuels for cooking include charcoal, coal, wood, agriculture, animal dung and shrub				
Definition of abbreviations: AOR = adjusted odds ratio; CI = confidence interval				

Using solid fuel for household heating was positive but not significantly associated with SBP (elevated BP = 1.41 mmHg, 95% CI=-1.18, 4.01) and its subtypes in the fully adjusted model in Table 2. The associations of solid fuel use with DBP were relatively weak compared to SBP. Results consistently showed that neither hypertension nor SBP or DBP was associated with household solid fuel use for cooking or never using heating, and the detailed results for base model could be seen in Table S1 which is consistent with the fully adjusted model.

Combined effects of using household solid fuel for heating and cooking on hypertension prevalence and blood pressure were inconsistent (Table 2). Compared with those using clean fuels for cooking and heating, a positive association with hypertension and SBP or DBP was observed among participants using solid fuel for heating only, and there was no association with solid cooking fuel use. Surprisingly, individuals who used solid fuels for both cooking and heating did not have additional risk for hypertension or SBP or DBP, compared with those using solid heating fuel only.

Further stratified analyses for the association of solid heating fuels with hypertension or SBP were performed according to the sociodemographic information, lifestyle factors and ambient PM2.5. As shown in Table 3, the magnitude of all associations between heating solid fuel and hypertension were consistently higher among older individuals (AOR = 1.23, 95% CI: 0.97, 1.56), females (AOR = 1.19, 95% CI: 1.02, 1.39), those with secondary education level (AOR = 1.24, 95% CI: 1.07, 1.42), among never smokers (AOR = 1.14, 95% CI: 1.00, 1.30) or among never drinkers (AOR = 1.18, 95% CI: 1.04, 1.35), being obese (AOR = 1.20, 95% CI: 0.95, 1.51), highest household wealth index (AOR = 1.14, 95% CI: 0.94, 1.39), and exposed to lower ambient PM2.5 exposure (AOR = 1.15, 95% CI: 0.96, 1.38). A similar pattern was suggested with the association with SBP. Stratified analyses were also performed for the association with solid fuel for cooking, as shown in Table 4, no association was observed for hypertension prevalence and SBP or DBP for any of the selected variables.

Table 3
Subgroup analyses for the associations between household solid heating fuels and hypertension prevalence and blood pressure level *

Variable	Hypertension† (AOR, 95%CI)	Systolic blood pressure † (mmHg, 95%CI)	Diastolic blood pressure † (mmHg, 95%CI)
Age			
<60y	1.05 (0.93, 1.19)	0.73 (-0.25, 1.72)	0.23 (-0.42, 0.88)
≥60y	1.23 (0.97, 1.56)	1.57 (-0.59, 3.73)	-0.16 (-1.40, 1.08)
Sex			
Female	1.19 (1.02, 1.39)	1.17 (-0.03, 2.36)	0.57 (-0.20, 1.35)
Male	1.03 (0.88, 1.21)	0.80 (-0.49, 2.09)	-0.18 (-1.02, 0.66)
Education			
Primary	0.96 (0.78, 1.19)	-0.21 (-2.07, 1.66)	-0.31 (-1.78, 0.85)
Secondary	1.24 (1.07, 1.42)	1.30 (0.21, 2.38)	0.21 (-0.52, 0.93)
Trade, college/university	0.92 (0.68, 1.25)	1.99 (-0.19, 4.17)	1.10 (-0.36, 2.55)
Cigarette smoking			
Ever	1.01 (0.83, 1.24)	-0.42 (-2.11, 1.26)	-0.96 (-1.99, 0.07)
Never	1.14 (1.00, 1.30)	1.40 (0.37, 2.44)	0.60 (-0.08, 1.29)
Alcohol drinking			
Ever	0.91 (0.73, 1.12)	-0.72 (-2.41, 0.98)	-1.04 (-2.26, 0.17)
Never	1.18 (1.04, 1.35)	1.51 (0.47, 2.54)	0.62 (-0.03, 1.27)
Physical activity			
Middle and High	1.10 (0.87, 1.40)	1.06 (-0.87, 2.99)	-0.01 (-1.19, 1.17)
Low	1.10 (0.97, 1.25)	0.85 (-0.17, 1.86)	0.25 (-0.42, 0.92)

* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop

† Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, season, BMI status, physical activity, energy intake, primary cooking source, season, random effect for community, fixed effect for center, ambient PM2.5

Definition of abbreviations: AOR = adjusted odds ratio; CI = confidence interval; NA = not available

Variable	Hypertension† (AOR, 95%CI)	Systolic blood pressure † (mmHg, 95%CI)	Diastolic blood pressure † (mmHg, 95%CI)
Body mass index			
<24	1.08 (0.91, 1.29)	0.98 (-0.34, 2.29)	0.47 (-0.37, 1.32)
≥ 24 and < 28	1.09 (0.93, 1.29)	1.23 (-0.15, 2.61)	0.04 (-0.88, 0.97)
≥ 28	1.20 (0.95, 1.51)	1.35 (-0.64, 3.34)	0.39 (-0.92, 1.69)
Household wealth index			
T1	1.04 (0.80, 1.36)	0.90 (-1.31, 3.11)	0.19 (-1.35, 1.74)
T2	1.08 (0.92, 1.27)	0.53 (-0.75, 1.80)	0.00 (-0.75, 0.75)
T3	1.14 (0.94, 1.39)	1.65 (0.17, 3.14)	0.31 (-0.64, 1.26)
Season			
Spring	NA	0.85 (-1.74, 3.45)	0.28 (-1.34, 1.90)
Summer	1.17 (0.95, 1.44)	0.21 (-1.30, 1.72)	0.41 (-0.50, 1.32)
Autumn	1.16 (0.92, 1.46)	2.03 (0.10, 3.96)	0.76 (-0.47, 1.99)
Winter	1.00 (0.90, 1.25)	0.12 (-1.65, 1.89)	-0.48 (-1.83, 0.86)
Ambient PM2.5			
<45.8	1.15 (0.96, 1.38)	1.68 (0.28, 3.08)	0.41 (-0.50, 1.31)
≥45.8	1.09 (0.95, 1.25)	0.56 (-0.53, 1.65)	0.16 (-0.56, 0.87)
Location			
Urban	1.12 (0.97, 1.30)	1.36 (0.24, 2.48)	0.31 (-0.39, 1.01)
Rural	1.13 (0.92, 1.39)	0.04 (-1.60, 1.68)	0.12 (-0.96, 1.21)
Geographic location			

* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop

† Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, season, BMI status, physical activity, energy intake, primary cooking source, season, random effect for community, fixed effect for center, ambient PM2.5

Definition of abbreviations: AOR = adjusted odds ratio; CI = confidence interval; NA = not available

Variable	Hypertension† (AOR, 95%CI)	Systolic blood pressure † (mmHg, 95%CI)	Diastolic blood pressure † (mmHg, 95%CI)
North	1.12 (0.99, 1.25)	1.07 (0.14, 2.01)	0.35 (-0.27, 0.96)
South	0.87 (0.65, 1.16)	-1.63 (-3.89, 0.63)	-0.02 (-1.39, 1.34)

* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop

† Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, season, BMI status, physical activity, energy intake, primary cooking source, season, random effect for community, fixed effect for center, ambient PM2.5

Definition of abbreviations: AOR = adjusted odds ratio; CI = confidence interval; NA = not available

Table 4
Subgroup analyses for the associations between household solid cooking fuels and hypertension prevalence and blood pressure level*

Variable	**Hypertension† (AOR, 95%CI)**	**Systolic blood pressure †** **(mmHg, 95%CI)**	**Diastolic blood pressure †** **(mmHg, 95%CI)**
Age			
<60y	0.96 (0.88, 1.06)	0.29 (-0.45, 1.03)	-0.25 (-0.73, 0.24)
≥60y	1.01 (0.82, 1.24)	-0.07 (-1.87, 1.73)	-0.21 (-1.22, 0.81)
Sex			
Female	0.96 (0.85, 1.08)	0.13 (-0.77, 1.04)	-0.16 (-0.75, 0.43)
Male	0.93 (0.82, 1.05)	-0.30 (-1.31, 0.70)	-0.57 (-1.21, 0.08)
Education			
Primary	0.99 (0.87, 1.13)	0.06 (-1.08, 1.20)	-0.42 (-1.12, 0.28)
Secondary	0.97 (0.86, 1.09)	0.17 (-0.74, 1.08)	-0.07 (-0.68, 0.53)
Trade, college/university	0.57 (0.39, 0.84)	-2.43 (-4.97, 0.10)	-1.42 (-3.09, 0.26)
Cigarette smoking			
Ever	0.95 (0.81, 1.11)	0.23 (-1.04, 1.49)	-0.56 (-1.32, 0.20)
Never	0.94 (0.85, 1.04)	-0.08 (-0.88, 0.72)	-0.19 (-0.72, 0.34)
Alcohol drinking			
Ever	0.96 (0.82, 1.13)	0.17 (-1.10, 1.45)	-0.36 (-1.26, 0.55)
Never	0.94 (0.85, 1.04)	-0.13 (-0.93, 0.66)	-0.34 (-0.83, 0.16)
Physical activity			
Middle and High	0.86 (0.71, 1.04)	-0.67 (-2.24, 0.90)	-0.27 (-1.20, 0.66)
Low	0.97 (0.88, 1.06)	0.09 (-0.67, 0.84)	-0.32 (-0.81, 0.17)
Body mass index			
<24	0.91 (0.80, 1.04)	-0.23 (-1.21, 0.76)	-0.09 (-0.71, 0.54)
≥ 24 and < 28	1.01 (0.88, 1.16)	0.66 (-0.46, 1.77)	-0.20 (-0.94, 0.54)
≥ 28	0.88 (0.73, 1.08)	-1.11 (-2.76, 0.54)	-1.24 (-2.28, -0.19)

Variable	Hypertension† (AOR, 95%CI)	Systolic blood pressure † (mmHg, 95%CI)	Diastolic blood pressure † (mmHg, 95%CI)
Household wealth index			
T1	0.97 (0.85, 1.11)	0.18 (-0.91, 1.27)	-0.31 (-1.07, 0.44)
T2	0.91 (0.79, 1.05)	-0.33 (-1.45, 0.78)	-0.49 (-1.14, 0.16)
T3	0.90 (0.74, 1.10)	-0.38 (-1.87, 1.11)	-0.49 (-1.45, 0.47)
Season			
Spring	NA	0.45 (-1.73, 2.63)	-0.97 (-2.33, 0.38)
Summer	1.02 (0.87, 1.19)	0.03 (-1.09, 1.15)	-0.46 (-1.13, 0.22)
Autumn	0.85 (0.75, 0.96)	-0.50 (-1.49, 0.49)	-0.32 (-0.96, 0.31)
Winter	0.91 (0.65, 1.27)	-0.32 (-2.99, 2.35)	0.80 (-1.22, 2.83)
Ambient PM2.5			
<45.8	0.96 (0.85, 1.09)	-0.52 (-1.49, 0.46)	-0.32 (-0.94, 0.30)
≥45.8	0.93 (0.83, 1.05)	0.44 (-0.49, 1.37)	-0.34 (-0.95, 0.27)
Location			
Urban	0.80 (0.64, 1.01)	-0.63 (-2.35, 1.09)	-1.00 (-2.07, 0.07)
Rural	0.96 (0.88, 1.06)	-0.03 (-0.79, 0.73)	-0.28 (-0.78, 0.22)
Geographic location			
North	0.90 (0.80, 1.01)	-0.06 (-0.90, 0.69)	-0.33 (-0.81, 0.15)
South	1.09 (0.86, 1.38)	-0.17 (-1.88, 1.53)	-0.37 (-1.37, 0.63)

* Clean household fuels for heating include electricity, gas and central heating; Solid fuels for heating includes coal open fire, wood open fire and agriculture/crop

† Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, season, BMI status, physical activity, energy intake, primary cooking source, season, random effect for community, fixed effect for center, ambient PM2.5

Definition of abbreviations: AOR = adjusted odds ratio; CI = confidence interval; NA = not available

* Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, BMI status, physical activity, energy intake, outdoor PM2.5.

Variable	Hypertension† (AOR, 95%CI)	Systolic blood pressure † (mmHg, 95%CI)	Diastolic blood pressure † (mmHg, 95%CI)
Definition of abbreviations: AOR = adjusted odds ratio; CI = confidence interval			
* Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, BMI status, physical activity, energy intake, outdoor PM2.5.			
Definition of abbreviations: AOR = adjusted odds ratio; CI = confidence interval			

Associations between heating solid fuels and hypertension prevalence or blood pressure were further explored using meta-analysis according to the geographic location (i.e., center). As shown in Fig. 1, the associations between heating solid fuels and hypertension prevalence was positive for all centers except for Qinghai and Inner-Mongolia, with a combined AOR of 1.07 (95% CI: 0.94, 1.20); however, the association between solid cooking fuels and BP among centers was inconsistent with a combined AOR of 0.98 (95% CI: 0.89, 1.06) (Fig. 2).

We conducted sensitivity analyses by removing the fixed effect for study center, as well as the random intercept for community, as these geographical variables may over-adjust model results since cooking and heating are distributed regionally in China. These models showed a similar pattern to our main models, but almost all associations with solid heating fuels were elevated with hypertension prevalence (AOR = 1.23, 95% CI: 1.13, 1.33 vs. AOR = 1.12, 95% CI: 1.01, 1.25) or SBP or DBP (Table S2, table S3). Consistently, no associations were observed for the association with solid cooking fuel use, and compared with the clean fuels for cooking and heating, combined use of solid heating fuel and solid cooking fuel did not introduce additional risk for hypertension or SBP or DBP.

Discussion

This is the first population-based multi-center study to investigate the separate and combined associations of household solid fuel use for heating and cooking with hypertension and blood pressure, after controlling for ambient PM2.5 air pollution and comprehensive individual and household factors. Association between solid fuel and hypertension for cooking fuel was neutral, and that for heating fuel was statistically insignificant increase. The combined exposure to solid fuel use for both heating and cooking was not associated with additional risk to hypertension and elevated blood pressure.

Our finding of no consistent association between cooking and heating with solid fuels and hypertension and blood pressure is different from previous studies conducted in China that identified a potential increased risk with solid fuel use (8, 15, 16, 19, 34). For example, one of them involved only 209 adults in China and reported a significantly increased SBP of 3.80% per IQR evaluation of indoor and outdoor PM2.5 level with a 2 days’ lag; however, this small Chinese study did not examine the potential long-term effect on blood pressure and the association with specific household heating source was not addressed

(8). Another hospital-based study analyzed 14,068 participants in Shanghai and found that using household solid fuel (cooking or heating) was positively associated with hypertension prevalence (OR = 1.70, 95% CI: 1.40–2.07), but the analysis did not control ambient PM2.5 (15). No separate effect of solid heating fuel and cooking fuel was reported in the Shanghai's study. In our study, we were able to separate the association of hypertension and blood pressure with heating solid fuel from that with solid cooking fuel, and specially demonstrated the pooled effect of combined exposure to both heating and cooking fuel that had never been reported in the previous studies.

We also observed an increased association with agriculture/crop type of solid fuel for heating This was more prominent for agriculture crop fuel use (hypertension adjusted OR = 1.49, 95%CI: 1.07, 2.06), which was the only fuel type showing a small and significant association with hypertension. The combustion of agriculture crop is ranked as one of the lowest energy ladder fuels, which emits more health-damaging pollutants than coal and wood (35). Similar to the overall study of solid fuel use for cooking in the overall PURE study (9), no association was observed in our study with large and diverse Chinese population.

The model of removing outdoor PM2.5 variable in an additional sensitivity analysis (Table S4) is consistent with the fully adjusted results for both heating and cooking in Table 2. Further research could examine fuel switching within PURE-China to examine how hypertension and BP changes once repeated measurement of BP and household fuel use data becomes available.

Excluding center from models increased the OR for hypertension to 1.23 (95% CI: 1.13, 1.33) for individuals heating with solid fuels compared to the clean fuels (Table S2) which is similar to the finding of other studies conducted in China(15, 16); however, these results may not reflect all of the random intercept caused by center. Including center in our models controls for regional differences and restricted our comparisons to individuals living with the same regions of China. About 63.7% of our participants living in north used solid fuel as their primary heating fuel (Table S5), compared to 6.8% in the south. However, a similar pattern of solid cooking fuel use was found between the north and south area (Table S6), which explains why the associations with solid cooking fuel remained stable regardless of the inclusion of center in the model. This makes isolating the true impact of solid fuel use for heating from other contextual factors difficult.

The strength of our study includes a standardized study design implemented in 12 regions in China capturing diverse populations and household cooking environments. We were also able to examine a large sample size from both the urban and rural communities, control for ambient PM2.5 concentration, and used robust modelling methods to control for potential unmeasured contextual factors. However, there are a few major limitations of this study. Firstly, we had information only on primary heating fuels, and no information was available on fuel stacking. We also do not have any information about previous use of heating fuels and how long individuals used different fuels throughout their lifetime. As shown in Table S5, a majority of people (59.3%) in the northern regions of China used coal as their primary heating source and 87.8% of them lived in a rural community. Another study reported that the percentage of household coal use was nearly 40% in Chinese rural area in 1990 and it was unchanged until 2007 (36), which is in line with our survey results from 2005–2009 (36). This indicates that most of the individuals living in northern communities kept their primary heating source stable during the 1980s to 2000s. In the southern part of China, most of our participants used clean fuels for heating (49.0%) or no heating (44.2%), and this is expected given the temperatures in the southern part of China (37). Another limitation is that we only estimated the annual concentration of PM2.5 for study communities and did not have information on short-term exposures at the time of BP measurements. We also did not have information of the chemical components of PM2.5 of information for other air pollutants. Cao et al collected nationwide PM2.5 sample in 14 cities of China and showed that the main component of PM2.5 varied substantially (38). It is likely that the composition of PM2.5 varied between our study communities and future research is needed to include this information in health analyses. This limitation is suggested to be addressed in future follow-up study which was called as PURE-AIR. Finally, we used the primary fuel type as an indicator of household and personal PM2.5 exposures, while adopting standard practice, it may incorporate substantial measurement error. In order to address this issue, we have already chosen several communities to collect indoor and outdoor air pollution samples to refine exposure estimates.

In conclusion, our study observed a non-significant association between the use of solid fuel for cooking or heating with BP or prevalence of hypertension in this large and diverse Chinese population. A small effect of household heating fuel use with hypertension and elevated blood pressure cannot be excluded but needs to be explored in future larger scale studies. Further research is needed using repeated BP measures as well as PM2.5 measures that address how heating versus cooking influences personal PM2.5 exposures.

Declarations

Availability of data and material

The datasets generated during and/or analysed during the current study are not publicly available due to the follow-up period of this study has not been ended.

Ethics approval and consent to participate

Ethics approval was obtained from local ethical committee of each study site before the fieldwork was commenced.

Consent for publication

Not applicable

Competing interests

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

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Authors’ contributions

Zhiguang Liu, Perry Hystad, Salim Yusuf, Wei Li and Lap Ah Tse designed research; Perry Hystad, Lu Yin, Shrikant I Bangdiwala, Salim Yusuf, Wei Li and Lap Ah Tse conducted review and editing; Salim Yusuf and Wei Li provided funding acquisition; Zhiguang Liu and Lap Ah Tse wrote the paper and Sumathy Rangarajan, Fanghong Lu, Bo Hu, Yihong Zhou, Yindong Li and Yang Wang response for data collection.

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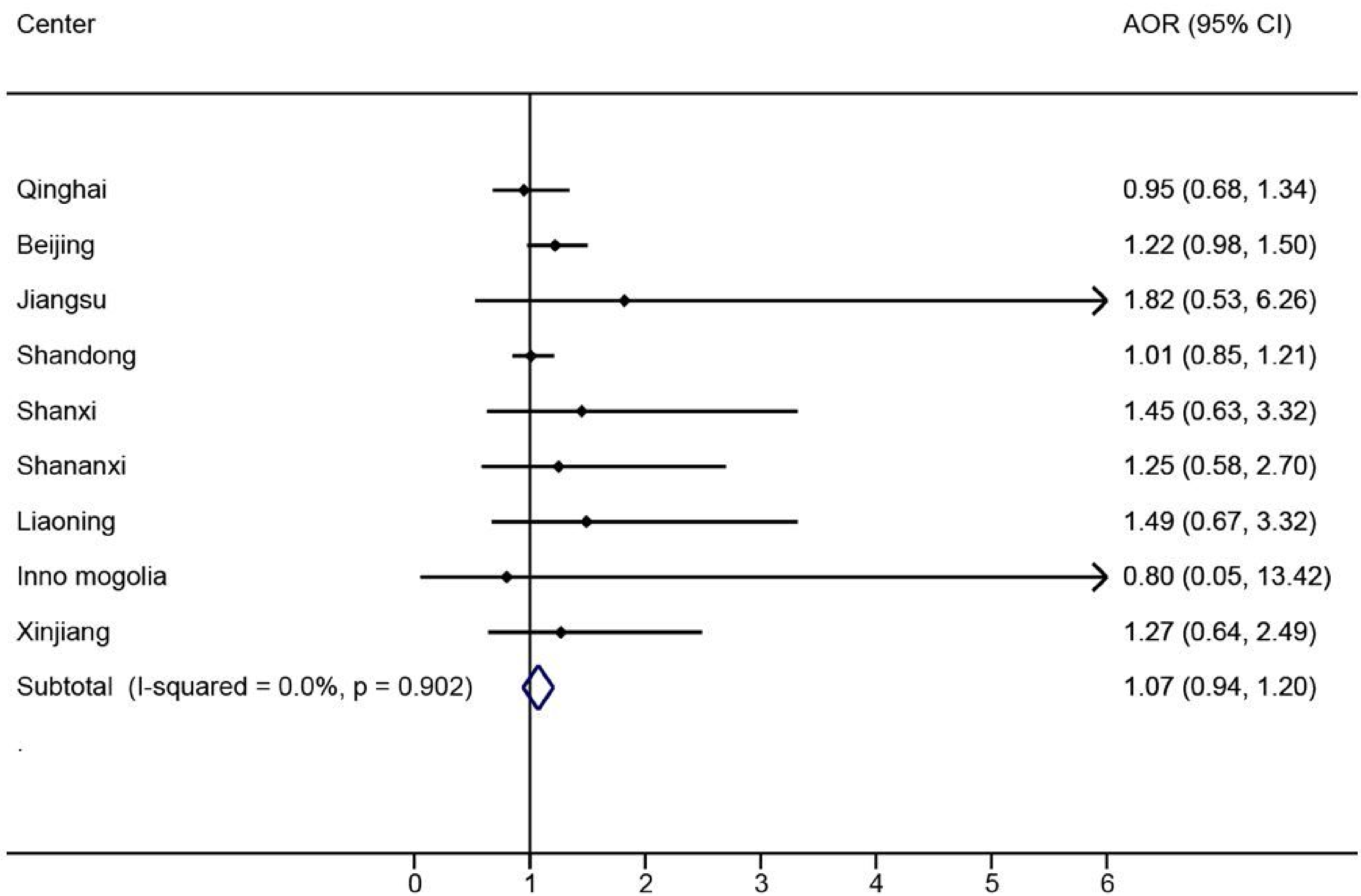
Figures

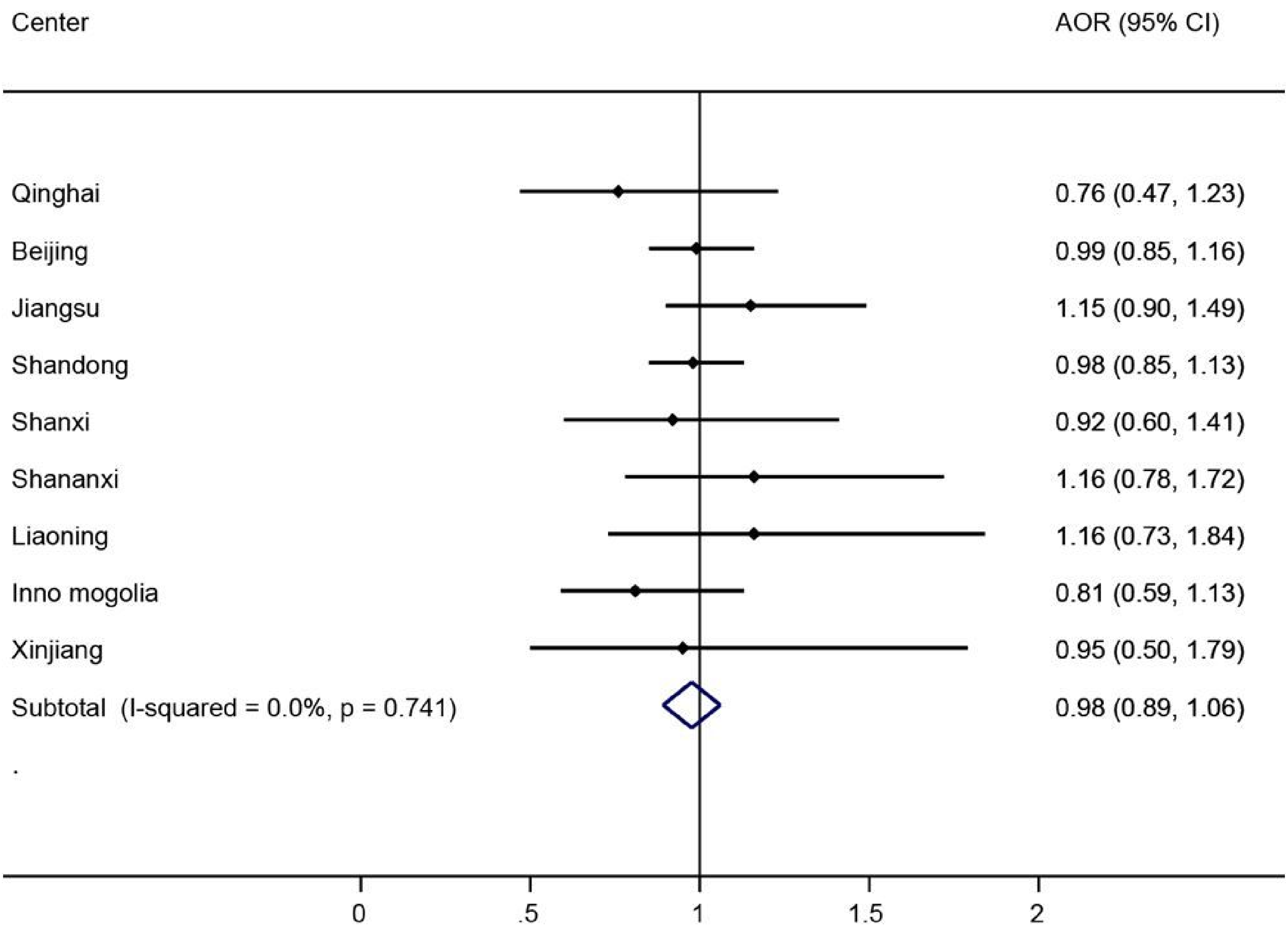


* Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, BMI status, physical activity, energy intake, outdoor PM2.5.

Definition of abbreviations: AOR= adjusted odds ratio; CI=confidence interval

Figure 1

Center specific adjusted odds ratio (AOR) and 95% confidence intervals for the association between hypertension prevalnce and solid and clean fuels for heating.



* Adjusted variables include age, sex, location (rural or urban), smoking status (never/current/former), drinking status (never/current/former), education level, occupational class, household wealth index, BMI status, physical activity, energy intake, outdoor PM2.5.

Definition of abbreviations: AOR= adjusted odds ratio; CI=confidence interval

Figure 2

Center specific adjusted odds ratio (AOR) and 95% confidence intervals for the association between hypertension prevalnce and solid and clean fuels for cooking.

Supplementary Files

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