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Modifiable factors of 20-year blood pressure trajectories among normotensives and their associations with hypertension : a prospective study

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Abstract

Little is known about the impact of modifiable risk factors on blood pressure (BP) trajectories and their associations with hypertension (HTN). We aimed to identify BP trajectories in normotensive Chinese adults and explore their influencing factors and associations with HTN. We used data from 3436 adults with at least four BP measurements between 1989 and 2018 in the China Health and Nutrition Survey, an ongoing cohort study. We measured BP using mercury sphygmomanometers with appropriate cuff sizes in all surveys. We used group-based trajectory modelling to identify BP trajectories between 1989 and 2009 and multiple logistic and Cox regression models to analyse their influencing factors and associations with HTN in 2011–2018. We identified five systolic blood pressure (SBP) trajectories, 'Low-increasing (LI)', 'Low–stable (LS)', 'Moderate-increasing (MI)', 'High-stable (HS)' and 'Moderate-decreasing (MD)', and four diastolic blood pressure (DBP) trajectories classified as 'Low-increasing (LI)', 'Moderate–stable (MS)', 'Low-stable (LS)' and 'High-increasing (HI)'. People with higher physical activity (PA) levels and lower waist circumferences (WC) were less likely to be in the SBP LI, MI, HS and MD groups ($P < 0{\cdot}05$). People with higher fruit and vegetable intakes, lower WCs and salt intakes and higher PA levels were less likely to be in the DBP LI, MS and HI groups ($P < 0{\cdot}05$). Participants in the SBP HS group (hazard ratio (HR) 2·01) or the DBP LI, MS and HI groups (HR 1·38, 1·40, 1·71, respectively) had higher risks of HTN ($P < 0{\cdot}05$). This study suggests that BP monitoring is necessary to prevent HTN in the Chinese population.

Key words: **Blood pressure pattern: Trajectory: Risk factors: Hypertension: Prospective study**

High blood pressure (BP) can increase the risks of heart disease, stroke and other illnesses[1,2]. It is the leading risk factor for death and disability worldwide[3], as globally more than one in four men and one in five women had the condition in 2015[4] The prevalence of hypertension (HTN) in China is high and increasing. Recent national surveys indicate that 23·2 % of the Chinese adult population (24·5 % of men and 21·9 % of women), or 244·5 million adults, had HTN in 2015, which represents a significant increase from previous surveys[5]. HTN and associated CVD and mortality are major public health challenges in China. Preventing BP increases would reduce the vascular consequences and would eliminate a large proportion of the BP-related CVD burden in the population[6].

Several longitudinal studies indicate that BP patterns over time (i.e., BP trajectories) are associated with increased risk of CVD[7,8]. However, data on the varied BP trajectories of normotensives and their effects on HTN risks are sparse. In one study, stable high and high increasing BP trajectories in ages 10–16 were associated with higher HTN risk at age 46[9]. A study of pregnant women showed that those with an upward systolic blood pressure (SBP) trajectory had a 41 % higher risk of gestational HTN[10]. However, both of those studies used only two BP measurements to determine BP trajectories, whereas three or more measurements can track HTN formation better. What is more, no association between BP trajectories and HTN has yet been reported in Asian populations.

We hypothesised that repeated BP measurements would allow identification of BP trajectories that can reliably predict future HTN. In addition, related diet and behavioural factors affect BP and can sustain an appropriate trajectory to reduce the risk of HTN, thus reducing the BP-related CVD burden. We therefore used 29 years of China Health and Nutrition

Abbreviations: BP, blood pressure; CHNS, China Health and Nutrition Survey; DBP, diastolic blood pressure; HTN, hypertension; PA, physical activity; SBP, systolic blood pressure; WC, waist circumference.

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Survey (CHNS) longitudinal prospective cohort data with up to eleven visits per participant to determine the associations between the BP trajectories of normotensives and the risks of HTN and related modifiable influencing factors.

Methods

Study design and participants

The CHNS is an ongoing longitudinal survey designed to investigate health and nutritional status in Chinese populations. Its study design and procedures have been described previously[11]. The CHNS completed rounds in 1989, 1991, 1993, 1997, 2000, 2004, 2006, 2009, 2011, 2015 and 2018. In the current analyses, we used all rounds of CHNS survey data. Our sample included adults who were over 18 years old in eight surveys between 1989 and 2009. We further analysed the relationship between the BP trajectories of this population and the subsequent HTN risks from 2009 to 2018. By the end of 2009, the CHNS had 27 441 participants. We excluded 7525 participants whose BP measurements met the diagnostic criteria for HTN, who reported having HTN, or who were taking antihypertensive drugs in or prior to 2009; 8448 participants who were younger than 18 years in the first survey; 197 participants without BP information; 5956 people who participated in only one or two surveys and 1879 participants without a follow-up visit after 2009 (Fig. 1). The number of visits between 1989 and 2009 that included BP measurements ranged from three to eight per participant: three visits, *n* 691; four visits, *n* 645; five visits, *n* 618; six visits, *n* 397; seven visits, *n* 607 and eight visits, *n* 478 (median, five visits). Our study included 3436 participants and 18 198 observations. The Institutional Review Board of the University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, USA (No. 07-1963), and the Institutional Review Committee of the China National Institute of Nutrition and Food Safety at the Chinese Center for Disease Control and Prevention, Beijing, China, approved the survey protocols and instruments and the process for obtaining informed consent. All participants provided written informed consent prior to the surveys.

Blood pressure assessment

Following standard protocol, trained surveyors measured BP in a quiet room on the right arm using mercury sphygmomanometers with appropriate cuff sizes. They collected three measurements at 5-min intervals after the participant rested seated with feet on the floor and arm supported at heart level for 10 min. Participants were told to avoid strenuous activities, caffeinated beverages, long-term exposure to excessively high or low temperatures and medications that affect BP for 1 h before the measurement. Also they were instructed to stop smoking, empty their bladders and maintain mental relaxation for 15 min before the measurement. Before each measurement, the investigator checked and calibrated the sphygmomanometer. If the investigator found a large difference in a participant's measurements (a difference >5 mm of mercury (mmHg) between any two measurements), the investigator asked the respondent to rest quietly for 5 min and then measured again until achieving

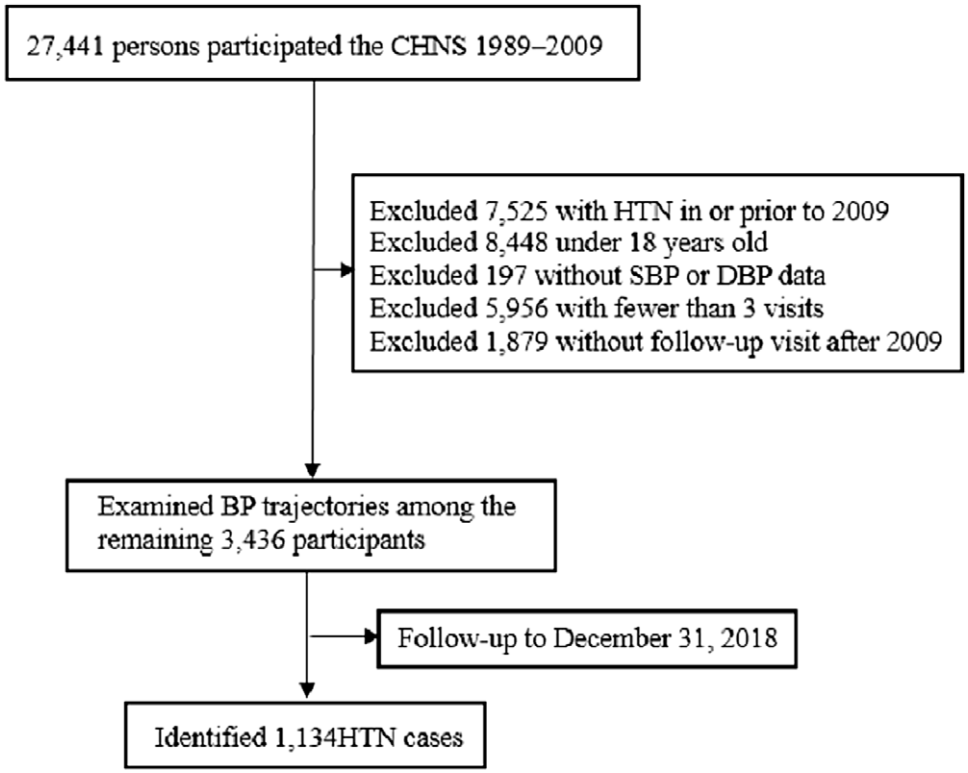

Fig. 1. Flow chart of the participants included in the current analysis.

three stable measurements. We used the mean of the three stable measurements in our analyses. SBP is the point at which the trained investigator hears the first of two or more Korotkoff sounds. The disappearance of Korotkoff sounds defines diastolic blood pressure (DBP)[12]. We defined adult HTN according to the 2018 Chinese guidelines cut point for the management of HTN (SBP/DBP ≥ 140/90 mmHg), taking BP medication, or a self-reported history of HTN[13].

Modifiable factors

Trained personnel conducted detailed in-person interviews using a structured questionnaire to collect information on demographic characteristics, dietary habits, lifestyle and physical condition. We used a combination of three consecutive 24-h dietary recalls (one weekend day and two weekdays) and a household inventory to assess individual consumption. We defined current smoking as a positive answer to the question, 'Do you still smoke cigarettes or a pipe?' We defined alcohol consumption as the participant drank beer or other alcohol last year. We defined physical activity (PA) as the combination of occupational, recreational, commuter and home activities, excluding 1989 because that survey collected home and occupational activities only. We determined the metabolic values of various activities according to the Compendium of PA[14]. The PA questionnaire asked the respondents about the intensity, frequency and duration of each activity. We applied the equation PA = PA intensity (metabolic equivalent of task (MET)) × PA time (hours per week). Each survey measured height without shoes to the nearest 0·1 cm using a portable SECA stadiometer (SECA). Each survey measured weight without shoes and wearing light clothing to the nearest 0·1 kg using a calibrated beam scale. We calculated BMI as weight in kg/m2. We measured waist circumference (WC) in cm midway between the lowest rib margin and the top of the iliac crest.

Biochemical analyses in 2009

The CHNS collected blood samples for the first time in 2009; therefore, this analysis uses the diabetes-related biomarkers and lipid-related indexes measured in 2009 as covariates in the relationship between BP trajectories and HTN risk. The 2009 survey collected a 12 ml blood sample after overnight fasting. We analysed all samples in a national central laboratory in Beijing (medical laboratory accreditation certificate ISO 15189:2007) under strict quality control. We measured glucose in the serum with a glucose oxidase phenol 4-amnioantipyrine peroxidase kit (Randox) in a Hitachi 7600 automated analyser (Hitachi Inc.). We measured glycated haemoglobin in whole blood by HPLC with an automated glycohaemoglobin analyser (model HLC-723G7, Tosoh)[15]. We identified type 2 diabetes in self-reports of a history of a diabetes diagnosis, fasting blood glucose ≥ 7·0 mmol/l, glycated haemoglobin ≥ 40·0 mmol/mole (6·5 %) and/or receiving treatment for diabetes. We measured total cholesterol, TAG and LDL-cholesterol using the glycerol-phosphate oxidase method and the polyethylene glycol-modified enzyme method, respectively, by determiner regents (Kyowa Medex Co. Ltd.). We measured all lipids on a Hitachi 7600 automated analyzer[16,17].

Statistical analyses

We performed all statistical analyses using SAS 9.4 (SAS Institute Inc.). We considered a two-sided P value < 0·05 as statistically significant. We used group-based trajectory modelling to identify distinctive groups of individual BP trajectories adjusted by sex. With Proc Traj, a statistical analysis software macro, we estimated the model parameters[18] using a censored normal model appropriate for continuous normally distributed data[19]. We used age as a timescale for the trajectories. We considered linear, quadratic and cubic terms of age and evaluated them based on their significance levels. We grouped participants into five classes of SBP trajectories and four classes of DBP trajectories and modelled these groups' changes in BP with a variety of different order polynomials. We used statistically rigorous criteria to determine best fit. (1) With the lowest Bayesian information criterion, we used the magnitude of difference in Bayesian information criterion (percentage change) to choose between more complex (with one additional specified trajectory group) and simpler models; (2) we included at least 2·0 % of the sample population in each trajectory class and (3) we ascertained within each group values of average posterior probability of membership in which values >0·7 indicate adequate internal reliability[20]. Once we determined BP trajectories, we created a nominal categorical variable to describe the trajectory class of each participant then used that in multiple logistic regression and Cox multivariate regression models.

We used multiple logistic regression models to analyse the modifiable influencing factors of the BP trajectories. We analysed population baseline characteristics in the whole model as influencing factors, including inherently invariable factors (age, gender, urban or rural status, north or south region, education and job) and modifiable behavioural factors (alcohol consumption; cigarette smoking; tea drinking; PA; fruit, vegetable and salt consumption; BMI and WC).

We used Cox multivariate regression models with age as the timescale to estimate associations between BP trajectories and risk of HTN. We calculated hazard ratios and 95 % CI. Entry time was the participant's age in 2009, and exit time was the age at which the participant was diagnosed with HTN (the age was determined by the survey questions, 'Have you ever been diagnosed with high blood pressure?' and 'How long have you had high blood pressure?') was lost to follow-up or was censored at the end of the follow-up period, whichever came first. We adjusted models for age, gender, urban or rural status, north or south region, BP levels at the last survey (2009), alcohol consumption, cigarette smoking, PA, salt consumption, BMI, WC, total cholesterol, TAG, LDL-cholesterol and diabetes status in 2009. In the sensitivity analysis, we excluded 252 measurements with obesity (BMI ≥ 28 kg/m2).

Results

Participant characteristics

Figure 1 shows the samples included and the design of this prospective study. We included 3436 subjects who had been surveyed three or more times between 1989 and 2009. We followed these subjects to the end of 2018 and 1134 of them developed HTN. Table 1 presents the characteristics of our study population

Table 1. Characteristics of the study population by China Health and Nutrition Survey (CHNS) year*
(Numbers and percentages; mean values and standard deviations; median values and interquartile range)

Variables	Survey year															
	1989 (*n* 1953)		1991 (*n* 1966)		1993 (*n* 1983)		1997 (*n* 2396)		2000 (*n* 2759)		2004 (*n* 2883)		2006 (*n* 2944)		2009 (*n* 2979)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age, years	32·4	9·6	34·1	9·6	35·9	9·7	38·5	10·2	40·8	10·2	44·5	10·8	46·5	10·7	49·3	10·7
Male	954	48·9	941	47·9	936	47·2	1063	44·4	1206	43·7	1196	41·5	1204	40·9	1236	41·5
Urban	430	22·0	426	21·7	426	21·5	628	26·2	749	27·1	841	29·2	850	28·9	863	29·0
North	540	27·6	544	27·7	540	27·2	687	28·7	946	34·3	1104	38·3	1121	38·1	1124	37·7
Education high school or above	854	43·7	918	46·7	951	48·0	1178	49·2	1528	55·4	1655	57·4	1719	58·4	1719	57·7
Currently working	1878	96·2	1854	94·3	1819	91·7	2144	89·5	2342	84·9	2058	71·4	2087	70·9	2041	68·5
Smoker			556	31·6	565	31·7	748	31·2	674	27·5	880	30·5	871	29·5	888	29·7
Alcohol drinker			617	35·1	581	32·6	838	35·0	756	30·8	880	30·5	879	29·8	937	31·4
Fruit consumer	150	7·7	144	7·3	133	6·7	232	9·7	315	11·4	497	17·2	668	22·7	974	32·7
Vegetable consumption, g																
Median	365·0		333·3		366·7		316·7		325·9		333·3		333·3		316·6	
IQR	233·3–541·7		216·7–466·7		250·0–500·0		216·7–433·3		225·0–450·0		226·7–473·7		229·2–466·7		216·7–425·0	
Tea drinker					755	41·4	1122	46·2	973	38·4	1043	35·9	975	33·1	1036	34·7
Salt consumption, g																
Mean	17·3		18·3		16·4		18·0		17·3		15·8		13·3		12·9	
SD	14·5		10·1		10·5		13·3		13·6		9·5		9·2		11·2	
PA, MET/week																
Median			540·4		436·2		412·0		310·0		201·7		199·3		184·6	
IQR			312·4–707·0		272·5–598·4		217·4–567·2		166·5–474·1		89·7–382·2		85·7–375·5		86·9–344·9	
BMI, kg/m^2																
Mean	21·1		21·0		21·2		21·6		22·1		22·4		22·6		22·8	
SD	2·1		2·2		2·2		2·5		2·7		2·8		3·5		3·1	
WC, cm																
Mean					73·1		74·9		76·5		78·3		79·0		80·5	
SD					7·1		7·7		8·3		8·6		8·9		9·2	
SBP, mmHg																
Mean	114·9		112·4		111·3		110·5		110·0		109·3		109·1		109·1	
SD	11·1		11·2		11·4		10·9		10·9		11·3		11·2		11·2	
DBP, mmHg																
Mean	74·6		73·2		72·3		72·7		72·3		71·7		71·3		71·3	
SD	7·6		7·7		8·2		7·9		8·0		8·2		8·4		8·3	

DBP, diastolic blood pressure; PA, physical activity; SBP, systolic blood pressure; WC, waist circumference.
* Values of age, salt consumption, BMI, WC, SBP and DBP are means (standard deviation); values of vegetable consumption and PA are median (interquartile range: Q1–Q3).

by CHNS survey year. BMI and WC showed increasing trends across survey years, whereas PA showed decreasing trends. Fruit consumption increased over the years, and salt intake decreased somewhat but still far exceeded the 6 g/d the Dietary Guidelines for Chinese Residents recommend.

BP trajectories

Figure 2 shows the SBP and DBP trajectories over a 20-year period. We identified five SBP trajectory groups. Group 1, SBP low increasing (LI), includes 601 (17·5 %) participants who started with a low SBP level that increased relatively rapidly. Group 2, SBP low stable (LS), includes 165 (4·8 %) participants with stable low SBP levels throughout adulthood. Group 3, SBP moderate increasing (MI), includes 1048 (30·5 %) participants whose SBP levels increased from moderate to pre-HTN throughout adulthood. Group 4, SBP high stable (HS), includes 1017 (29·6 %) participants who had stable high SBP levels throughout adulthood. Group 5, SBP moderate decreasing (MD), includes 605 (17·6 %) participants who started with moderate SBP levels that slightly declined with age. We identified four DBP trajectory groups. Group 1, DBP low increasing (LI), includes 852 (24·8 %) participants who started with low DBP levels that rapidly increased. Group 2, DBP moderate stable (MS), includes 777 (22·6 %) participants with stable moderate DBP levels throughout adulthood. Group 3, DBP low stable (LS), includes 433 (12·6 %) participants with stable low DBP levels throughout adulthood. Group 4, DBP high increasing (HI), includes 1374 (40·0 %) participants who started with high DBP levels that increased.

Baseline characteristics by blood pressure trajectories

Table 2 presents the baseline characteristics by the different SBP and DBP trajectories. Individuals with the SBP HS trajectory and the DBP HI trajectory were more likely to be men, reside in urban areas and in the north region, have lower PAs, have high school or higher educations, smoke cigarettes, consume alcohol and have higher BMI and waist circumferences.

Modifiable factors by blood pressure trajectories

We examined both inherently invariable factors and modifiable behavioural factors in relation to SBP and DBP trajectories (Tables 3 and 4). In the fully adjusted model (including all covariates), study members whose PAs were in quartile 4 (Q4) (the PA values greater than the upper quartile are classified as Q4) had lower odds of being in the SBP MI (OR = 0·45, 95 % CI 0·21, 0·98) or the SBP HS (OR = 0·44, 95 % CI 0·19, 0·98) trajectory groups compared with the SBP LS group. Increasing WC was significantly associated with an upward shift in all SBP groups except LS. The WC effect was significantly stronger for the SBP MI ($\chi^2 = 19{\cdot}16$, $P < 0{\cdot}01$) and SBP HS ($\chi^2 = 29{\cdot}94$, $P < 0{\cdot}01$) groups (Table 3). Fruit consumption, higher PA and higher vegetable intake were beneficial to a DBP LS trajectory. Participants who ate fruit had lower odds of being in the DBP HI group (OR = 0·61, 95 % CI 0·39, 0·95) compared with the DBP LS group. Participants who ate more than 300 g of vegetables a day had lower odds of being in the DBP LI, MS and HI groups compared with the DBP LS group. The greater the vegetable intake, the greater the effect. In contrast, WC and salt intake were unfavourable for maintaining a DBP LS trajectory (Table 4).

Associations between blood pressure trajectories and HTN

Table 5 presents the associations between BP trajectories and risk of HTN. Compared with the SBP LS trajectory, the SBP HS (HR 2·01, 95 % CI 1·18, 3·43) trajectory was significantly associated with increased risk of HTN with adjustment for all covariates, while we found no association between the SBP MI (HR 1·64, 95 % CI 0·97, 2·77) and MD (HR 1·27, 95 % CI 0·75, 2·14) trajectories and risk of HTN. Compared with the DBP LS trajectory, the DBP LI (HR 1·38, 95 % CI 1·05, 1·82), MS (HR 1·40, 95 % CI 1·04, 1·88) and HI (HR 1·71, 95 % CI 1·28, 2·27) trajectories were all significantly associated with increased risk of HTN with adjustment for all covariates.

Sensitivity analyses

The SBP trajectories we identified in the BP data, excluding obesity, were similar to those of the total cohort (online Supplementary Fig. A.1.A). PA and WC also influenced SBP trajectories (online Supplementary Table B.1). The DBP trajectories changed slightly. Although the number of groups remained the same, two new groups, high decreasing (HD) and moderate increasing (MI), emerged and replaced DBP MS and HI in the total cohort. After excluding obese people, the trajectory of higher BP showed a downward trend, which also proved the effect of obesity on BP (online Supplementary Fig. A.1.B). Multiple logistic regression results showed that PA, BMI, WC and vegetable and salt intakes could affect DBP trajectories (online Supplementary Table B.2). We ran sensitivity analyses for the associations between BP trajectories and HTN, excluding individuals with obesity (BMI ≥ 28 kg/m2) during 1989–2009 (online Supplementary Table B.3). The analyses replicated the relationships between BP trajectories and HTN.

Discussion

We identified five SBP trajectory groups and four DBP trajectory groups during young adulthood and middle age among normotensives. We found that higher PA levels were favourable for low and steady trajectories of both SBP and DBP, while greater WC was an unfavourable risk factor for both. In addition, higher fruit and vegetable intakes were favourable for a healthy DBP trajectory, and a higher salt intake was unfavourable. The present findings supported the interpretation that BP trajectories themselves throughout young to middle-aged adulthood were significant predictors for future HTN independent of BP levels at one point in time. The SBP and the DBP trajectories were both significantly associated with HTN, the leading global preventable risk factor for CVD and premature death[21,22]. Higher BP levels in young adulthood were associated with a more rapidly increasing BP and a higher risk of HTN. We examined for the first time modifiable factors influencing BP trajectories of normotensives and their significant associations with HTN risk later in life among an Asian population.

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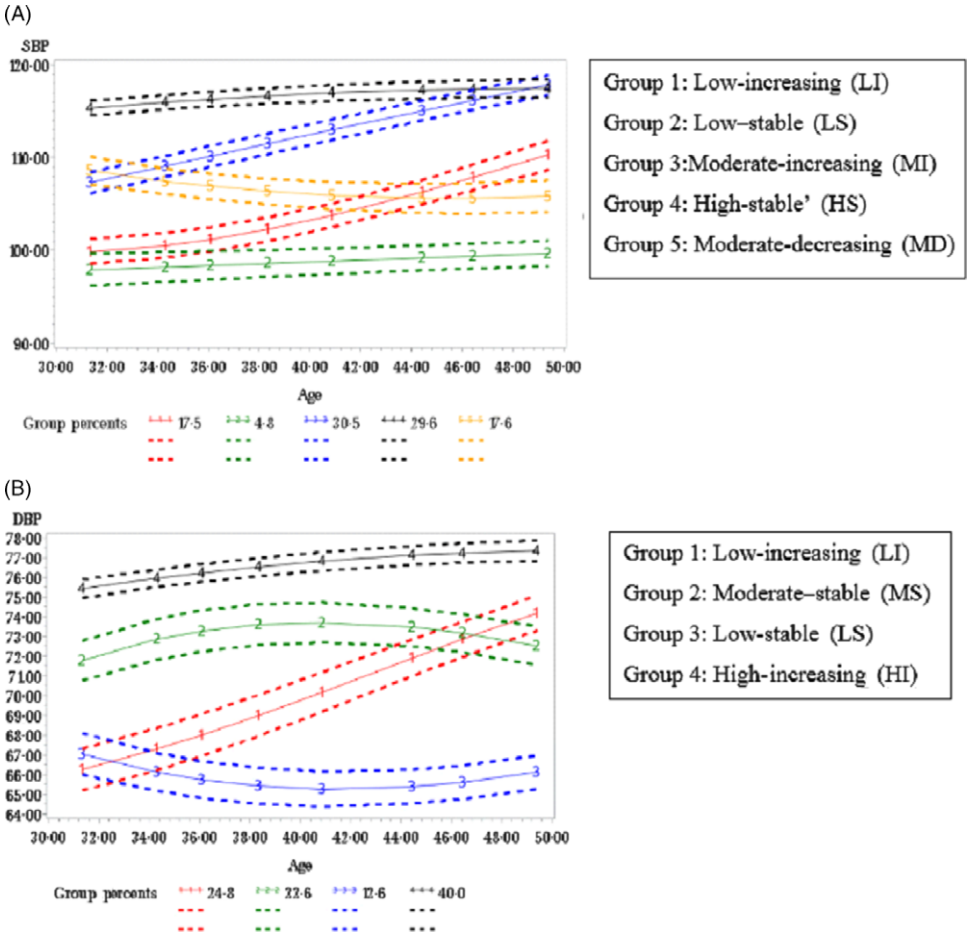

Fig. 2. Plots of predicted systolic blood pressure (SBP) (a) and diastolic blood pressure (DBP) (b) trajectories with 95 % CI, 1989–2009.

Several studies have demonstrated that BP changes in adult populations follow four to five trajectories[23,24]. Weijuan Li *et al.* identified five distinct trajectories in both SBP and DBP over a 4-year period[8]. In the 'Rotterdam Study', Marileen L. P. Portegies *et al.* identified four SBP trajectories in 6745 participants aged 55 to 106 years[2]. However, little is known about the trajectories of BP changes among normotensives before an HTN diagnosis. The differences in BP trajectories between populations have important implications. Atherosclerosis is a slowly progressive disease and reduced lifetime exposure to atherosclerotic CVD (ASCVD) risk factors, such as increased SBP, lowers an individual's risk of an ASCVD event[25,26]. One recent cohort study of 1457 participants with normal SBPs (90 to 129 mmHg) reported a stepwise increase in the prevalence of coronary artery Ca and ASCVD risk. For every 10-mmHg increase in SBP the study found a 53 % higher risk of ASCVD[27]. Therefore, our data on BP trajectories could help define an optimal adulthood BP trajectory for early disease prevention.

Prior BP research has linked measured risk factors with HTN at a single point in time later in life. This present research goes beyond that by linking risk factors to trajectories capturing the entire developmental BP course from early adulthood to middle age. Knowledge about modifiable risk factors that alter BP trajectories can help determine intervention foci. This study showed that increasing WC predicted an upward shift in BP trajectory levels. The impact of a higher WC was greatest among the groups with higher BP, suggesting that excess WC may be particularly problematic for individuals already developing a higher BP trajectory. However, BMI was not associated with BP trajectories, suggesting that WC rather than BMI predicts development of HTN among Chinese adults. However, a longitudinal birth cohort study in New Zealand reported that higher BMIs resulted in increasing BP across trajectories[28]. It is still controversial that anthropometric indicator could best predict HTN[29,30]. Further research is required to ascertain if this association persists at different ages. We found that higher PA and fruit and vegetable intakes were significant protective factors and were associated with a downward shift in the trajectories of those in the higher BP trajectory groups. Our results support recommendations for PA as an important lifestyle modification that may aid in the prevention of HTN. Conversely, another analysis found no association between fruit and vegetable intakes and BP trajectories in older age, but that study made no appropriate adjustments for salt intake. Salt intake may have a large impact on BP trends and could have masked the association with fruit and vegetable intakes[31]. Numerous epidemiological, clinical and experimental studies have linked dietary Na intake to BP and have documented that a reduction in dietary salt intake can lower BP[32].

Table 2. Participants' characteristics by trajectory group at baseline*
(Numbers and percentages; mean values and standard deviations; median values and interquartile range)

	SBP trajectories										DBP trajectories							
	LI		LS		MI		HS		MD		LI		MS		LS		HI	
Variables	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
n (%)	601	17·5	165	4·8	1048	30·5	1017	29·6	605	17·6	852	24·8	777	22·6	433	12·6	1374	40·0
Age, years	33·8	8·6	41·4	10·5	33·2	9·8	33·6	10·8	37·8	11·0	34·2	9·0	34·6	11·6	37·5	10·3	33·5	10·3
Male	66	11·0	18	10·9	205	19·5	666	65·5	157	26·0	115	13·5	182	23·4	55	12·7	760	55·3
Urban	144	24·0	19	11·5	315	30·1	250	24·6	103	17·0	208	24·4	157	20·2	65	15·0	401	29·2
North	127	21·1	15	9·1	377	36·0	383	37·7	99	16·4	241	28·3	138	17·8	57	13·2	565	41·1
Education high school or above	237	39·4	18	10·9	541	51·6	517	50·8	155	25·6	372	43·7	245	31·5	107	24·7	744	54·1
Currently working	455	75·7	84	50·9	847	80·8	731	71·9	364	60·2	674	79·1	444	57·1	287	66·3	1076	78·3
Smoker	58	9·7	18	10·9	152	14·5	436	42·9	123	20·3	100	11·7	131	16·9	48	11·1	508	37·0
Alcohol consumer	98	16·3	21	12·7	199	19·0	439	43·2	136	22·5	150	17·6	144	18·5	74	17·1	525	38·2
Fruit consumer	69	11·5	4	2·4	153	14·6	102	10·0	52	8·6	100	11·7	65	8·4	34	7·9	181	13·2
Vegetable consumption, g																		
Median	322·9		333·3		324·2		325·0		341·7		333·3		316·7		375·0		316·7	
IQR	216·7–490·0		216·7–484·2		208·3–458·3		215·0–475·0		218·3–465·5		216·7–483·3		203·3–450·0		239·6–533·3		208·3–458·3	
Tea drinker	201	33·4	29	17·6	343	32·7	350	34·4	181	29·9	281	33·0	202	26·0	118	27·3	503	36·6
Salt consumption, g																		
Mean	17·2		16·4		16·8		17·3		17·7		16·6		17·8		17·2		17·2	
SD	12·3		11·7		12·5		12·8		14·8		12·1		14·8		12·3		12·7	
PA, METs/week																		
Median	465·2		622·5		395·7		363·9		485·9		446·7		434·1		556·9		375·7	
IQR	210·9–658·9		427·3–807·3		180·5–615·0		169·0–588·0		273·0–654·0		199·4–646·1		199·2–629·2		332·8–738·0		168·3–590·3	
BMI, kg/m^2																		
Mean	21·1		20·8		21·6		21·6		21·1		21·3		21·0		20·9		21·8	
SD	2·4		2·4		2·6		2·5		2·3		2·4		2·2		2·4		2·6	
WC, cm																		
Mean	72·7		70·6		74·2		76·6		73·3		73·1		73·2		71·4		76·4	
SD	7·7		6·8		8·2		8·2		6·9		7·5		7·6		6·9		8·3	

DBP, diastolic blood pressure; HS, high stable; HI, high increasing; LI, low increasing; LS, low stable; MI, moderate increasing; MD, moderate decreasing; MS, moderate stable; PA, physical activity; SBP, systolic blood pressure; WC, waist circumference.

* Values of age, salt consumption, BMI, WC, SBP and DBP are means (standard deviation); values of vegetable consumption and PA are median (interquartile range: Q1–Q3).

Table 3. Modifiable factors for systolic blood pressure (SBP) trajectory groups: multivariable analyses (Odd ratio and 95 % confidence intervals)

Modifiable factors*	Trajectory groups	β value	χ^2 value	*P* value	OR	95 % CI
PA (*v.* Q1†)						
Q2	LI‡ (*v.* LS)	0·39	0·58	0·45	1·47	0·55, 3·97
	MI (*v.* LS)	0·46	0·83	0·36	1·58	0·59, 4·20
	HS (*v.* LS)	0·48	0·90	0·34	1·62	0·60, 4·39
	MD (*v.* LS)	0·94	3·36	0·07	2·57	0·94, 7·03
Q3	LI (*v.* LS)	–0·33	0·60	0·44	0·72	0·31, 1·66
	MI (*v.* LS)	–0·33	0·62	0·43	0·72	0·32, 1·64
	HS (*v.* LS)	–0·27	0·38	0·54	0·77	0·33, 1·79
	MD (*v.* LS)	0·39	0·78	0·38	1·47	0·62, 3·47
Q4	LI (*v.* LS)	–0·81	3·96	0·05	0·45	0·20, 0·99
	MI (*v.* LS)	–0·80	4·04	0·04	0·45	0·21, 0·98
	HS (*v.* LS)	–0·83	4·02	0·04	0·44	0·19, 0·98
	MD (*v.* LS)	–0·29	0·47	0·49	0·75	0·33, 1·70
WC						
	LI (*v.* LS)	0·06	11·64	<0·01	1·07	1·03, 1·11
	MI (*v.* LS)	0·08	19·16	<0·01	1·08	1·05, 1·12
	HS (*v.* LS)	0·10	29·94	<0·01	1·11	1·07, 1·15
	MD (*v.* LS)	0·06	10·88	<0·01	1·06	1·03, 1·11

DBP, diastolic blood pressure; HS, high stable; HI, high increasing; LI, low increasing; LS, low stable; MI, moderate increasing; MD, moderate decreasing; MS, moderate stable; PA, physical activity; WC, waist circumference.

* Model includes age; gender; urban or rural status; north or south region; education; working; alcohol consumption; cigarette smoking; tea drinking; PA; fruit, vegetable, and salt consumption; BMI and WC. Only modifiable factors with statistically significant *P* values are listed in the table.

† Q1–Q4 are classified according to the quartile of PA. Those less than the lower quartile are classified as Q1 (0.0–194.6 MET/week), those between the lower quartile and the median are classified as Q2 (194.6–429.1 MET/week), those between the median and the upper quartile are classified as Q3 (429.1–631.8 MET/week) and those greater than the upper quartile are classified as Q4 (≥ 631.8 MET/week).

‡ LI, LS, MI, HS and MD refer to the SBP trajectory groups.

§ LI, MS, LS and HI refer to the DBP trajectory groups.

To a large extent agreeing with these results, we found that a higher salt intake was unfavourable for a healthy DBP trajectory. This study found that a salt intake of 6–11 g/d was significantly associated with LI, MS and HI DBP trajectories. However, our study did not find any associations between fruit, vegetable and salt intakes and SBP trajectories. These may be related to the fact that we only analysed the relationships between baseline vegetable, fruit and salt intakes and BP trajectories. As we know, dietary intake is not constant. The present study covers a large time span, and it is possible that changes in economic levels affect people's dietary intakes over time. We mention this as one limitation of the study.

Our study results suggest the higher the early BP level in normotensives, the greater the risk of HTN. This is consistent with the findings of Mark Hamer *et al.* on the relationship between BP trajectory in youth and HTN risk in adulthood[9]. The highest levels of both SBP and DBP in early adulthood have the greatest effect on future HTN risk, suggesting that keeping a normal BP level as low as possible in young adulthood is preferable. What is more, an upward trend later in life contributes to future HTN risk. Individuals with an SBP MD trajectory had a lower HTN risk compared with individuals with an SBP MI trajectory even though they had similar BP level in early adulthood. On the other hand, if we take 2009 as a time point connecting the BP trajectory to the new onset of HTN, it is not always the case that higher BP in one point is associated with higher HTN risk after 2009. Individuals with a DBP LI trajectory had a lower HTN risk than those with a DBP MS trajectory even though their DBP LI trajectories had increased to a higher DBP level by 2009. These results show that relying on a single BP value to predict HTN risk could misclassify risk groups and that long-term BP changes provide more insight into evolving risks. Studies of the associations between BP trajectories and other diseases have shown similar results[8,23]. Our findings support recommendations to track BP trajectories early in clinical settings.

In the sensitivity analysis two new groups emerged and replaced DBP MS and HI after the exclusion of obesity, which suggests the influence of obesity on BP trajectory. Obesity is a significant risk factor for high BP, and obesity-associated HTN is a serious public health concern. Obesity increases BP through various mechanisms. First, sympathetic nervous system overactivity, especially in the kidneys, is one of the most important mechanisms[33]. Second, various hormones that adipocytes in visceral adipose tissues release play important roles[34]. Third, obesity-caused gut dysbiosis might lead to increased BP[35]. Therefore, lifestyle modification, especially to improve obesity, should be a first treatment for HTN.

Our study has strengths and limitations. A major strength is that it involves up to 11 BP measurements over a 29-year period from young adulthood to middle age. In addition, this is the first study to investigate the modifiable factors of BP trajectories among normotensives and their associations with HTN risk with such a breadth of data. The study also has limitations. First, because we used only 3436 CHNS participants for the analysis, the representativeness of the current study could be questionable. But it is still rare for studies to measure BP as many as eleven times, and this study provides a new way of thinking about BP trajectories. Second, we did not adjust for changes in covariates (e.g., alcohol, smoking, PA, BMI and salt intake) from 1989 to 2009 in the Cox models, which could lead to deviation in the results. Third, we did not measure sleep problems in the present study. Previous studies showed an association between

Table 4. Modifiable factors for diastolic blood pressure (DBP) trajectory groups: multivariable analyses (Odd ratio and 95 % confidence intervals)

Modifiable factors*	Trajectory groups	β value	χ^2 value	*P* value	OR	95 % CI
PA (*v.* Q1†)						
Q2	LI§ (*v.* LS)	–0·40	2·92	0·09	0·67	0·42, 1·06
	MS (*v.* LS)	–0·36	2·09	0·15	0·70	0·43, 1·14
	HI (*v.* LS)	–0·47	3·82	0·05	0·63	0·39, 1·00
Q3	LI (*v.* LS)	–0·56	5·45	0·02	0·57	0·36, 0·92
	MS (*v.* LS)	–0·43	2·90	0·09	0·65	0·40, 1·07
	HI (*v.* LS)	–0·60	6·06	0·01	0·55	0·34, 0·89
Q4	LI (*v.* LS)	–0·70	9·03	<0·01	0·49	0·31, 0·78
	MS (*v.* LS)	–0·70	7·65	0·01	0·50	0·30, 0·82
	HI (*v.* LS)	–0·73	9·17	<0·01	0·48	0·30, 0·77
Fruit consumption (*v.* no)						
	LI (*v.* LS)	–0·36	2·71	0·10	0·70	0·45, 1·07
	MS (*v.* LS)	–0·31	1·75	0·19	0·73	0·46, 1·16
	HI (*v.* LS)	–0·50	4·87	0·03	0·61	0·39, 0·95
Vegetable consumption, g/d (*v.* <300 g)						
300–499 g	LI (*v.* LS)	–0·36	4·82	0·03	0·70	0·51, 0·96
	MS (*v.* LS)	–0·56	10·44	<0·01	0·57	0·40, 0·80
	HI (*v.* LS)	–0·49	8·65	<0·01	0·61	0·44, 0·85
≥ 500 g	LI (*v.* LS)	–0·38	4·31	0·04	0·69	0·48, 0·98
	MS (*v.* LS)	–0·78	15·10	<0·01	0·46	0·31, 0·68
	HI (*v.* LS)	–0·58	9·28	<0·01	0·56	0·39, 0·81
WC						
	LI (*v.* LS)	0·05	16·36	<0·01	1·05	1·02, 1·07
	MS (*v.* LS)	0·05	13·79	<0·01	1·05	1·02, 1·07
	HI (*v.* LS)	0·08	42·67	<0·01	1·08	1·06, 1·11
Salt consumption, g/d (*v.* <6 g)						
6–11 g	LI (*v.* LS)	0·68	8·51	0·00	1·97	1·25, 3·10
	MS (*v.* LS)	0·51	4·16	0·04	1·67	1·02, 2·73
	HI (*v.* LS)	0·75	9·60	<0·01	2·11	1·32, 3·38
12–17 g	LI (*v.* LS)	0·18	0·65	0·42	1·20	0·77, 1·85
	MS (*v.* LS)	0·18	0·53	0·46	1·19	0·74, 1·91
	HI (*v.* LS)	0·29	1·56	0·21	1·33	0·85, 2·10
≥ 18 g	LI (*v.* LS)	0·35	3·36	0·07	1·43	0·98, 2·08
	MS (*v.* LS)	0·23	1·20	0·27	1·26	0·83, 1·91
	HI (*v.* LS)	0·40	3·99	0·05	1·50	1·01, 2·23

HS, high stable; HI, high increasing, LI, low increasing; LS, low stable; MI, moderate increasing; MD, moderate decreasing; MS, moderate stable; PA, physical activity; SBP, systolic blood pressure; WC, waist circumference.
* Model includes age; gender; urban or rural status; north or south region; education; working; alcohol consumption; cigarette smoking; tea drinking; PA; fruit, vegetable, and salt consumption; BMI; and WC. Only modifiable factors with statistically significant *P* values are listed in the table.
† Q1–Q4 are classified according to the quartile of PA. Those less than the lower quartile are classified as Q1 (0·0–194·6 METs/week), those between the lower quartile and the median are classified as Q2 (194·6–429·1 METs/week), those between the median and the upper quartile are classified as Q3 (429·1–631·8 METs/week) and those greater than the upper quartile are classified as Q4 (≥ 631·8 METs/week).
‡ LI, LS, MI, HS and MD refer to the SBP trajectory groups.
§ LI, MS, LS and HI refer to the DBP trajectory groups.

Table 5. Adjusted hazard ration (HR) and 95 % CI for risk of hypertension (HTN) in 2011–2018 according to systolic blood pressure (SBP) and diastolic blood pressure (DBP) trajectory groups in 1989–2009 (Hazard ratio and 95 % confidence intervals)

	Model 1*			Model 2†			Model 3‡		
Trajectories	*P* value	HR	95 % CI	*P* value	HR	95 % CI	*P* value	HR	95 % CI
SBP trajectories									
LI (*v.* LS)	0·38	1·26	0·75, 2·12	0·44	1·23	0·73, 2·07	0·91	1·03	0·61, 1·75
MI (*v.* LS)	<0·01	2·00	1·19, 3·34	0·01	1·91	1·14, 3·21	0·06	1·64	0·97, 2·77
HS (*v.* LS)	<0·01	2·51	1·48, 4·24	<0·01	2·41	1·42, 4·08	0·01	2·01	1·18, 3·43
MD (*v.* LS)	0·20	1·41	0·84, 2·36	0·25	1·36	0·81, 2·28	0·37	1·27	0·75, 2·14
DBP trajectories									
LI (*v.* LS)	<0·01	1·53	1·17, 1·99	<0·01	1·51	1·16, 1·98	0·02	1·38	1·05, 1·82
MS (*v.* LS)	<0·01	1·52	1·14, 2·02	<0·01	1·48	1·11, 1·96	0·02	1·40	1·04, 1·88
HI (*v.* LS)	<0·01	1·89	1·44, 2·49	<0·01	1·83	1·38, 2·41	<0·01	1·71	1·28, 2·27

HS, high stable; HI, high increasing; LI, low increasing; LS, low stable; MI, moderate increasing; MD, moderate decreasing; MS, moderate stable; TC, total cholesterol.
* Model 1 adjusted by age, gender, urban or rural status, north or south region and BP in 2009.
† Model 2 further adjusted by alcohol consumption, cigarette smoking, PA and salt consumption.
‡ Model 3 further adjusted by BMI, WC, TC, TAG, LDL-cholesterol and diabetes status.

sleep problems and prevalence or incidence of HTN[36,37]. Finally, the fact that only 5 % of participants are included in the reference group (LS) for SBP trajectories when the association between various BP trajectories and modifiable risk factors was analysed may affect the precision of the estimates. More studies are needed to determine the optimal age-specific BP trajectories to watch for HTN and CVD prevention.

Conclusion

In conclusion, our study confirmed that subgroups among normotensive Chinese adults have different BP trajectories and found the key modifiable risk factors for elevated BP trajectories. SBP and DBP trajectories throughout adult normotensives were significant predictors of future HTN. This is the first such study in an Asian population. Monitoring BP trajectories from young adulthood may be an important approach to identify populations with higher risks for developing HTN. Early prevention and intervention, such as changing associated risk factors, may effectively reduce HTN and cardiovascular risks in these populations later in life. More studies at different ages are needed.

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Supplementary material

For supplementary material/s referred to in this article, please visit https://doi.org/10.1017/S0007114521003378

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