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ORIGINAL ARTICLE

Generational differences in longitudinal blood pressure trajectories by geographic region during socioeconomic transitions in China

Jinjing Wu[1] · Peter A. Muennig[2] · Katherine Keyes[3] · Jilei Wu[4]

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Abstract

Objectives To examine generational differences in longitudinal blood pressure trajectories by region following socioeconomic transitions, which is important for establishing the population risk of cardiovascular diseases (CVDs).

Methods With data from the China Health and Nutrition Survey (1991–2011), we used multilevel growth-curve models to estimate systolic/diastolic blood pressure (SBP/DBP) levels at the mean age and rates of change by cohort (born between 1931 and 1980), region, and sex.

Results Younger cohorts generally had higher SBP/DBP levels at 44.5 years but lower growth rates in SBP/DBP than older cohorts. They became prehypertensive (SBP $\geq$ 120 mm Hg or DBP $\geq$ 80 mm Hg) at an earlier age. The upward shift of SBP/DBP trajectories across cohorts was more pronounced in the Coastal and Southern Mountainous Regions than the Northeastern and Inland Regions, and for males versus females.

Conclusions Younger cohorts have a longer lifetime duration of being susceptible to CVDs, posing warnings for an increased burden of CVDs. Generational differences in BP trajectories and geographic and sex variations in the cohort trends highlight the need for tailored interventions to tackle the generation, region, and sex-based risk of CVDs.

Keywords Systolic/diastolic blood pressure trajectories · Socioeconomic transitions · Life course perspective · Generational differences · Geographic variations · China

Introduction

China has undergone an epidemiological transition from predominant causes of mortality centered around infectious diseases to non-communicable diseases, particularly cardiovascular diseases (CVDs) (Yang et al. 2008). High blood pressure (BP) has been one of the leading contributors to the overall burden of disease in China (Forouzanfar et al. 2017). Having a continuous association with cardiovascular morbidity and mortality (Lewington et al. 2002; Wang et al. 2018), systolic and diastolic blood pressure (SBP and DBP) are major modifiable CVD risk factors (Ettehad et al. 2016).

Social and economic contexts of early life are strong determinants of long-term health (Elder and George 2016). For example, early-life environmental exposures are

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✉ Jilei Wu
wujl@pku.edu.cn

Jinjing Wu
jinjingwu1105@gmail.com

Peter A. Muennig
pm124@cumc.columbia.edu

Katherine Keyes
kmk2104@cumc.columbia.edu

[1] Asian Demographic Research Institute, Shanghai University, Shanghai, China

[2] Department of Health Policy and Management, Mailman School of Public Health, Columbia University, New York, USA

[3] Department of Epidemiology, Mailman School of Public Health, Columbia University, New York, USA

[4] Institute of Population Research, Peking University, Beijing, China

hypothesized to affect biological, behavioral, and psychosocial development, leading to an enduring impact on the risk of CVDs (Barker 1990; Ben-Shlomo and Kuh 2002; Gluckman et al. 2008).

Before the 1990s, China was a predominantly rural country with low economic growth. Since the 1990s, China has undergone unprecedented economic growth attributable to the implementation of open-door policies and market-oriented economic reforms (Kanbur and Zhang 2005). This may have contributed to generational gaps in early-life socioeconomic circumstances that have been hypothesized to have a long-term effect on cardiovascular health (Gluckman et al. 2008). Moreover, regional inequalities in economic growth and human capital investment have increased during the reform era (Zhang and Kanbur 2005). As such, the generational changes in cardiovascular risk profile may vary among regions. Additionally, the socioeconomic transformations' influences might be gendered; cardiovascular health can be mediated by socially and biologically constructed gender differences in exposure and vulnerability to risk factors of CVDs (O'Neil et al. 2018).

Analyzing changes in age patterns of SBP/DBP across birth cohorts by region and sex is valuable for exploring whether the initial capacity of cardiovascular system increases and rate of decline over time slows down following socioeconomic transitions as predicted by the theory of technophysio evolution (Fogel 2004) and illustrating underlying changes in CVD burden. Much of what we learned about the cohort dynamics in cardiovascular risk profile was obtained from nations that developed before the age of motorized transport and processed foods (e.g., Norway and the USA) (Choh et al. 2011; Hopstock et al. 2015).

People living in rapidly developing nations today may confront unique risk factors of CVDs. To the extent that we can understand how cardiovascular risk profile changes through generational replacement, we can formulate policies that address health hazards before they become CVDs. Some studies have examined cohort variations in mean BP levels or the prevalence of hypertension among Chinese adults (Attard et al. 2015; Yang et al. 2017). However, few studies have investigated the cohort-specific longitudinal SBP/DBP trajectories that are associated with the onset and progression of CVDs and death (Lewington et al. 2002; Wang et al. 2018). Furthermore, whether the generational changes differ by region and sex remains unclear. Using longitudinal data from the China Health and Nutrition Survey (1991–2011), we aim to estimate cohort-specific SBP/DBP trajectories by region and sex.

Methods

We used data from the China Health and Nutrition Survey (CHNS). The survey is an ongoing open cohort longitudinal survey of nine waves (1989, 1991, 1993, 1997, 2000, 2004, 2006, 2009, and 2011). It employed a multistage, random-cluster process to select samples by provincial areas (Beijing, Chongqing, Guangxi, Guizhou, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Liaoning, Shandong, and Shanghai) that vary in socioeconomic development and geography (Popkin et al. 2010; Zhang et al. 2014).

We excluded observations from the wave of 1989 in which only adults aged 20–45 were surveyed. Also, we excluded newly recruited respondents in Beijing, Shanghai, and Chongqing as we only knew their SBP/DBP levels in the 2011 wave. We, therefore, were unable to estimate cohort-specific SBP/DBP trajectories in the three cities. We based our analyses on data from the nine provinces. The nine provinces contain approximately 56% of China's population and are vastly different in geography and socioeconomic conditions (Jones-Smith and Popkin 2010). Consistent with the previous studies (Chen et al. 2010; Schafer and Kwon 2012), we grouped the nine provinces into four regions—the Northeast Region (Heilongjiang, Liaoning), the Inland Region (Hubei, Hunan, Henan), the Coastal Region (Shandong, Jiangsu), and the Southern Mountainous Region (Guangxi, Guizhou). The Northeast Region is the reference group. Figure A1 in the Online Resource shows the map of regions studied.

The selection of the sample

We selected a sample of individuals who were born in 1931–1980. There are 19,993 respondents in total, yielding 93,345 observations. We further excluded 30,146 observations with missing values on SBP/DBP. But, 90.6% of respondents had at least one measurement of SBP/DBP. And we excluded 3596 observations with missing values on control variables. We reported the details of sample exclusion process in Fig. A2 of Online Resource.

Table S1 of the Online Resource shows that people who were young, male, unmarried, rural residents, lived in Southern Mountainous Region, with lower education and income were more likely to have missing values on SBP/DBP or covariates. Observations in the earlier waves were also more likely to have missing values. In addition to the main analysis based on the data excluding observations with missing values, we built models based on the data after conducting multiple imputations to evaluate the potential bias caused by missing values and reported results in the Online Resource.

The main analysis included 17,737 respondents. These respondents yield 63,199 observations, with an average of 3.6 observations for each respondent. The mean age of the sample was 44.5 years. Among those respondents, 4.6% had died by the end of 2011. 36.9% who were not included in the 2011 wave but surveyed in the other waves were considered lost to follow-up. To adjust for the selection bias due to death and loss to follow-up, we built time-constant dummy variables to indicate deaths and dropouts and included them in statistical analyses.

BP measurement

BP has two components: the maximal pressure when the heart has contracted (SBP) and the residual pressure after the heart has relaxed (DBP). Trained physicians measured seated SBP/DBP using standardized mercury sphygmomanometers. SBP and DBP were measured three times after 5-min rest, and three measurements were taken at one–two-minute intervals. We averaged the three readings of SBP and DBP, respectively, and used them as dependent variables.

The definition of birth cohorts

We used birth cohorts as a proxy for social contexts to which life trajectories are exposed (Elder and George 2016; Ryder 1965), which was consistent with the previous studies (Chen et al. 2010; Schafer and Kwon 2012; Lynch 2003). We created 10-year cohorts, except for the 1951–1955, the 1956–1961, and the 1962–1970 cohorts due to the potential impact of the 1959–1961 famine on the 1956–1961 cohort (Li and Lumey 2017). The 1931–1940 cohort was the reference group. We included cohort as a continuous variable (coded from 0 to 5), which was consistent with prior studies (Chen et al. 2010; Schafer and Kwon 2012).

Control variables

Age, sex, urban/rural residence, educational attainment, household income per capita, marital status, current smoking status, current alcohol drinking status, and overweight are determinants of elevated BP (Wang et al. 2014), and these determinants were taken as control variables. We centered the age at the mean (44.5 years). Additionally, we included time-constant dummy variables indicating the deceased and non-respondents. Table 1 presents the statistics of the variables used in analyses.

Statistical analyses

We applied the multilevel growth-curve model to estimate cohort-specific SBP/DBP trajectories by region and sex. The model is more flexible than traditional approaches for analyzing repeated measures as it allows the inclusion of unbalanced data of respondents with a varied number of observations, and time-varying covariates (Curran et al. 2010). The previous works have illustrated that the multilevel growth-curve model allows distinguishing between the aging and cohort effects on health (Chen et al. 2010; Schafer and Kwon 2012; Lynch 2003).

First is the level 1 model. y_{ti} is the levels of SBP/DBP for respondent i at time t, which was regressed on linear and quadratic terms of age. The level 1 model is expressed as follows:

$$y_{ti} = \beta_{0i} + \beta_{1i}\left(\mathrm{Age}_{ti} - \overline{\mathrm{Age}}\right) + \beta_{2i}\left(\mathrm{Age}_{ti} - \overline{\mathrm{Age}}\right)^2 + e_{ti}$$

where $\beta_{0i}, \beta_{1i}, \beta_{2i}$ represent the estimated SBP/DBP levels of respondent i at the mean age, the growth rate per year of age, and the quadratic growth rate, respectively. e_{ti} represents the random within-person error term and is assumed to be normally distributed.

Then, the level 2 model includes the models for the intercept and the slope of age. For the model of the intercept, the estimated SBP/DBP levels at the mean age were further regressed on individual-level attributes. For the model of the slope, the linear growth rates were further regressed on individual-level attributes. We included interaction terms to estimate the cohort effect on the intercepts and slopes of BP trajectories by region. As men and women have different physiology and CVD risk factors (Appelman et al. 2015; O'Neil et al. 2018), we also included interaction terms to examine whether the cohort effect varied by sex. Those two of the level 2 models are expressed as follows:

(1) Model for the intercept:

$$\begin{aligned}\beta_{0i} = {} & \gamma_{00} + \gamma_{01}\mathrm{Cohort}_i + \gamma_{02}\mathrm{Region}_i + \gamma_{03}\mathrm{Sex}_i \\ & + \gamma_{04}\mathrm{Cohort}_i \cdot \mathrm{Region}_i + \gamma_{05}\mathrm{Cohort}_i \cdot \mathrm{Sex}_i \\ & + \gamma_{06}\mathrm{Cohort}_i \cdot \mathrm{Region}_i \cdot \mathrm{Sex}_i + \mu_{0i} + \mu_{0\mathrm{prov}}\end{aligned}$$

where γ_{00} represents the estimated SBP/DBP levels at the mean age among the 1931–1940 cohort. γ_{01} is the difference in SBP/DBP levels at the mean age between cohorts. γ_{02} is the difference in SBP/DBP at the mean age between one of the three other regions and Northeast.γ_{03} is the difference in SBP/DBP at the mean age between men and women. γ_{04} represents cohort by region interaction effect. γ_{05} represents cohort by sex interaction effect.γ_{06} represents the three-way interaction among cohort, region, and

Table 1 Descriptive statistics of all variables in our analyses, China Health and Nutrition Survey (1991–2011)

Variables	Whole sample (N = 63,199 observations)	
	Mean	S.D.
Systolic blood pressure (mm Hg)	119.02	18.03
Diastolic blood pressure (mm Hg)	77.40	11.33
Age (years)	44.49	14.63
Birth cohort (0 to 5)	2.70	1.69
Region		
Northeast (reference group)	0.18	0.39
Coastal	0.23	0.42
Southern Mountainous	0.25	0.43
Inland	0.33	0.47
Male	0.47	0.50
Married	0.83	0.38
Household income per capita (RMB)	7539.45	10,847.95
First quintile (< 2274.6, reference group)	0.25	0.43
Second quintile (2274.6 $\leq$ income < 4475.1)	0.25	0.43
Third quintile (4475.1 $\leq$ income < 8997.7)	0.25	0.43
Fourth quintile (income $\geq$ 8997.7)	0.25	0.43
Education attainment		
Illiterate or primary school (reference group)	0.46	0.50
Junior high school	0.32	0.47
High school or above	0.22	0.41
Urban residence	0.33	0.47
Overweight (body mass index $\geq$ 25 kg/m^2)	0.23	0.42
Current smoker	0.30	0.46
Current alcohol drinker	0.34	0.47
Dead	0.04	0.19
Non-dropout	0.62	0.49

sex. μ_{0i} and $\mu_{0\text{prov}}$ represent the residual random effects of individual and province for the intercept, respectively.

(2) Model for the slope of age:

$$\begin{aligned}\beta_{1i} = {} & \gamma_{10} + \gamma_{11}\text{Cohort}_i + \gamma_{12}\text{Region}_i + \gamma_{13}\text{Sex}_i \\ & + \gamma_{14}\text{Cohort}_i \cdot \text{Region}_i + \gamma_{15}\text{Cohort}_i \cdot \text{Sex}_i \\ & + \mu_{1i} + \mu_{1\text{prov}}\end{aligned}$$

where γ_{10} represents the linear growth rates among the 1931–1940 cohort. $\gamma_{11}, \gamma_{12}, \gamma_{13}$ represent the effects of cohorts, regions, and sex on the linear growth rates, respectively. γ_{14}, γ_{15} represent the three-way interaction among cohort, region, and age, and the three-way interaction among cohort, sex, and age, respectively. μ_{1i} and $\mu_{1\text{prov}}$ represent the residual random effects of individual and province for the slope of age, respectively.

We entered time-varying variables in the level 1 model and time-constant variables in the level 2 model. We examined whether the SBP/DBP trajectories varied by cohort and whether the cohort effect varied by region by comparing nested models. And we used the Akaike information criterion (AIC) and Bayesian information criterion (BIC) to evaluate the model fit between nested models. We used the NLME (Linear and Nonlinear Mixed-effects Models) package in R (version 3.5.1) to build the multilevel growth-curve models.

Sensitivity analyses

We built models without including the overweight indicator and examined changes in estimates after controlling for overweight status. Moreover, we performed a sensitivity analysis to check whether excluding antihypertensive medicine users (3647 observations) altered our findings. Also, to evaluate the potential bias caused by missing data, we performed multiple imputations with the MICE (Multivariate Imputation by Chained Equations) package in R (version 3.5.1) and created five multiply imputed datasets. We built the multilevel growth-curve model on each imputed dataset and pooled the estimates from each model into a single set of estimates and standard errors.

Table 2 Hierarchical growth-curve models of systolic/diastolic blood pressure (SBP/DBP) for Chinese born between 1931 and 1980[a], China Health and Nutrition Survey (1991–2011)

Fixed effects	SBP			DBP		
	Model 1 Coefficient (S.E.)	Model 2 Coefficient (S.E.)	Model 3 Coefficient (S.E.)	Model 1 Coefficient (S.E.)	Model 2 Coefficient (S.E.)	Model 3 Coefficient (S.E.)
Intercept model						
Intercept	118.12	113.07	116.72	79.32	76.97	79.22
	(0.93)***	(1.03)***	(1.23)***	(0.61)***	(0.66)***	(0.81)***
Cohort		2.99	1.64		0.92	0.10
		(0.41)***	(0.47)***		(0.28)**	(0.32)
Cohort square		−0.34	−0.30		−0.03	−0.01
		(0.07)***	(0.07)***		(0.05)	(0.05)
Southern Mountainous Region	−6.13	−6.30	−13.00	−5.27	−5.39	−9.78
	(1.25)**	(1.20)**	(1.49)***	(0.82)**	(0.74)***	(0.96)***
Coastal Region	−2.16	−2.00	−6.23	−3.05	−2.96	−5.96
	(1.25)	(1.20)	(1.49)**	(0.82)*	(0.74)*	(0.96)**
Inland Region	−3.16	−3.23	−4.84	−3.68	−3.74	−4.27
	(1.14)*	(1.10)*	(1.39)*	(0.75)**	(0.68)**	(0.89)**
Southern Mountainous Region × cohort			2.24			1.44
			(0.28)***			(0.19)***
Coastal Region × cohort			1.56			1.07
			(0.29)***			(0.19)***
Inland Region × cohort			0.57			0.19
			(0.27)*			(0.18)
Male	2.81	1.58	−0.10	2.82	1.92	0.72
	(0.38)***	(0.59)**	(0.99)	(0.26)***	(0.40)***	(0.63)
Male × cohort		0.66	1.13		0.47	0.82
		(0.15)***	(0.27)***		(0.10)***	(0.18)***
Male × Southern Mountainous Region	0.68	0.94	5.11	0.14	0.34	2.85
	(0.47)	(0.46)*	(1.22)***	(0.32)	(0.32)	(0.76)***
Male × Coastal Region	1.36	1.67	3.85	0.75	0.95	2.31
	(0.48)**	(0.47)***	(1.22)**	(0.33)*	(0.33)**	(0.76)**
Male × Inland Region	−0.16	0.08	0.32	−0.39	−0.23	0.43
	(0.44)	(0.44)	(1.16)	(0.31)	(0.31)	(0.73)
Male × cohort × Southern Mountainous Region			−1.15			−0.75
			(0.31)***			(0.21)***
Male × cohort × Coastal Region			−0.61			−0.41
			(0.32)			(0.21)
Male × cohort × Inland Region			−0.07			−0.20
			(0.30)			(0.20)
Slope model						
Intercept	0.57	1.12	1.06	0.27	0.52	0.47
	(0.02)***	(0.05)***	(0.06)***	(0.02)***	(0.04)***	(0.04)***
Cohort		−0.15	−0.16		−0.05	−0.05
		(0.02)***	(0.02)***		(0.01)***	(0.01)***
Southern Mountainous Region	0.04	0.01	0.10	−0.01	−0.02	0.08
	(0.03)	(0.03)	(0.05)*	(0.02)	(0.03)	(0.04)*
Coastal Region	0.05	0.03	0.03	−0.01	−0.02	0.03
	(0.03)	(0.03)	(0.05)	(0.02)	(0.03)	(0.04)

Table 2 (continued)

Fixed effects	SBP			DBP		
	Model 1 Coefficient (S.E.)	Model 2 Coefficient (S.E.)	Model 3 Coefficient (S.E.)	Model 1 Coefficient (S.E.)	Model 2 Coefficient (S.E.)	Model 3 Coefficient (S.E.)
Inland Region	0.07	0.04	0.05	−0.01	−0.02	−0.03
	(0.03)*	(0.03)	(0.05)	(0.02)	(0.02)	(0.03)
Southern Mountainous Region × cohort			0.01			−0.003
			(0.01)			(0.01)
Coastal Region × cohort			0.03			0.01
			(0.01)**			(0.01)
Inland Region × cohort			0.01			0.01
			(0.01)			(0.01)
Male	−0.11	−0.19	−0.19	−0.02	−0.06	−0.06
	(0.01)***	(0.03)***	(0.03)***	(0.01)**	(0.02)***	(0.02)***
Male × cohort		0.04	0.04		0.03	0.03
		(0.01)***	(0.01)***		(0.004)***	(0.004)***
Age square	0.006	−0.004	−0.004	−0.003	−0.008	−0.008
	(0.000)***	(0.001)***	(0.001)***	(0.000)***	(0.001)***	(0.001)***
Age square × cohort[b]					0.001	0.001
					(0.000)***	(0.0001)***
Random effects	S.D.	S.D.	S.D.	S.D.	S.D.	S.D.
Province level: intercept	1.20	1.15	1.13	0.78	0.70	0.71
Growth rate	0.03	0.02	0.03	0.02	0.02	0.02
Individual level: intercept	8.10	8.04	8.01	5.20	5.17	5.15
Growth rate	0.32	0.32	0.32	0.14	0.14	0.14
AIC	511701.80	511189.50	511113.80	463713.40	463287.40	463197.2
BIC	512000.60	511533.60	511539.30	464012.10	463640.50	463631.70

All models also controlled for time-varying variables including age square, educational attainment, household income, marital status, overweight, smoking, alcohol drinking, and time-constant variables indicating whether respondents had been lost to follow-up or had died before the 2011 China Health and Nutrition Survey

AIC Akaike information criterion, *BIC* Bayesian information criterion

Significance levels: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

[a]In a preliminary analysis, we compared estimates obtained from a model with dummy variables of the cohort membership and a model with a continuous variable of the cohort membership. The two models produced consistent findings that there were an increase in the estimated SBP/DBP levels at 44.5 years and a decrease in the growth rates of SBP/DBP in the succession of cohorts (Online Resource Table S3-6)

[b]We included the interaction between cohort and age square in the DBP model but did not include it in the SBP model as a preliminary analysis showed that including it improved the DBP model's fit but did not improve the SBP model's fit (Online Resource Table S7)

Results

Table 2 presents major findings obtained from the multilevel growth-curve models, and Table S2 of the Online Resource reports estimates of control variables. Model 1 shows the average age patterns of SBP/DBP by sex and region, regardless of the cohort variation. The estimated SBP and DBP levels at 44.5 years among women in the Northeast (the reference group) were about 118.12 and 79.32 mm Hg, respectively. SBP increased at a rate of 0.57 mm Hg per year of age, accelerating at a rate of 0.006 mm Hg. And DBP grew at a rate of 0.27 mm Hg, slowing at a rate of − 0.003 mm Hg.

Furthermore, men had a significantly higher estimated SBP/DBP at 44.5 years but lower growth rates than women. Moreover, residents of the Southern Mountainous, Coastal, and Inland Regions had lower estimated SBP/DBP levels at 44.5 years than the Northeastern residents. But, the difference between the Coast and Northeast was not statistically significant. Additionally, the Inland residents had a significantly higher growth rate of SBP than the Northeastern residents.

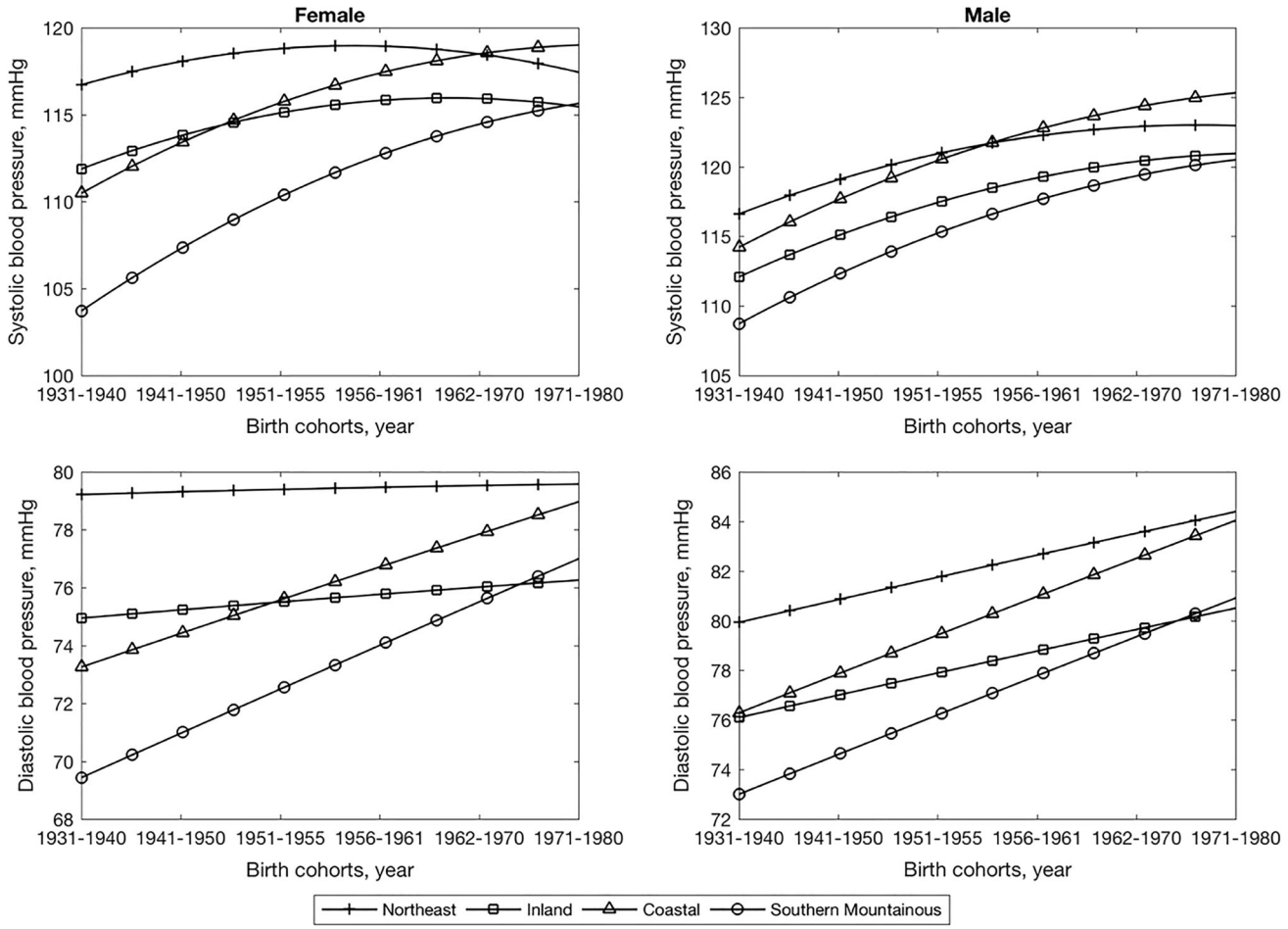

Fig. 1 Estimated levels of systolic blood pressure and diastolic blood pressure at 44.5 years old by birth cohort, region, and sex, China Health and Nutrition Survey (1991–2011)

We included cohort variables in Model 2 based on Model 1 and found that including the cohort variation improved the model fit. After adjusting for cohort variables, the intercepts and slopes of age represent the 1931–1940 Northeast female cohort's estimated SBP/DBP at 44.5 years and growth rates in SBP/DBP, respectively. The intercepts were lower, whereas the slopes of age were higher in Model 2 compared with Model 1. For each successive cohort, the estimated SBP/DBP at 44.5 years increased by an average of 2.99/0.92 mm Hg, slowing at a rate of − 0.34/− 0.03 mm Hg. Additionally, the growth rates in SBP/DBP decreased at an average rate of − 0.15/− 0.05 across cohorts.

We included the interactions between cohort and region in Model 3 based on Model 2, and the model fit further improved, indicating that the cohort effect varied by region. After adjusting for the interactions, the magnitude of the main effect of cohort notably decreased in both the SBP and DBP models and became nonsignificant in the DBP model. The main effects of cohort in Model 3 represent the increase in the estimated SBP/DBP levels at 44.5 years for each successive cohort among women in the Northeast.

The coefficients of the interactions between cohort and region were positive and statistically significant, suggesting that the cohort-based increase in the estimated SBP/DBP levels at 44.5 years was greater in the other regions than the Northeast. The exception was the Inland residents, whose cohort effect on the intercept of DBP was not significantly different from the Northeastern residents. As shown in Fig. 1, the Coastal and Southern Mountainous Regions had a larger increase in the estimated SBP/DBP levels at 44.5 years for each successive cohort than the Northeast Region for both sexes. And males had a larger increase in the estimated SBP/DBP levels at 44.5 years across cohorts than females.

The regional variation in the cohort effect on the growth rates of SBP/DBP was not statistically significant except that the Coastal residents had a smaller cohort-based decrease in the growth rate of SBP compared with the Northeastern residents. Moreover, the male had a slower

decrease in the SBP/DBP growth rates across cohorts than their female counterparts.

Figures 2 and 3 illustrate that the estimated SBP/DBP trajectories shifted upward across cohorts. The upward trend was more pronounced in the Coastal and Southern Mountainous Regions relative to the Northeastern and Inland Regions, and for males versus females.

The horizontal lines in Figs. 2 and 3 represent the threshold of prehypertension (SBP $\geq$ 120 or DBP $\geq$ 80 mm Hg) and illustrate the cohort-specific ages at which the SBP/DBP levels went beyond the threshold. Generally, men who belong to more recent cohorts became prehypertensive younger than men in earlier cohorts. Among men in the Coastal Region, for example, the 1931–1940 cohort reached 120 mm Hg in SBP and 80 mm Hg in DBP by about 52 and 55 years of age, respectively. But, the 1971–1980 cohort crossed the threshold about 20 years earlier. Among women in the Northeastern Region and Inland Region, however, the estimated SBP/DBP trajectories approximated the average age patterns of SBP/DBP estimated by Model 1 (the dashed line in Figs. 2, 3).

Table S8 of the Online Resource shows estimates from models without controlling for overweight status. By comparing results in Table S8 with estimates from Model 3 of Table 2, we found that adjusting for overweight status slightly reduced the magnitude of main effects of cohort and interactions between cohort and region. Also, excluding antihypertensive drug users did not alter the significant cohort variations in SBP/DBP trajectories and geographic differences in the cohort trend, although the magnitude of interactions between age and cohort and interactions between cohort and region attenuated (Online Resource Table S9). Additionally, after performing multiple imputations, the cohort effect on the intercepts and slopes of age became more pronounced, but the geographic variation in the cohort effect on the intercepts had a notable decrease (Online Resource Table S10). However, our major findings of cohort-based changes in SBP/DBP trajectories and more pronounced cohort effects in the Coastal and Southern Mountainous Regions remain largely unchanged.

Discussion

To our knowledge, our study is the first investigation of generational changes in longitudinal SBP/DBP trajectories by geographic region and sex. Except for women in the Northeast and Inland, we found an apparent upward shift in SBP/DBP trajectories across cohorts.

Our findings are inconsistent with the cohort trends observed in developed countries (e.g., Norway and the USA) that showed a downward trend or little cohort variation in SBP trajectories (Choh et al. 2011; Hopstock et al. 2015). However, they are consistent with evidence from Sardinia (Italy), an island that underwent rapid economic growth during the 1950–1960s (Pes et al. 2017). Those generations born after 1950 had a higher prevalence of all cancers than pretransition generations (Pes et al. 2017). Both the Sardinia study and our research suggest the adverse effects that socioeconomic transitions might have on risk profiles for non-communicable diseases, particularly for people who were born or grew up in the transition era.

Why do younger cohorts have higher SBP/DBP trajectories than older cohorts in China? With industrialization, urbanization, and globalization, China has undergone a nutrition transition characterized by a shift to energy-dense diets and physical inactivity (Popkin et al. 2012). However, the socioeconomic transitions' influences on cardiovascular risk profile are not equally distributed among generations and contingent upon the magnitude of exposure and susceptibility to these changes (Diderichsen et al. 2018). One the one hand, younger cohorts probably have had a greater amount of exposure to energy-dense foods and a more sedentary lifestyle. The cohort pattern observed in our study fits with an increase in BMI and a decrease in physical activity across cohorts observed in prior studies (Schafer and Kwon 2012; Zang and Ng 2016). However, our estimates suggested that adjusting for overweight status could not fully explain the rising SBP/DBP trajectories. Dietary patterns have been established as a critical determinant for hypertension (Gao et al. 2018). Generational differences in dietary patterns in China remain an underinvestigated issue, but there is some evidence that younger age groups have had a larger increase in snacking and eating away from home than older age groups from 1991 to 2011 (Zhai et al. 2014). On the other hand, younger cohorts have been exposed to the nutrition transition during earlier life stages that are probably more sensitive to environmental hazards for cardiovascular system development (Tiu et al. 2017), which may further contribute to a worsening cardiovascular risk profile across cohorts.

Over the observation period, many cohorts had reached the threshold for prehypertension, although they were still within the threshold for hypertension diagnosis (SBP $\geq$ 140 mm Hg or DBP $\geq$ 90 mm Hg). Importantly, prehypertension had occurred to younger cohorts at earlier ages relative to older cohorts, particularly for males and residents in the Coastal and Southern Mountainous Regions. As SBP/DBP in the prehypertension range was related to increased cardiovascular events (Gu et al. 2009; Huang et al. 2014), younger generations, with an earlier onset of prehypertension, would have a longer lifetime duration of being susceptible to CVDs.

But, younger cohorts had a lower increase rate in SBP/DBP with age than older cohorts, indicating an important

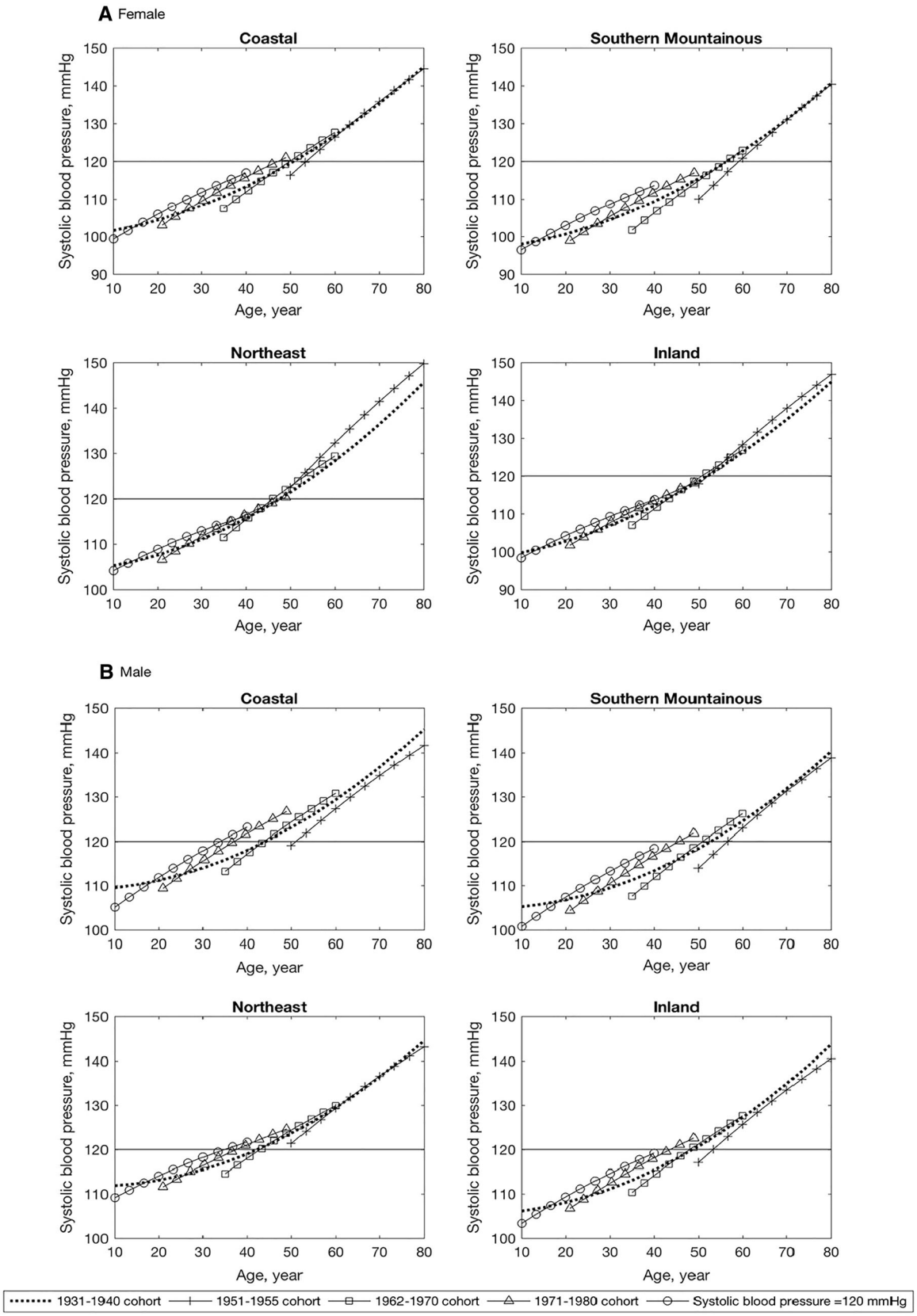

Fig. 2 Estimated trajectories of systolic blood pressure among females (**a**) and males (**b**) by birth cohort, region, and sex, China Health and Nutrition Survey (1991–2011)

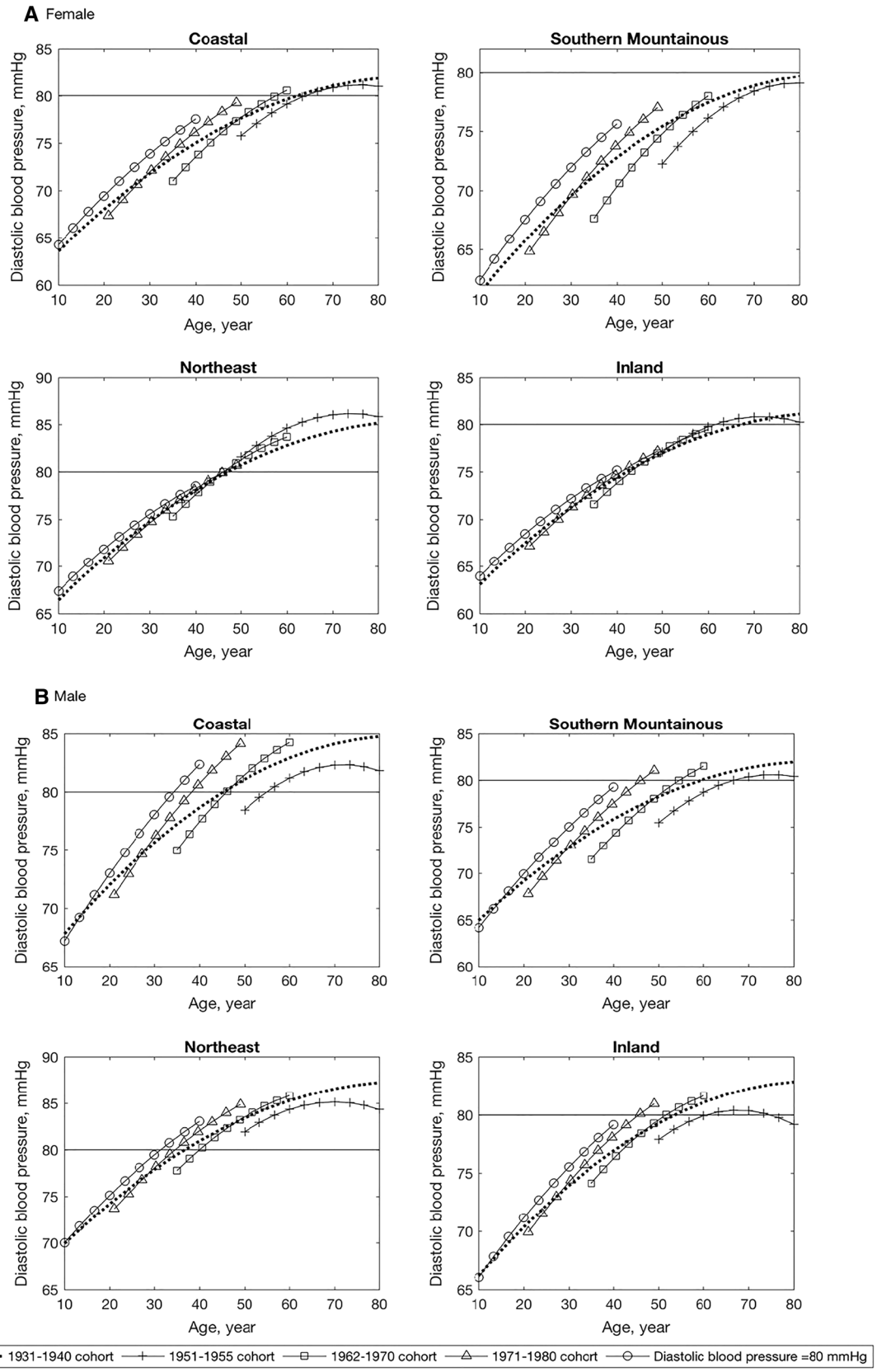

Fig. 3 Estimated trajectories of diastolic blood pressure among females (**a**) and males (**b**) by birth cohort, region, and sex, China Health and Nutrition Survey (1991–2011)

interaction between socioeconomic transitions and age-related decline in cardiovascular function. If the observed BP trajectories continue to the future, younger cohorts would have lower SBP/DBP levels in late adulthood and not necessarily reach the hypertension threshold earlier than older cohorts. While our findings could lead one to speculate that rapid economic growth is a distal risk factor for prehypertension, it might also slow the progression to hypertension. While more speculative still, it could be that economic prosperity produces unhealthy diets, a sedentary lifestyle, stress, and environmental pollution, while it also increases awareness of health hazards and availability of medical treatments that could delay the hypertension development.

In addition to clarifying generational differences in SBP/DBP trajectories, we also provide a richer look at how unbalanced economic growth and social development might be driving the cohort trends in cardiovascular risk profile. According to cross-sectional studies, the Northeast and Inland have a higher CVD burden than the other regions of China (Wang et al. 2017). However, our study found a narrowing gap in SBP/DBP levels among regions in the succession of cohorts as the Coastal and Southern Mountainous Regions had a larger cohort-based increase in the estimated levels of SBP/DBP at 44.5 years relative to the Northeastern and Inland Regions.

Since the economic reform, most economic growth has happened in the Coastal Region (Kanbur and Zhang 2005), with a subsequent increase in the prevalence of overweight and cardiovascular events (Ji and Cheng 2009), which fits with the Coastal Region's notable upward shift in SBP/DBP trajectories across cohorts. However, in the Southern Mountainous Region, a much less developed area, we also found an apparent upward shift. One possible explanation is that economic development and internal migration may have facilitated a convergence in diets and lifestyle and thus resulted in a 'catch-up growth' of SBP/DBP through the cohort turnover in the Coastal and Southern Mountainous Regions. Additionally, residents of the Southern Mountainous Region have less adequate access to quality health care (Huang et al. 2016), which is likely to have lasting adverse effects on cardiovascular function. For example, the numbers of physicians per 10,000 people in the Southern Mountainous Region were much lower than the national average (National Health Commission of the People's Republic of China 2017). Further studies are needed to investigate geographic differences in the nutrition transition and access to health care and their associations with the generational changes in SBP/DBP trajectories.

Finally, we found a more pronounced upward shift in SBP/DBP trajectories across cohorts in men than in women, a finding that is consistent with a global analysis that found a larger increase in the mean SBP/DBP from 1985–1994 to 2005–2016 in men than in women in the East and South East Asia Region that includes China (NCD Risk Factor Collaboration 2018). However, our finding is inconsistent with a prior study that found a greater rise in the BMI trajectory across cohorts in females than males in China (Schafer and Kwon 2012). The greater cohort effect on SBP/DBP trajectories of men may attribute to their greater exposure to risky behaviors like smoking. Evidence suggested that the prevalence of smoking decreased across cohorts in women but not in men, and men of younger generations started smoking at an earlier age (Chen et al. 2015). Sex differences in health care use might be another explanation as evidence showed that the treatment and control rates of hypertension were higher among females than males (Wang et al. 2014). However, how gender differences in health care utilization change through generational replacement and its association with the cohort trend in SBP/DBP trajectories need to be clarified.

Our study was subject to several limitations. Firstly, while geographically diverse, CHNS is not nationally representative. Therefore, our results are only generalizable to the nine provinces included in our study. Prior studies, however, have indicated that the characteristics of the CHNS sample are comparable to those from national samples (Du et al. 2002). Secondly, the observation period is only 20 years. Further follow-up surveys are needed to examine each cohort's future SBP/DBP trajectories. Thirdly, our analyses were based on place of residence at the time of the survey but did not account for differential patterns of movement. Individuals who migrate may be younger and healthier. Thus, at least a portion of the results is likely due to the selection of individuals into location rather than the effect of location. Finally, we did not estimate the period effect as age and period are perfectly collinear with the longitudinal data design. Further research could use a repeated cross-sectional data design to untangle age, period, and cohort effect on SBP/DBP.

Our study demonstrates differential impacts that socioeconomic transitions have on SBP/DBP trajectories of varied generations, geographic regions, and sex. In general, older cohorts are being replaced by cohorts with a worsening cardiovascular risk profile. In the long run, however, slower growth rates in SBP/DBP among younger cohorts provide hope of a reversal of the trend. Our study also identified the Coastal and Southern Mountainous Regions and males as the key target groups for interventions for the worrying cohort trend and highlighted the need for tailored interventions to tackle the generational-, regional-, and sex-based risk factors of CVDs.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was exempt from ethical approval because it was limited to the publicly available China Health and Nutrition Survey dataset that contained no personally identifiable information beyond birthdates.

Informed consent All participants provided informed consent before being enrolled in the China Health and Nutrition Survey.

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