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Original Report

Age-Specific Association Between Visit-to-Visit Blood Pressure Variability and Hearing Loss: A Population-Based Cohort Study

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Abstract

Background and Objectives: Hearing loss is common and undertreated, and the impact of blood pressure variability (BPV) on the development of hearing loss remains unclear. We aimed to examine the age-specific association between visit-to-visit BPV and hearing loss.

Research Design and Methods: This nationally representative cohort study included 3,939 adults over 50 years from the Health and Retirement Study in the United States. Variabilities of systolic blood pressure (SBP) and diastolic blood pressure (DBP) were assessed by standard deviation (*SD*), coefficient of variation, and variability independent of the mean (VIM), using SBP and DBP from 3 visits. Hearing loss was assessed by self-rated questions. Cox proportional risk models were used to evaluate age-specific associations (50–64, 65–79, and ≥80 years) between BPV and hearing loss. The generalized additive Cox models were further used to visualize the combined effect of age and BPV.

Results: During the follow-up up to 7.0 years, 700 participants developed hearing loss. Among people aged under 65 years, we observed a 36% increased risk of hearing loss with per-*SD* increment in VIM of SBP (hazard ratio [HR] per *SD* 1.36, 95% confidence interval [CI] 1.13–1.63) and a slightly significant association between VIM of DBP (HR per *SD* 1.21, 95% CI 1.01–1.45) and hearing loss. We did not observe significant associations among groups aged over 65 years ($p > .05$). The generalized additive Cox models also showed younger participants had stronger associations between BPV and hearing loss.

Discussion and Implications: Higher visit-to-visit variabilities of SBP were associated with an increased risk of hearing loss in middle-aged adults (50–65 years). Intervention in early BPV may help decrease hearing loss in adults aged over 50 years.

Translational Significance: It remains unclear whether and how visit-to-visit blood pressure variability (BPV) and hearing loss is associated among different age groups. The study results showed an increased risk of hearing loss with per standard deviation increment in variability independent of the mean of systolic blood pressure among people aged under 65 years. It is necessary to consider BPV in routine blood pressure management, especially SBP variability. Early intervention in BPV may reduce the risk of hearing loss and improve health status in middle-aged and older adults over 50 years.

Keywords: Blood pressure, Generalized Cox additive model, Hearing health, Visit-to-visit variability

Background and Objectives

Hearing loss is one of the most prevalent disabilities worldwide yet undertreated (Cunningham & Tucci, 2017; Nieman & Oh, 2020). The prevalence of hearing loss increases with age, and studies among the American population showed the prevalence of hearing loss up to 63.1% in people over 70 years old (Lin et al., 2011). Hearing loss can notably affect how people age (Nieman & Oh, 2020). Researchers have found hearing loss was associated with physical and psychological morbidity, such as frailty, falls, loneliness, social isolation, depression, cognitive decline, and dementia (Gopinath et al., 2016; Liljas et al., 2017; Lin et al., 2013; Rutherford et al., 2018; Wang et al., 2022). Considering its high prevalence and adverse outcomes, exploring potential risk factors of hearing loss may be helpful in improving the hearing and health conditions of middle-aged and older adults.

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Blood pressure variability (BPV), defined as the extent of blood pressure fluctuation over a period, is increasingly viewed as a potential risk factor independent of blood pressure level (Bao et al., 2019). Visit-to-visit BPV has been found to be associated with various adverse events, including cardiovascular outcomes, cognitive decline, stroke, and mortality (Heshmatollah et al., 2022; Rothwell et al., 2010; Sabayan et al., 2013; Stevens et al., 2016). Potential mechanisms may be high BPV can induce arterial stiffness, inflammation, hypoperfusion, and brain structural changes (Brickman et al., 2010; Kim et al., 2008; Ma et al., 2020; Tedla et al., 2017). The above mechanisms may also prompt apoptosis of hair cells, cochlear impairment, and even affect central auditory processing (Chen et al., 2022; Fujioka et al., 2006; Griffiths, 2002; Watson et al., 2017). So high BPV may also be a risk factor for hearing loss. However, population-based evidence of the association between BPV and hearing loss is limited. A previous study indicated BPV was associated with hearing loss, yet the cross-sectional association was only observed among Chinese male coal miners (Bao et al., 2019). In addition, several researchers found the effects of BPV varied in different age groups (de Heus et al., 2021; Rapsomaniki et al., 2014; Wan et al., 2021). Thus, more longitudinal evidence among the general population is needed to determine the age-specific associations between BPV and hearing loss.

In this national cohort study, we explored the age-specific associations between visit-to-visit BPV and the risk of hearing loss among individuals aged over 50 years in the United States. We hypothesized that the effect of BPV on hearing loss varies with age and that variabilities of systolic blood pressure (SBP) have a stronger effect than variabilities of diastolic blood pressure (DBP). Cox proportional risk models in different age groups and the generalized additive Cox models taking age as a continuous variable were used to fully analyze the age-specific associations.

Research Design and Methods

Study Population

This study is based on the Health and Retirement Study (HRS), which is a nationally representative survey of individuals aged over 50 years in the United States (Sonnega et al., 2014). Core interviews of participants in the HRS were followed-up every 2 years through face-to-face interviews or by telephone. Since 2006 (Wave 8), half of the sample has been assigned an enhanced face-to-face interview including physical measures, and the other half completed physical measures in 2008 (Wave 9). That is to say, the physical measures of respondents were followed-up every 4 years at the individual level. Both half-samples kept national representativity. Other details of HRS have been stated previously (Sonnega et al., 2014). The HRS is sponsored by the National Institute on Aging (grant number NIA U01AG009740) and is conducted by the University of Michigan. All participants provided informed consent on their entry.

This study used survey data from 2006 (Wave 8) to 2020 (Wave 15). To assess BPV, we included 7,157 participants who finished 3 blood pressure assessments during Waves 8, 10, 12 or Waves 9, 11, 13. At each wave, the blood pressure of each respondent was measured at least twice. Individuals with abnormal blood pressure data ($n = 15$), missing hearing evaluation or hearing loss ($n = 2581$), and missing or abnormal covariates ($n = 245$) were excluded. The remaining participants were followed-up every 2 years to assess hearing loss and those without at least one evaluation during follow-up were further excluded ($n = 377$). Finally, 3,939 respondents were included in the analysis (Figure 1).

Blood Pressure Variability

BPV was evaluated using three blood pressure assessments during Waves 8, 10, 12 or Waves 9, 11, 13. During each assessment, participants were asked to relax and remain seated and quiet, and blood pressure was measured three times at the left upper arm using the Omron HEM-780N Monitor. If a participant only finished measurements twice, blood pressure was calculated as the mean of the two readings. Otherwise, blood pressure was calculated as the mean of the last two readings (Li et al., 2022; Mahinrad et al., 2020).

We chose three widely used parameters to assess intraindividual visit-to-visit BPV: standard deviation (*SD*), coefficient of variation (CV), and variability independent of the mean (VIM; Li et al., 2021; Rothwell et al., 2010). *SD* was calculated as $\sqrt{\sum_1^3 (\mathrm{BP}_i - \mathrm{mean})^2/2}$, where BP_i was the value of BP at a single assessment and mean was calculated as the average of three BP assessments. CV was defined as *SD*/mean. VIM was calculated as $\mathrm{MEAN}^p \times SD/\mathrm{mean}^p$, where MEAN is the mean blood pressure of the sample, and mean is the intraindividual parameter as well as *SD*. Parameter p equals the regression coefficient of nonlinear regression of intraindividual *SD* over mean (Nwabuo et al., 2020; Yano, 2017). Blood pressure variabilities of SBP and DBP were calculated separately.

Hearing Loss

Hearing ability was evaluated every 2 years based on two items: "Do you ever wear a hearing aid?" and "Is your hearing excellent, very good, good, fair, or poor (using a hearing aid as usual)?" Hearing loss was defined as reporting hearing aid use or fair or poor hearing (McKee et al., 2019). According to previous studies, the sensitivity of the self-reported question ranged from 43.0% to 81.5%, and the specificity ranged from 76.4% to 93% (Ferrite et al., 2011; Nondahl et al., 1998).

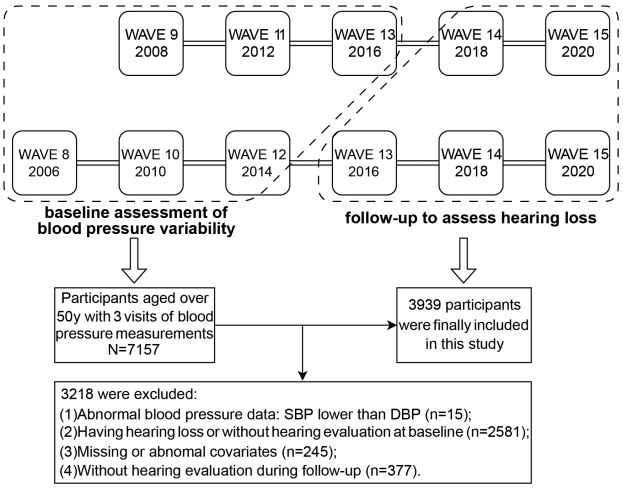

Figure 1. Study design and recruitment of study population. SBP = systolic blood pressure; DBP = diastolic blood pressure.

Covariates

Covariates were obtained during the baseline blood pressure measurements. Demographic characteristics, lifestyle factors, body mass index (BMI), antihypertension medication use and personal history of diabetes, high cholesterol, and cardiovascular diseases (CVD) were collected and included in the analyses. Demographic characteristics included age, gender, race (non-Hispanic White, non-Hispanic Black, Hispanic, and other), marital status (married or not), and educational level (less than upper secondary education, upper secondary/vocational training, and tertiary education). Lifestyle factors included smoking (nonsmokers, previous smokers, current smokers), drinking (never, less than once per week, no less than once per week), and physical activity (vigorous or moderate activities at least once per week or not). BMI was calculated as weight (kg) divided by the square of height (m). As for antihypertension medication use, participants with self-reported hypertension were then asked whether they were taking any medication to lower blood pressure, and over 99% of them answered the question with "yes" or "no." Participants who answered "yes" were considered antihypertension medication users, whereas the others were considered not. Diabetes was defined as reporting a physician-confirmed diagnosis or using medications for diabetes. Personal history of high cholesterol and CVD (including heart attack, coronary heart disease, angina, congestive heart failure, or other heart problems) were confirmed by self-reporting diagnoses from physicians.

Statistical Analysis

The baseline characteristics of participants were described using median (IQR) for continuous variables and numbers (percentage) for categorical variables. Differences among different age groups (50–64, 65–79, and ≥80 years old) were tested using Kruskal–Wallis or Chi-square tests.

Cox proportion hazards models were used to explore the age-specific association between BPV and hearing loss. Blood pressure variabilities were analyzed as continuous variables, and HRs for per-*SD* change of each parameter and 95% confidence intervals (95% CIs) were estimated. The proportional hazards assumption was tested using Schoenfeld residuals (Grambsch & Therneau, 1994). Individual average SBP or DBP, age, gender, race, marital status, educational level, antihypertensive medication use, diabetes, high cholesterol, CVD, smoking, drinking, physical activity, and BMI were adjusted. To further explore whether the association of BPV and hearing loss varied among people with different characteristics, subgroup analysis was taken.

Generalized additive Cox models were also used to further explore the association between BPV and hearing loss at different ages. Bivariate exposure–response models were chosen to take both BPV and age into account as continuous variables (Wang et al., 2017). The bivariate model was as follows:

$$\begin{aligned}\ln\frac{h(t,X)}{h_0(t)} = {} & s(\text{BPV},\ \text{age}) + \beta_1 \times \text{SBP/DBP} + \beta_2 \times \text{gender} \\ & + \beta_3 \times \text{race} + \beta_4 \times \text{marriage} + \beta_5 \times \text{education} \\ & + \beta_6 \times \text{antihypertension} + \beta_7 \times \text{diabetes} \\ & + \beta_8 \times \text{cholesterol} + \beta_9 \times \text{CVD} + \beta_{10} \times \text{smoking} \\ & + \beta_{11} \times \text{drinking} + \beta_{12} \times \text{exercise} + \beta_{13} \times \text{BMI}\end{aligned}$$

where $h(t, X)$ was the hazard function at moment t in the presence of factor X, and $h_0(t)$ was the baseline function at moment t. BPV and age were included in the model as continuous variables in the form of bivariate smoothing functions as the term s(BPV, age). Other terms represented adjusted factors stated in the Cox proportion hazards models. Results were visualized as surface plots. To avoid minimal sample sizes and better estimate the effect of BPV, we further excluded the population whose BPV was 1% largest while the range was approximately equal to the range of the remaining 99%, and analyzed 3,899 participants in the generalized additive Cox models.

Sensitivity analysis excluded the population who only finished the first follow-up to guard against the potential reverse causality. We also examined the age-specific association among participants who never used antihypertensive medication and had average blood pressure <140/90 mmHg, to eliminate the potential effects of antihypertensive medication and high average blood pressure level.

All analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC) and R 4.2.2 (R Foundation for Statistical Computing). Two-sided tests were used and $p < .05$ was considered as statistically significant.

Results

Basic Characteristics

Of 3,939 participants without hearing loss, the mean age was 71.4 years old and 2,619 (66.5%) were women. The average SBP in this population was 127.5 mmHg, and the mean DBP was 77.8 mmHg; 2,377 (60.3%) used antihypertensive medication. Visit-to-visit individual BPV and other baseline characteristics can be seen in Table 1.

Compared with participants under 65 years old, older adults were more likely to be non-Hispanic White, have a low educational level, use antihypertensive medication, have a history of diabetes and CVD, and lack physical activities.

During the 17,617.7 person-years of follow-up, 700 (17.8%) participants developed hearing loss. Overall, people tended to have a higher cumulative incidence of hearing loss as age increased.

Age-Specific Association Between BPV and Hearing Loss

In the group under 65 years old, higher variabilities of SBP were associated with an increased risk of hearing loss. The results were similar among *SD* (HR for per-*SD* increase 1.42, 95% CI 1.15–1.76), CV (HR per *SD* 1.38, 95% CI 1.14–1.67), and VIM (HR per *SD* 1.36, 95% CI 1.13–1.63). Variabilities of DBP were also associated with hearing loss in the group under 65 years old while the lower limits of 95% CI were close to 1.00, including *SD* (HR for per *SD* increase: 1.22, 95% CI: 1.02–1.47), CV (HR per *SD* 1.21, 95% CI 1.01–1.45), VIM (HR per *SD* 1.21, 95% CI 1.01–1.45). When focused on groups aged over 65 years, we did not observe significant associations between blood pressure variabilities and hearing loss either using the variation of SBP or DBP, with HRs close to 1.00 and 95% CIs cross 1.00 (Table 2).

Table 3 shows the results of subgroup analysis by baseline characteristics among people under 65 years old. For per-*SD* increment of SBP VIM, the risk of hearing loss increased significantly from 25% to 95% among all selected subgroups, except people with high cholesterol (HR per *SD* 1.25, 95% CI 0.94–1.65). However, for DBP, per-*SD* increment of VIM was not statistically significantly associated with the risk of

Table 1. Baseline Characteristics of Participants by Age[a]

Characteristic	Total, *N* = 3,939	Age groups			*p*
		50–64 years, *n* = 902	65–79 years, *n* = 2,330	≥80 years, *n* = 707	
Hearing loss	700 (17.8)	99 (11.0)	404 (17.3)	197 (27.9)	<.001
Visit-to-visit individual BPV					
SD of SBP, mmHg	10.3 (9.3)	8.9 (7.7)	10.3 (9.3)	11.8 (10.3)	<.001
SD of DBP, mmHg	6.5 (5.2)	6.1 (4.9)	6.5 (5.2)	6.9 (5.8)	.005
CV of SBP, %	8.1 (7.0)	7.2 (6.0)	8.1 (7.0)	9.0 (7.8)	<.001
CV of DBP, %	8.3 (6.7)	7.8 (6.1)	8.3 (6.6)	9.2 (7.2)	<.001
VIM of SBP, mmHg	10.5 (8.9)	9.6 (7.8)	10.5 (8.9)	11.4 (9.9)	<.001
VIM of DBP, mmHg	6.5 (5.2)	6.1 (4.7)	6.5 (5.2)	7.3 (5.6)	<.001
SBP, mmHg	127.5 (20.2)	121.5 (20.1)	128.0 (19.2)	132.5 (18.9)	<.001
DBP, mmHg	77.8 (11.8)	78.8 (12.6)	78.0 (11.3)	75.7 (11.8)	<.001
Gender					.055
Male	1,320 (33.5)	278 (30.8)	815 (35.0)	227 (32.1)	
Female	2,619 (66.5)	624 (69.2)	1,515 (65.0)	480 (67.9)	
Race/ethnicity					<.001
Non-Hispanic White	3,040 (77.2)	641 (71.1)	1,803 (77.4)	596 (84.3)	
Non-Hispanic Black	513 (13.0)	134 (14.9)	307 (13.2)	72 (10.2)	
Hispanic	285 (7.2)	95 (10.5)	162 (7.0)	28 (4.0)	
Other	101 (2.6)	32 (3.5)	58 (2.5)	11 (1.6)	
Married	2,384 (60.5)	637 (70.6)	1,442 (61.9)	305 (43.1)	<.001
Educational level					<.001
Less than upper secondary education	418 (10.6)	71 (7.9)	248 (10.6)	99 (14.0)	
Upper secondary/vocational training	2,208 (56.1)	460 (51.0)	1,318 (56.6)	430 (60.8)	
Tertiary education	1,313 (33.3)	371 (41.1)	764 (32.8)	178 (25.2)	
Using antihypertensive medication	2,377 (60.3)	399 (44.2)	1,463 (62.8)	515 (72.8)	<.001
Diabetes	906 (23.0)	160 (17.7)	586 (25.2)	160 (22.6)	<.001
High cholesterol	1,732 (44.0)	386 (42.8)	1,075 (46.1)	271 (38.3)	.001
CVD	1,003 (25.5)	123 (13.6)	622 (26.7)	258 (36.5)	<.001
Smoking					<.001
Nonsmokers	1,932 (49.0)	453 (50.2)	1,106 (47.5)	373 (52.8)	
Previous smokers	1,659 (42.1)	314 (34.8)	1,030 (44.2)	315 (44.6)	
Current smokers	348 (8.8)	135 (15.0)	194 (8.3)	19 (2.7)	
Drinking					<.001
Never	1,618 (41.1)	281 (31.2)	987 (42.4)	350 (49.5)	
Less than once per week	697 (17.7)	164 (18.2)	422 (18.1)	111 (15.7)	
More than once per week	1,624 (41.2)	457 (50.7)	921 (39.5)	246 (34.8)	
Physical activity	2,805 (71.2)	694 (76.9)	1,679 (72.1)	432 (61.1)	<.001
BMI, kg/m^2	28.8 (7.4)	29.0 (7.8)	29.1 (7.4)	27.6 (6.4)	<.001

Notes: BMI = body mass index; BPV = blood pressure variability; CV = coefficient of variation; CVD = cardiovascular diseases; DBP = diastolic blood pressure; IQR = interquartile range; SBP = systolic blood pressure; *SD* = standard deviation; VIM = variability independent of the mean.
[a]Continuous data were expressed as median (IQR), and categorical data were expressed as *n* (%).

hearing loss when stratified by gender, CVD, antihypertension medication use, smoke status, and physical activity. Different effects of VIM were observed in terms of diabetes (HR per *SD* 1.97, 95% CI 1.30–2.99 in having diabetes versus HR per *SD* 1.09, 95% CI 0.88–1.36 in not) and cholesterol level (HR per *SD* 1.14, 95% CI 0.85–1.53 in high versus HR per *SD* 1.30, 95% CI 1.01–1.66 in normal) and drink status (HR per *SD* 1.13, 95% CI 0.87–1.46 in ever vs HR per *SD* 1.41, 95% CI 1.07–1.87 in never). Results remained consistent when using *SD* and CV as BPV metrics (Supplementary Tables 1 and 2).

Among people over 65 years old (Supplementary Tables 3–8), the associations of SBP/DBP variability and hearing loss were not statistically significant among all selected subgroups (except for the subgroup who never smoke with HR for per-*SD* increase of CV, 1.17, 95% CI 1.00–1.37; VIM 1.18, 95% CI 1.01–1.38), similar to the results of the total population.

Bivariate Exposure–Response Models

Figure 2 visually showed associations between BPV and hearing loss considering the separate and combined effect of age and BPV, which demonstrated consistent results with Table 2. The risk of hearing loss increased with age regardless of the level of BPV. The magnitude of slopes between blood pressure variabilities and hearing loss changed with age, and steeper

Table 2. Association Between Visit-to-Visit Individual BPV and Hearing Loss by Age (n = 3,939)

Subgroups	*n*	Case	Rate/per 1,000 person-years	Adjusted HR for per-*SD* increase (95% CI)[a]		
				SD	CV	VIM
SBP						
50–65	902	99	22.31	**1.42 (1.15–1.76)**	**1.38 (1.14–1.67)**	**1.36 (1.13–1.63)**
65–80	2,330	404	38.43	1.03 (0.92–1.15)	1.03 (0.93–1.14)	1.03 (0.93–1.15)
≥80	707	197	73.86	1.02 (0.90–1.15)	1.02 (0.90–1.15)	1.02 (0.90–1.16)
DBP						
50–65	902	99	22.31	**1.22 (1.02–1.47)**	**1.21 (1.01–1.45)**	**1.21 (1.01–1.45)**
65–80	2,330	404	38.43	0.98 (0.88–1.08)	0.97 (0.87–1.08)	0.97 (0.87–1.08)
≥80	707	197	73.86	1.03 (0.90–1.18)	1.04 (0.91–1.18)	1.04 (0.91–1.18)

Notes: BPV = blood pressure variability; CV = coefficient of variation; DBP = diastolic blood pressure; HR = hazard ratio; SBP = systolic blood pressure; *SD* = standard deviation; VIM = variability independent of the mean.
[a]Multivariate Cox proportional regression models were used for all assessments. Individual average SBP or DBP, gender, race/ethnicity, marital status, educational level, antihypertensive medication use, diabetes, high cholesterol, cardiovascular diseases, smoking, drinking, physical activity, and body mass index were adjusted. Statistically significant results are in bold ($p < .05$).

Table 3. Association Between Variability Independent of the Mean (VIM) and Hearing Loss by Baseline Characteristics Among Population Aged Under 65 Years (n = 902)

Subgroups	*n*	Case	Rate/per 1,000 person-years	Adjusted HR for per-*SD* increase (95% CI)[a]	
				SBP	DBP
Gender					
Male	278	34	24.55	**1.56 (1.09–2.24)**	1.18 (0.80–1.74)
Female	624	65	21.30	**1.28 (1.01–1.61)**	1.21 (0.97–1.52)
Diabetes					
Yes	160	28	35.89	**1.80 (1.20–2.69)**	**1.97 (1.30–2.99)**
No	742	71	19.42	**1.25 (1.00–1.56)**	1.09 (0.88–1.36)
High cholesterol					
Yes	386	42	21.80	1.25 (0.94–1.65)	1.14 (0.85–1.53)
No	516	57	22.71	**1.48 (1.14–1.93)**	**1.30 (1.01–1.66)**
CVD					
Yes	123	18	30.93	**1.95 (1.20–3.16)**	1.35 (0.90–2.02)
No	779	81	21.01	**1.29 (1.05–1.60)**	1.23 (0.99–1.52)
Antihypertension medication use					
Yes	399	52	26.98	**1.33 (1.05–1.69)**	1.21 (0.96–1.52)
No	503	47	18.73	**1.56 (1.13–2.14)**	1.25 (0.91–1.71)
Smoking					
Yes	449	52	23.63	**1.42 (1.11–1.83)**	1.26 (0.98–1.61)
No	453	47	21.02	**1.43 (1.07–1.91)**	1.19 (0.88–1.60)
Drinking					
Yes	621	58	18.82	**1.31 (1.01–1.71)**	1.13 (0.87–1.46)
No	281	41	30.28	**1.47 (1.12–1.94)**	**1.41 (1.07–1.87)**
Physical activity					
Yes	694	73	21.45	**1.31 (1.04–1.65)**	1.19 (0.95–1.48)
No	208	26	25.18	**1.61 (1.11–2.33)**	1.36 (0.92–2.01)

Notes: CVD = cardiovascular diseases; DBP = diastolic blood pressure; HR = hazard ratio; SBP = systolic blood pressure; *SD* = standard deviation.
[a]Multivariate Cox proportional regression models were used for all assessments. Individual average SBP or DBP, gender, race/ethnicity, marital status, educational level, antihypertensive medication use, diabetes, high cholesterol, CVD, smoking, drinking, physical activity, and body mass index were adjusted excluding the strata variable. Statistically significant results are in bold ($p < .05$).

slopes were observed at younger than older ages. Slopes of the bivariate surface plots were greater using the variation of SBP rather than DBP, which means the risk of hearing loss increased more rapidly as SBP variability rose.

Sensitivity Analyses

After excluding the population who only finished the first follow-up (n = 752), the results stayed similar with the whole population (Supplementary Table 9). Only

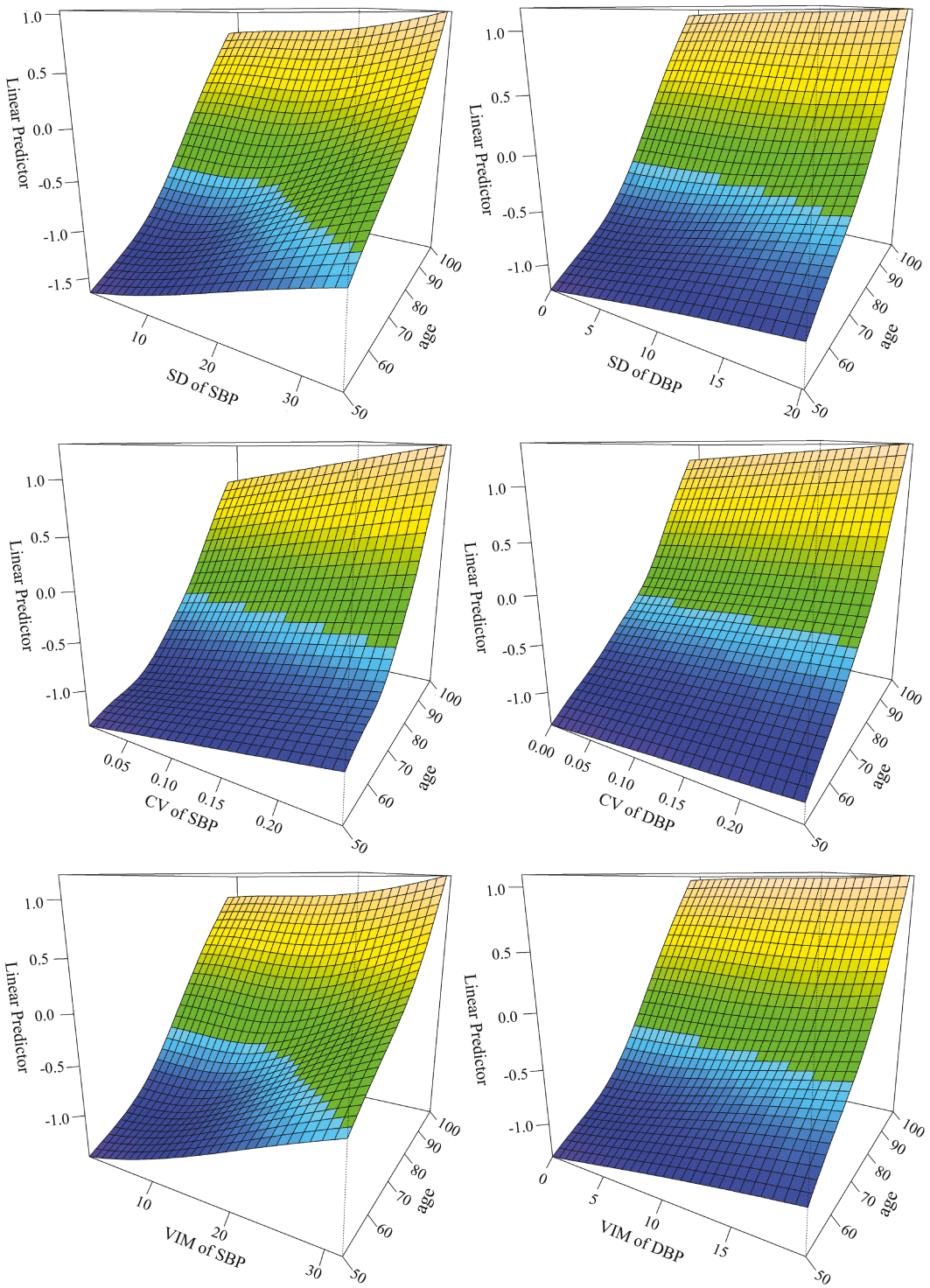

Figure 2. Bivariate exposure–response surface plots of age and BPV (*SD*, CV, VIM) (n = 3,899).

[a] *Notes*: BPV = blood pressure variability; CV = coefficient of variation; DBP = diastolic blood pressure; *SD* = standard deviation; VIM = variability independent of the mean.

[a]Excluded participants whose BPV was in the largest 1%. Adjusted for individual average SBP or DBP, gender, race/ethnicity, marital status, educational level, antihypertensive medication use, diabetes, high cholesterol, cardiovascular diseases, smoking, drinking, physical activity, and body mass index.

variabilities of SBP were associated with hearing loss in the population aged below 65. We further conducted the analysis among people without antihypertensive medication use and abnormal blood pressure (≥140/90 mmHg), and the associations did not change (n = 1,355), as seen in Supplementary Table 10.

Discussion and Implications

This longitudinal study found that the association between BPV and hearing loss differed in SBP/DBP and different age groups. A larger visit-to-visit variation in SBP was associated with an increased risk of hearing loss among the middle-aged population after adjusting for mean blood pressure levels,

antihypertensive medication use, and other confounders. Although among people aged over 65 years, the association was not statistically significant. We did not observe a consistent association between DBP variability and hearing loss. Bivariate exposure–response models and additional sensitivity analyses with a lag period and among participants without antihypertensive medication and high average blood pressure (≥140/90 mmHg) supported the above associations.

Visit-to-visit BPV is a reproducible indicator to reflect long-term cardiovascular burden (Muntner et al., 2011; Parati et al., 2013). Vascular and cerebral damage may impair the function of peripheral and central auditory pathways (Hull & Kerschen, 2010; Jafari et al., 2021; Ting et al., 2022), resulting in hearing loss. Our study evaluated the association between BPV and hearing loss and found a stable association between the increasing variation of SBP and a higher risk of hearing loss among people under 65 years old. Subgroup and additional sensitivity analyses yielded consistent results. A previous population-based study also demonstrated a similar association. The cross-sectional study among Chinese men also found a positive association between SBP variability and the risk of hearing loss at intermediate and high frequencies (Bao et al., 2019). Our results provided additional evidence for women and longitudinal associations. Some potential mechanisms have been proposed. SBP variability is positively related to inflammatory markers, and inflammation may result in hair cell apoptosis and cochlear impairment (Chen et al., 2022; Fujioka et al., 2006; Kim et al., 2008). Moreover, high variability reflects repeated fluctuations in blood flow, which can induce arterial stiffness and inadequate blood flow (Brickman et al., 2010; Tedla et al., 2017), affecting homeostasis of the cochlear blood supply. Cochlear ischemia and hypoxia will cumulate oxidative stress and cellular necrosis, impairing the cochlear ability to deal with peripheral auditory signals (Bao et al., 2019; Brickman et al., 2010). In addition to peripheral lesions, variability of SBP also impacts cerebrovascular blood supply and induces brain structural changes and cerebral small vessel disease, which may affect central auditory pathways (Griffiths, 2002; Heshmatollah et al., 2022; Ma et al., 2020).

We did not observe an association between variability and hearing loss among older adults, suggesting the associations between variability and hearing loss differed by age. Two previous studies found the effects of BPV on cardiovascular diseases were higher in younger age groups compared to older age groups (Rapsomaniki et al., 2014; Wan et al., 2021), and a meta-analysis on dementia and cognitive impairment also found the odds ratio of systolic BPV in the age group below 60 years old was higher than that in the age group from 60 to 80 years old (de Heus et al., 2021), supporting our hypothesis that the effect of BPV varied in different ages. The age-specific effects may result from the following reasons. First of all, BPV in older adults may be less significant for subsequent health outcomes compared to BPV in earlier life. The above research showed stronger effects of BPV in lower age groups (de Heus et al., 2021; Rapsomaniki et al., 2014; Rouch et al., 2021). A study among the population aged 62.9 ± 5.7 years old did not observe the association between residual *SD* of SBP and cardiovascular events (de Havenon et al., 2021). The relationships between VIM and total mortality and all cardiovascular events were not statistically significant among the Belgian over 60 years old either (Schutte et al., 2012). However, many researchers demonstrated blood pressure variation was a modifiable risk factor for morbidity and mortality among older adults (Mallamaci et al., 2019; Rouch et al., 2021; Sabayan et al., 2013; Wan et al., 2021). The statistically nonsignificant finding in our study may also be potentially attributed to age-specific distributions of risk factors. Age and diabetes are both vital risk factors for hearing loss (Bowl & Dawson, 2019; Nieman & Oh, 2020) and the proportion of people with diabetes is higher in the older population, which may overshadow the association between blood pressure variation and hearing loss. Visit-to-visit BPV may have a relatively distant effect, so our study with only 4–6 years of follow-up may be not long enough to observe the effect comprehensively. A larger population with longer-term follow-up is needed in the future to further clarify the association between BPV and hearing loss at different ages.

Although we found a slightly significant association between DBP variability and hearing loss among people under 65 years old, the association was not statistically significant when we conducted subgroup and additional sensitivity analyses. A previous study among Chinese men also did not observe an association between DBP variation and hearing loss (Bao et al., 2019). Several previous studies on BPV and other outcomes had also not found an association between DBP variability and outcomes. A multicentered study found an association between BPV and adverse cardiovascular events only in SBP rather than DBP (Clark et al., 2019). Another study in France and Monaco also stated DBP variability was not significantly associated with incident frailty (Rouch et al., 2021), although in some studies regarding depression and cognitive function, DBP variability showed effects on these outcomes, even more significant than SBP variability (de Heus et al., 2021; Sible et al., 2022). The variation of SBP and DBP may have different mechanisms and relate to different outcomes (Sible et al., 2022). Our results showed that SBP variability may be a more important predictor of hearing loss compared to DBP variability. Further evidence is needed to confirm the mechanisms of SBP and DBP variability and their relationship with hearing loss.

Several limitations of this study need to be considered. First, this study only enrolled a population over 50 years old in the United States, which may restrict the applicability of our findings to younger or other ethnic populations. However, the prevalence of hearing loss among people under 50 years old is relatively low (Goman & Lin, 2016), whereas exploring and controlling risk factors among middle-aged and older people may have greater public health significance. Moreover, office blood pressure measurements used in our study may have the white-coat effect and may be less stable and consistent compared to home blood pressure monitoring. However, home blood pressure monitoring in this nationally representative survey is infeasible. All the blood pressure assessment procedures were in accordance with the recommendations of the American Medical Association and the American Heart Association, which may be more vital to the accuracy and reliability of blood pressure readings (Boonyasai et al., 2017; Pickering et al., 2005). In addition, hearing loss in our study is assessed using self-rated questions, not measured hearing thresholds, which may affect accuracy and cannot distinguish between presbycusis and other forms of hearing loss. However, several researchers have used the self-rated question to define hearing loss with proven accuracy (Feltner et al., 2021; McKee et al., 2019; Sindhusake et al., 2001; Tsimpida et al., 2022; Wang et al., 2022).

Furthermore, noise exposure is an important risk factor for hearing loss (Nieman & Oh, 2020), and noise exposure may also relate to blood pressure (Lee et al., 2019; Tomei et al., 2010), yet we lacked relative data to evaluate and control noise exposure in our population. Instead, we calculated the *e*-value to evaluate the potential influence of noise exposure. Based on the HR estimate of three indicators, the *e*-value in this study was about 1.8, which means the risk ratios of both noise exposure–hearing loss and noise exposure–BPV need to be at least 1.8 to fully explain our observed association between BPV and hearing loss (VanderWeele & Ding, 2017). A study among the national population in the United States estimated the odds ratio of noise exposure and hearing threshold shift as 1.29 (Mahboubi et al., 2013), which means our findings are relatively reliable even without controlling noise exposure.

This study analyzed population-based data to explore the age-specific association between BPV and hearing loss. We estimated BPV over about 8 years and then followed hearing loss in a population free of hearing loss at baseline, which enhanced the causal relationship. We further applied the generalized additive Cox model and took age into account as a continuous variable, exploring the age-specific effects of BPV more comprehensively. Additional subgroup and sensitivity analyses enhanced the reliability of our findings.

Above all, our analysis showed consistent results that SBP variability was associated with hearing loss in a middle-aged population, rather than DBP variability or in the population aging over 65 years old. These findings stress the necessity of considering BPV in routine blood pressure management, especially SBP variability. Further studies are needed to further demonstrate the association, confirm the potential mechanism between BPV and hearing loss, explore possible interventions, and whether BPV interventions could improve hearing loss.

Conclusion

In conclusion, we observed the age-specific association and found that SBP variability was associated with hearing loss in a middle-aged population (50–65 years). Our results provide further evidence for the age-specific risk factors of hearing loss and expand the results of visit-to-visit BPV on adverse outcomes, suggesting that assessing BPV in routine practice may be essential and intervention in early BPV may reduce the risk of hearing loss in middle-aged and older adults over the age of 50.

Supplementary Material

Supplementary data are available at *Innovation in Aging* online.

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Conflict of Interest

None.

Data Availability

This study was not preregistered. Publicly available data sets were used in this study. The data can be found at: https://hrs-data.isr.umich.edu/data-products/public-survey-data

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