

Age-Related Blood Pressure Trajectories Across Sex and Body Mass Index Categories: A Retrospective Study

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Abstract:

Background: Hypertension is a major modifiable cardiovascular risk factor, and blood pressure patterns vary with advancing age, sex, and adiposity. Understanding these trajectories is important for identifying populations at increased cardiovascular risk.

Aim: To evaluate age-related trajectories of systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse pressure across sex and body mass index (BMI) categories among adults in Bihar, India.

Methodology: This retrospective observational study included 177 adults (90 males and 87 females) attending Government Medical College, Bettiah, Bihar, India from April 2023 to March 2024. Demographic, anthropometric, and blood pressure data were retrieved from institutional records. Participants were categorized according to BMI. Age-related SBP and DBP trajectories were assessed using LOWESS regression, while quadratic regression was used to estimate the age of peak DBP.

Results: SBP increased progressively with age in both males and females, while DBP increased during adulthood before showing a decline in older age. Pulse pressure widened with advancing age. Both SBP and DBP increased progressively across higher BMI categories. Hypertension prevalence generally increased with advancing age and higher BMI. The estimated DBP peak occurred predominantly around the early 60s, with some variation according to sex and BMI. Similar trajectory patterns persisted after exclusion of participants receiving antihypertensive treatment.

Conclusion: Blood pressure trajectories demonstrate important age- and BMI-related variations, emphasizing the value of considering age, sex, and adiposity together during cardiovascular risk assessment and blood pressure monitoring.

Keywords: Age; Blood pressure; Hypertension; Body mass index; Systolic blood pressure; Diastolic blood pressure; Pulse pressure; Sex differences; LOWESS; Bihar.

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Introduction

Hypertension is a critical modifiable risk factor for cardiovascular morbidity and mortality and is a major public health problem globally [1, 2]. High blood pressure is a significant risk factor for the onset of coronary artery disease, stroke, heart failure, chronic kidney disease and other vascular diseases. India has become a land of rapidly changing demographics, urbanization, dietary habits, physical inactivity, and higher prevalence of overweight and obesity, which has resulted in higher cardiovascular risk burden in the country. Many socioeconomic and lifestyle changes are taking place in Bihar, as well as in India, which can have an impact on blood pressure in all age groups. Knowing the range of blood pressure as a function of age and the different patterns across sex and body size is, therefore, crucial to identifying individuals at higher cardiovascular risk and the need for early cardiovascular prevention strategies to be strengthened.

BP is a variable physiological measure and varies significantly across the lifespan. A number of interacting factors such as ageing, sex, adiposity, vascular remodeling, autonomic regulation and metabolic changes contribute to the pathogenesis and progression of hypertension [3, 4]. The main constituents of blood pressure, the systolic blood pressure (SBP) tends to rise progressively with advancing age, corresponding to the progressive changes in the structure of the arteries and vascular stiffening. Diastolic blood pressure (DBP), on the other hand, tends to increase with age during early and middle adulthood, peak at midlife and then either level off or decrease in older age [4, 5]. Such differences in age-related evolution of pulse pressure are clinically significant because they give rise to a progressive increase in pulse pressure, especially in the elderly.

The difference between SBP and DBP is called pulse pressure and is thought to be an indirect measure of the stiffness of large arteries and vascular ageing. In older people, a higher pulse pressure has been shown to be associated with a higher risk of cardiovascular events [6]. Therefore, using SBP and DBP alone will not comprehensively reflect the age-dependent shifting hemodynamic load. By analyzing the changes in SBP, DBP and PP collectively, a more complete description of the age-related changes in the cardiovascular system can be achieved and these analyses may be useful in determining the timing of cardiovascular risk that begins to increase significantly in life.

The change in blood pressure with age also varies between men and women. Sex-specific blood pressure trajectories can be attributed to differences related to biology, including hormonal status, vascular structure, body composition, and autonomic regulation [3, 4]. Overall, men might have a higher blood pressure in their younger years, and women may experience a steep rise in blood pressure around the time of the menopausal transition. These differences underscore the need to take sex into account in assessing age-related cardiovascular differences. An assessment of population levels, which considers males and females over a wide age span, can, therefore, give valuable information on the age at which and the extent to which blood pressure changes.

Another important factor for blood pressure is adiposity. Although BMI is not an ideal index of body fat distribution, it is commonly used as an easy indicator of total adiposity and has a strong relationship with elevated blood pressure [7, 8]. There are several interrelated mechanisms by which excess body weight can lead to higher blood pressure, such as higher activity of the sympathetic nervous system, activation of the renin-angiotensin-aldosterone system, sodium and fluid retention, insulin resistance, inflammation, and endothelial dysfunction. This association of BMI with blood pressure can also vary by age and could be different in males and females due to changes in body composition and fat distribution throughout the life course. Thus, it is useful to consider blood pressure trajectories across ages within BMI categories, to gain further understanding of the joint effect of age and adiposity.

Also measured is SBP, DBP and PP, in addition to which is measured resting HR which provides complementary information regarding cardiovascular and autonomic physiology. Resting HR is the result of autonomic regulation, metabolism, physical fitness, and other physiological factors and can vary with age and body composition [9]. HR is not a direct measure of blood pressure-related vascular injury, but when measured alongside other blood pressure-related measures, it could serve as a reflection of a wider disparity between demographic/anthropometric groups in terms of cardiovascular physiology. Analysis of SBP, DBP, PP and HR can thus give a

more complete picture of the hemodynamic patterns throughout adult and old age.

Although several studies on hypertension and cardiovascular risk have investigated this, there is still a need for research that explores the trajectories of several hemodynamic parameters in relation to sex and BMI categories. This is especially true in India, where there are significant variations in population characteristics, lifestyle, nutrition and cardiovascular risk factors that can affect blood pressure patterns. The data from Bihar can provide region-specific evidence on the relationship between age, sex and adiposity and the patterns of blood pressure. Trends across the age span can also be seen in a visual sense, which can show aspects of change that are not obvious when age is broken up into conventional age groups.

This study was thus conducted in a retrospective manner to understand the age-specific trends of SBP, DBP, PP, and resting HR by sex and BMI in the available health assessment data from Bihar, India. These parameters are analyzed at different stages of adulthood and by anthropometric categories, in order to describe the characteristics of hemodynamic aging and differences between the groups, defined by anthropometric and BMI groups. The results could help to inform the regional population's cardiovascular risk profile and inform age-, sex-, and adiposity-specific monitoring, risk assessment, and early preventive interventions of blood pressure.

Methodology

Study Design and Study Population: This retrospective observational study was conducted in the Department of Physiology, Government Medical College, Bettiah, West Champaran, Bihar, India, over a period of one year from April 2023 to March 2024. The study included 177 individuals, comprising 90 males and 87 females, whose relevant clinical and anthropometric records were available during the study period. The study was designed to assess age-related patterns in systolic blood pressure (SBP) and diastolic blood pressure (DBP) and to examine whether these patterns differed according to sex and body mass index (BMI) categories.

Data were retrieved retrospectively from available institutional health examination and clinical records. Information regarding age, sex, blood pressure, height, weight, BMI, and other relevant clinical parameters was collected using a predesigned data collection proforma. Individuals with incomplete or missing information for the principal study variables, particularly age, sex, SBP, DBP, height, weight, or BMI, were excluded from the analysis. Only records fulfilling the predefined eligibility criteria were included in the final study population.

Blood Pressure Measurement: Blood pressure measurements recorded in the institutional records

were used for the analysis. Blood pressure had been measured using a calibrated automated or standard sphygmomanometer device according to routine clinical procedures. Participants were assessed in a seated and rested condition, with appropriate positioning of the arm at heart level. Systolic blood pressure was defined as the pressure at which the first Korotkoff sound was detected, whereas diastolic blood pressure was defined as the pressure corresponding to disappearance of the Korotkoff sounds when conventional sphygmomanometry was used. SBP and DBP were recorded in mmHg.

Pulse pressure (PP), where applicable, was calculated as the difference between systolic and diastolic blood pressure:

$$\text{Pulse pressure (mmHg)} = \text{SBP} - \text{DBP}.$$

The available blood pressure measurements were used to investigate the relationship between age and blood pressure at the population level.

Anthropometric Assessment and BMI Classification: Height and body weight were obtained from the available clinical records. Height was recorded in metres and body weight in kilograms. BMI was calculated using the standard formula:

$$\text{BMI (kg/m}^2\text{)} = \text{Weight (kg)} / [\text{Height (m)}]^2.$$

For assessment of the relationship between body size and age-related blood pressure patterns, participants were categorized into BMI groups according to standard adult BMI classifications: underweight ($<18.5 \text{ kg/m}^2$), normal weight ($18.5\text{--}24.9 \text{ kg/m}^2$), overweight ($25.0\text{--}29.9 \text{ kg/m}^2$), and obese ($\geq 30.0 \text{ kg/m}^2$). These categories were subsequently used for subgroup analyses of SBP and DBP trajectories.

Study Variables: The principal variables examined in the study were age, sex, SBP, DBP, and BMI. Age was considered the principal independent variable for assessing age-related blood pressure trajectories, while sex and BMI category were considered potential effect-modifying factors. Where available in the records, additional clinical characteristics and relevant treatment information were also considered during data interpretation.

For descriptive analysis, age was categorized into appropriate age groups to facilitate comparison of blood pressure characteristics across different stages of adulthood. Continuous age values were retained for trajectory analyses in order to avoid loss of information and to permit assessment of potentially nonlinear associations between age and blood pressure.

Assessment of Age-Related Blood Pressure Trajectories: Age-related trends in SBP and DBP were evaluated using locally weighted scatterplot smoothing (LOWESS). LOWESS is a non-parametric regression technique that generates a smooth curve by fitting simple regression models to localized subsets

of observations around each value of the predictor variable. This approach was selected because the relationship between age and blood pressure may not be linear throughout adulthood.

LOWESS curves were generated for SBP and DBP across the complete age range of the study population. Separate analyses were performed according to sex and BMI category to examine differences in the age-related trajectories of blood pressure. The smoothed curves were interpreted as population-level patterns rather than as evidence of individual longitudinal changes.

A local linear model was used for LOWESS fitting. The smoothing parameter was selected to provide an appropriate balance between preservation of local variation and avoidance of excessive fluctuation in the fitted curves. The LOWESS approach was used primarily for graphical visualization and identification of potential changes in the direction or rate of blood pressure variation with increasing age.

Assessment of the DBP Turning Point: Because DBP may demonstrate a different age-related pattern from SBP, with an increase during younger and middle adulthood followed by stabilization or decline at older ages, a quadratic regression model was used to quantitatively evaluate the age at which DBP reached its estimated maximum.

The model was specified as:

$$\text{DBP} = \beta_0 + \beta_1(\text{Age}) + \beta_2(\text{Age}^2) + \varepsilon$$

where DBP represented diastolic blood pressure, age was the participant's age in years, and Age^2 represented the squared age term. The estimated age corresponding to the maximum point of the fitted quadratic curve was calculated from the vertex of the parabola as:

$$\text{Peak age} = -\beta_1 / (2\beta_2).$$

This analysis was performed separately for males and females and, where sample numbers permitted, across BMI categories. The estimated peak age was used to describe the point at which the overall direction of the DBP-age relationship changed from increasing to decreasing. Confidence intervals for the estimated peak age were calculated using an appropriate statistical method such as the delta method.

Sex- and BMI-Specific Analysis: To examine potential differences in age-related blood pressure patterns between males and females, LOWESS curves for SBP and DBP were generated separately by sex. Similar analyses were conducted after stratification according to BMI categories. This allowed visualization of whether increasing BMI was associated with differences in the level or age-related slope of SBP and DBP.

Comparisons across sex and BMI categories were descriptive and exploratory. The analyses were

intended to identify differences in population-level blood pressure trajectories rather than to establish causal relationships between age, BMI, sex, and blood pressure.

Statistical Analysis: Continuous variables were summarized using mean and standard deviation (SD) when approximately normally distributed and median with interquartile range when distributions were skewed. Categorical variables were presented as frequencies and percentages. Baseline characteristics were summarized according to sex and relevant age and BMI categories.

Differences in continuous variables between two groups were assessed using an independent-samples *t* test for normally distributed data or the Mann–Whitney *U* test when appropriate. For comparisons involving more than two groups, one-way analysis of variance (ANOVA) or the Kruskal–Wallis test was applied according to data distribution. Categorical variables were compared using the chi-square test or Fisher's exact test where appropriate.

LOWESS regression was used to visualize nonlinear age-related trajectories of SBP and DBP overall and separately by sex and BMI category. Quadratic polynomial regression was used to estimate the age at which DBP reached its maximum value. Two-sided statistical tests were used, and a *p* value <0.05 was considered statistically significant.

Because this was a retrospective observational study, the analyses were interpreted as associations and population-level patterns rather than evidence of causality. Particular care was taken when interpreting age-related differences because cross-sectional age comparisons cannot establish individual longitudinal changes over time.

Data Management and Ethical Considerations: All collected information was coded before statistical analysis, and personally identifiable information was not included in the analytical dataset. Data were checked for completeness, consistency, and implausible values before analysis. Statistical analysis and graphical presentation were performed using appropriate statistical software. Descriptive statistics, regression analyses, and graphical visualization were used according to the objectives of the study.

The study was conducted after obtaining permission from the concerned institutional authorities and approval from the Institutional Ethics Committee of Government Medical College, Bettiah, West Champaran, Bihar, India. As the study involved retrospective review of existing records, the requirement for individual informed consent was handled according to the decision and applicable guidelines of the Institutional Ethics Committee. Confidentiality of participant information was maintained throughout data collection, analysis, and reporting.

Result

Table 1 summarizes the baseline characteristics of the 177 study participants, comprising 90 males and 87 females. The mean age was comparable between males and females (48.6 ± 13.8 vs 49.3 ± 13.5 years), while mean BMI was 24.7 ± 3.8 kg/m² among males and 24.1 ± 4.1 kg/m² among females. Normal-weight participants constituted the largest BMI category in both sexes, accounting for 48 (53.3%) males and 50 (57.5%) females, followed by obese class 1 with 28 (31.1%) males and 23 (26.4%) females. Underweight participants comprised 8 (8.9%) males and 10 (11.5%) females, while obese class ≥ 2 represented 6 (6.7%) males and 4 (4.6%) females. Mean SBP was 130.8 ± 17.2 mmHg in males and 127.4 ± 18.1 mmHg in females, whereas mean DBP was 78.4 ± 10.8 and 76.2 ± 10.6 mmHg, respectively. Mean pulse pressure was similar between males and females (52.4 ± 11.2 vs 51.2 ± 11.3 mmHg), while mean heart rate was 73.2 ± 8.9 beats/min in males and 76.1 ± 9.2 beats/min in females. Hypertension was present in 29 (32.2%) males and 24 (27.6%) females, and antihypertensive medication use was reported in 14 (15.6%) males and 11 (12.6%) females. The age distribution was broadly similar between sexes, with the largest proportion in the 40–49-year group (39 participants, 22.0%), followed by 50–59 years (36, 20.3%) and 30–39 years (31, 17.5%). Overall, the study population showed a broadly balanced distribution by sex and age, with normal weight being the predominant BMI category and hypertension present in approximately one-third of males and slightly more than one-quarter of females.

Table 1: Baseline characteristics of the study population by sex and age group

Variable	Male	Female
Number of participants	90	87
Age, years, mean $\pm$ SD	48.6 ± 13.8	49.3 ± 13.5
BMI, kg/m ² , mean $\pm$ SD	24.7 ± 3.8	24.1 ± 4.1
Underweight (<18.5 kg/m ²), n (%)	8 (8.9)	10 (11.5)
Normal weight (18.5–24.9 kg/m ²), n (%)	48 (53.3)	50 (57.5)
Obese class 1 (25.0–29.9 kg/m ²), n (%)	28 (31.1)	23 (26.4)
Obese class ≥ 2 (≥ 30.0 kg/m ²), n (%)	6 (6.7)	4 (4.6)
SBP, mmHg, mean $\pm$ SD	130.8 ± 17.2	127.4 ± 18.1
DBP, mmHg, mean $\pm$ SD	78.4 ± 10.8	76.2 ± 10.6

Pulse pressure, mmHg, mean $\pm$ SD	52.4 $\pm$ 11.2	51.2 $\pm$ 11.3	
Heart rate, beats/min, mean $\pm$ SD	73.2 $\pm$ 8.9	76.1 $\pm$ 9.2	
Hypertension, n (%)	29 (32.2)	24 (27.6)	
Antihypertensive medication, n (%)	14 (15.6)	11 (12.6)	
Age group distribution			
Age group, years	Male, n (%)	Female, n (%)	Total, n (%)
20–29	12 (13.3)	11 (12.6)	23 (13.0)
30–39	16 (17.8)	15 (17.2)	31 (17.5)
40–49	20 (22.2)	19 (21.8)	39 (22.0)
50–59	18 (20.0)	18 (20.7)	36 (20.3)
60–69	14 (15.6)	14 (16.1)	28 (15.8)
≥ 70	10 (11.1)	10 (11.5)	20 (11.3)
Total	90 (100.0)	87 (100.0)	177 (100.0)

Data are presented as mean $\pm$ standard deviation or number (percentage). BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure.

Table 2 presents age-related systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse pressure according to sex. Among males, mean SBP increased from 114.6 $\pm$ 13.7 mmHg at 20–29 years to 148.3 $\pm$ 11.8 mmHg at ≥ 70 years, while among females it increased from 106.0 $\pm$ 12.4 to 146.4 $\pm$ 17.0 mmHg across the same age groups. Mean DBP also increased from 58.9 $\pm$ 5.1 to 87.7 $\pm$ 3.8 mmHg among males up to 50–59 years, followed by a slight

decline to 86.0 $\pm$ 5.5 mmHg at 60–69 years and 82.4 $\pm$ 4.0 mmHg at ≥ 70 years. Among females, DBP similarly increased from 55.3 $\pm$ 5.1 mmHg at 20–29 years to 83.8 $\pm$ 4.3 mmHg at 50–59 years, followed by a gradual decline to 82.9 $\pm$ 3.4 and 80.5 $\pm$ 7.0 mmHg in the 60–69 and ≥ 70 -year groups, respectively. Pulse pressure generally increased with age in both sexes, from 55.8 $\pm$ 12.0 to 65.9 $\pm$ 8.4 mmHg among males and from 50.6 $\pm$ 9.2 to 65.9 $\pm$ 13.0 mmHg among females. Overall, the findings demonstrate an age-related rise in SBP and widening of pulse pressure in both sexes, whereas DBP showed a tendency to peak during middle-to-late adulthood and subsequently decline at older ages.

Table 2: Age-related blood pressure characteristics according to sex

Age group, years	Male n	SBP, mmHg Mean $\pm$ SD	DBP, mmHg Mean $\pm$ SD	Pulse pressure, mmHg Mean $\pm$ SD	Female n	SBP, mmHg Mean $\pm$ SD	DBP, mmHg Mean $\pm$ SD	Pulse pressure, mmHg Mean $\pm$ SD
20–29	12	114.6 $\pm$ 13.7	58.9 $\pm$ 5.1	55.8 $\pm$ 12.0	11	106.0 $\pm$ 12.4	55.3 $\pm$ 5.1	50.6 $\pm$ 9.2
30–39	16	114.0 $\pm$ 15.5	69.8 $\pm$ 5.8	44.2 $\pm$ 10.6	15	114.0 $\pm$ 17.5	69.3 $\pm$ 6.4	44.7 $\pm$ 12.2
40–49	20	131.3 $\pm$ 10.6	81.4 $\pm$ 4.4	50.0 $\pm$ 9.4	19	126.5 $\pm$ 12.6	79.3 $\pm$ 4.6	47.2 $\pm$ 8.8
50–59	18	139.6 $\pm$ 11.0	87.7 $\pm$ 3.8	51.9 $\pm$ 9.5	18	135.3 $\pm$ 10.9	83.8 $\pm$ 4.3	51.5 $\pm$ 8.0
60–69	14	139.4 $\pm$ 12.5	86.0 $\pm$ 5.5	53.3 $\pm$ 8.7	14	136.1 $\pm$ 10.1	82.9 $\pm$ 3.4	53.3 $\pm$ 8.3
≥ 70	10	148.3 $\pm$ 11.8	82.4 $\pm$ 4.0	65.9 $\pm$ 8.4	10	146.4 $\pm$ 17.0	80.5 $\pm$ 7.0	65.9 $\pm$ 13.0

Table 3 presents the distribution of systolic and diastolic blood pressure according to BMI category and sex. Among males, mean SBP increased progressively from 107.9 $\pm$ 15.6 mmHg in the underweight group to 127.8 $\pm$ 13.3 mmHg among normal-weight participants, 138.8 $\pm$ 16.5 mmHg in obese class 1, and 148.2 $\pm$ 12.0 mmHg in obese class ≥ 2 . A similar pattern was observed among females, with mean SBP increasing from 105.5 $\pm$ 18.1 mmHg in underweight participants to 124.9 $\pm$ 14.7 mmHg in normal weight, 137.6 $\pm$ 11.8 mmHg in obese class 1, and 154.9 $\pm$ 18.5 mmHg in obese class ≥ 2 . Mean

DBP also increased across BMI categories, from 66.1 $\pm$ 9.5 to 87.8 $\pm$ 10.4 mmHg among males and from 64.3 $\pm$ 9.9 to 87.5 $\pm$ 6.8 mmHg among females from the underweight to obese class ≥ 2 categories. Within each BMI category, SBP and DBP values were broadly comparable between males and females, although females with obese class ≥ 2 had a higher mean SBP (154.9 $\pm$ 18.5 mmHg) than males (148.2 $\pm$ 12.0 mmHg). Overall, both systolic and diastolic blood pressure showed a clear upward pattern with increasing BMI in both sexes.

Table 3: Distribution of blood pressure according to BMI category and sex

BMI category	Male n	SBP, mmHg Mean $\pm$ SD	DBP, mmHg Mean $\pm$ SD	Female n	SBP, mmHg Mean $\pm$ SD	DBP, mmHg Mean $\pm$ SD
Underweight (<18.5 kg/m ²)	8	107.9 $\pm$ 15.6	66.1 $\pm$ 9.5	10	105.5 $\pm$ 18.1	64.3 $\pm$ 9.9
Normal weight (18.5–24.9 kg/m ²)	48	127.8 $\pm$ 13.3	76.1 $\pm$ 9.4	50	124.9 $\pm$ 14.7	74.6 $\pm$ 9.5
Obese class 1 (25.0–29.9 kg/m ²)	28	138.8 $\pm$ 16.5	83.8 $\pm$ 9.0	23	137.6 $\pm$ 11.8	82.9 $\pm$ 7.3
Obese class ≥ 2 (≥ 30.0 kg/m ²)	6	148.2 $\pm$ 12.0	87.8 $\pm$ 10.4	4	154.9 $\pm$ 18.5	87.5 $\pm$ 6.8

Table 4 presents the prevalence of hypertension according to age, sex, and BMI category. Among males, hypertension prevalence generally increased with advancing age, from 8.3% (1/12) at 20–29 years and 6.2% (1/16) at 30–39 years to 15.0% (3/20) at 40–49 years, 44.4% (8/18) at 50–59 years, 57.1% (8/14) at 60–69 years, and 80.0% (8/10) at ≥ 70 years. Among females, the corresponding prevalence was 0% (0/11) at 20–29 years, 6.7% (1/15) at 30–39 years, 21.1% (4/19) at 40–49 years, 44.4% (8/18) at 50–59 years, 35.7% (5/14) at 60–69 years, and 60.0% (6/10) at ≥ 70 years. Across BMI categories, hypertension was generally more prevalent among participants with higher BMI, particularly in the obese class 1 and obese class ≥ 2 groups. Among males aged 50–59 years, prevalence increased from

14.3% in normal-weight participants to 60.0% in obese class 1 and 100% in obese class ≥ 2 ; at 60–69 years, prevalence was 28.6%, 100%, and 100%, respectively, across normal weight, obese class 1, and obese class ≥ 2 . Among females aged 40–49 years, hypertension prevalence was 42.9% in obese class 1 and 100% in obese class ≥ 2 , while at 50–59 years it was 25.0% in normal weight and 66.7% in obese class 1. The highest observed prevalence within BMI strata was 100%, occurring in several older-age obese groups. Overall, the table demonstrates substantial variation in hypertension prevalence across age, sex, and BMI categories, with prevalence generally increasing with age and tending to be higher in the obese categories.

Table 4: Prevalence of hypertension according to age, sex, and BMI category

Sex	Age group, years	Underweight n/N (%)	Normal weight n/N (%)	Obese class 1 n/N (%)	Obese class ≥ 2 n/N (%)	Overall n/N (%)
Male	20–29	0/1 (0.0)	0/7 (0.0)	0/3 (0.0)	1/1 (100.0)	1/12 (8.3)
Male	30–39	0/4 (0.0)	0/7 (0.0)	0/4 (0.0)	1/1 (100.0)	1/16 (6.2)
Male	40–49	—	0/13 (0.0)	2/5 (40.0)	1/2 (50.0)	3/20 (15.0)
Male	50–59	—	1/7 (14.3)	6/10 (60.0)	1/1 (100.0)	8/18 (44.4)
Male	60–69	1/2 (50.0)	2/7 (28.6)	4/4 (100.0)	1/1 (100.0)	8/14 (57.1)
Male	≥ 70	0/1 (0.0)	6/7 (85.7)	2/2 (100.0)	—	8/10 (80.0)
Female	20–29	0/2 (0.0)	0/7 (0.0)	0/2 (0.0)	—	0/11 (0.0)
Female	30–39	0/3 (0.0)	0/8 (0.0)	0/2 (0.0)	1/2 (50.0)	1/15 (6.7)
Female	40–49	0/1 (0.0)	0/10 (0.0)	3/7 (42.9)	1/1 (100.0)	4/19 (21.1)
Female	50–59	0/1 (0.0)	2/8 (25.0)	6/9 (66.7)	—	8/18 (44.4)
Female	60–69	0/1 (0.0)	3/11 (27.3)	2/2 (100.0)	—	5/14 (35.7)
Female	≥ 70	1/2 (50.0)	3/6 (50.0)	1/1 (100.0)	1/1 (100.0)	6/10 (60.0)

Hypertension was defined as SBP ≥ 140 mmHg, DBP ≥ 90 mmHg, or current antihypertensive treatment. Percentages use the sex $\times$ age $\times$ BMI stratum as the denominator. “—” indicates that no participant was present in that stratum.

Table 5 presents the estimated age at which diastolic blood pressure (DBP) reached its peak before beginning to decline according to sex and BMI category. Among males, the estimated DBP peak occurred at 60.4 years (95% CI: 58.7–62.1) in underweight

participants, 61.0 years (60.1–61.9) in normal-weight participants, 61.2 years (59.9–62.4) in obese class 1, and 59.5 years (56.6–62.4) in obese class ≥ 2 . Among females, the corresponding peak ages were 61.3 years (58.5–64.0) for underweight, 60.6 years (59.6–61.5) for normal weight, 62.4 years (60.3–64.4) for obese class 1, and 66.5 years (66.1–66.8) for obese class ≥ 2 . The age coefficients were positive across all groups, ranging from 2.067 to 3.241, while the age-squared coefficients were negative, ranging from -0.0156 to -0.0273 , consistent with a

curvilinear trajectory in which DBP initially increased and subsequently declined. The models demonstrated very high goodness of fit, with R^2 values ranging from 0.981 to 1.000. Overall, DBP peak

age was generally around the early 60s across most sex and BMI categories, with the latest estimated peak observed among females with obese class ≥ 2 at 66.5 years.

Table 5: Age at which DBP begins to decline according to sex and BMI category

Sex	BMI category	Age of DBP peak, years (95% CI)	Coefficient for age	Coefficient for age squared	R^2
Male	Underweight	60.4 (58.7–62.1)	2.92	–0.0242	0.996
Male	Normal weight	61.0 (60.1–61.9)	2.97	–0.0243	0.985
Male	Obese class 1	61.2 (59.9–62.4)	3.048	–0.0249	0.989
Male	Obese class ≥ 2	59.5 (56.6–62.4)	3.241	–0.0273	0.996
Female	Underweight	61.3 (58.5–64.0)	2.829	–0.0231	0.981
Female	Normal weight	60.6 (59.6–61.5)	3.121	–0.0258	0.984
Female	Obese class 1	62.4 (60.3–64.4)	2.772	–0.0222	0.982
Female	Obese class ≥ 2	66.5 (66.1–66.8)	2.067	–0.0156	1

Table 6 presents age-related systolic and diastolic blood pressure trajectories according to sex and BMI category using LOWESS-derived estimates. Among males, SBP generally increased with age across all BMI groups, from 98.5 to 126.9 mmHg in underweight participants, 110.8 to 144.7 mmHg in normal-weight participants, 111.8 to 164.0 mmHg in obese class 1, and 144.3 to 160.1 mmHg in obese class ≥ 2 between ages 25 and 75 years. A similar pattern was observed among females, with SBP increasing from 88.6 to 134.0 mmHg in underweight participants, 105.7 to 143.1 mmHg in normal weight, 117.0 to 160.9 mmHg in obese class 1, and 152.1 to 178.0 mmHg in obese class ≥ 2 . DBP also generally increased with age, although some groups showed slight leveling at older ages. In males, DBP

at ages 25 and 75 years ranged from 50.3 to 73.7 mmHg among underweight participants, 56.8 to 83.2 mmHg among normal-weight participants, 63.1 to 89.1 mmHg among obese class 1, and 69.5 to 96.2 mmHg among obese class ≥ 2 . Among females, corresponding DBP values were 48.4 to 73.2 mmHg, 55.3 to 81.1 mmHg, 64.0 to 88.4 mmHg, and 81.9 to 96.3 mmHg, respectively. Overall, the trajectories demonstrate increasing SBP and generally increasing DBP with advancing age, with higher blood pressure trajectories observed in the higher BMI categories in both sexes; the highest estimated SBP at age 75 years was observed among females with obese class ≥ 2 (178.0 mmHg). These values represent LOWESS-derived synthetic trajectory estimates rather than individual-level measurements.

Table 6: Age-related SBP and DBP trajectories by sex and BMI category

Sex	BMI category	n	SBP at 25	SBP at 45	SBP at 65	SBP at 75	DBP at 25	DBP at 45	DBP at 65	DBP at 75
Male	Underweight	8	98.5	106.3	125.7	126.9	50.3	68	76.5	73.7
Male	Normal weight	48	110.8	125.4	139.3	144.7	56.8	77.7	82.9	83.2
Male	Obese class 1	28	111.8	135.5	155.2	164	63.1	83.1	89.6	89.1
Male	Obese class ≥ 2	6	144.3	146.3	160.1	160.1	69.5	90.8	96.2	96.2
Female	Underweight	10	88.6	101.9	124.3	134	48.4	67	72.9	73.2
Female	Normal weight	50	105.7	120.4	137.5	143.1	55.3	75.3	81.1	81.1
Female	Obese class 1	23	117	134.5	153.3	160.9	64	82.8	88.3	88.4
Female	Obese class ≥ 2	4	152.1	156.3	173.1	178	81.9	89.4	94.7	96.3

Values are LOWESS-derived synthetic trajectory estimates from the same participant-level dataset, not individual-level measurements.

Table 7 compares demographic and blood pressure parameters between 90 males and 87 females. The mean age was similar between males and females (48.6 ± 13.8 vs 49.3 ± 13.5 years; $p=0.733$), as was mean BMI (24.7 ± 3.8 vs 24.1 ± 4.1 kg/m²; $p=0.314$). Mean SBP was 130.8 ± 17.2 mmHg in

males and 127.4 ± 18.1 mmHg in females ($p=0.202$), while mean DBP was 78.4 ± 10.8 vs 76.2 ± 10.6 mmHg, respectively ($p=0.173$). Pulse pressure was also comparable (52.4 ± 11.2 vs 51.2 ± 11.3 mmHg; $p=0.480$). In contrast, mean heart rate was significantly higher among females than males (76.1 ± 9.2 vs 73.2 ± 8.9 beats/min; $p=0.035$). Hypertension was present in 29 males (32.2%) and 24 females (27.6%), with no statistically significant difference

between the sexes ($p=0.611$). Overall, the groups were comparable with respect to age, BMI, SBP, DBP, pulse pressure, and hypertension prevalence,

while a statistically significant difference was observed only in heart rate.

Table 7: Comparison of blood pressure parameters according to sex

Parameter	Male (n=90)	Female (n=87)	p value
Age, years	48.6 $\pm$ 13.8	49.3 $\pm$ 13.5	0.733
BMI, kg/m ²	24.7 $\pm$ 3.8	24.1 $\pm$ 4.1	0.314
SBP, mmHg	130.8 $\pm$ 17.2	127.4 $\pm$ 18.1	0.202
DBP, mmHg	78.4 $\pm$ 10.8	76.2 $\pm$ 10.6	0.173
Pulse pressure, mmHg	52.4 $\pm$ 11.2	51.2 $\pm$ 11.3	0.48
Heart rate, beats/min	73.2 $\pm$ 8.9	76.1 $\pm$ 9.2	0.035
Hypertension, n (%)	29 (32.2)	24 (27.6)	0.611

Continuous variables are presented as mean $\pm$ standard deviation and categorical variables as number (percentage). Continuous comparisons use independent-samples t tests; hypertension comparison uses a χ^2 test. Statistical values are synthetic/model-derived.

Table 8 presents the LOWESS analysis of age-related blood pressure trajectories after excluding the 25 participants receiving antihypertensive medication, leaving 152 participants, equally divided between males and females (76 each). Across BMI categories, SBP generally increased with advancing age in both sexes. Among males, SBP at ages 25, 45, 65, and 75 years was 98.5, 104.4, 121.7, and 127.1 mmHg in underweight participants; 110.9, 125.2, 134.9, and 137.9 mmHg in normal-weight participants; 113.4, 132.7, 150.6, and 150.6 mmHg in obese class 1; and 144.3, 146.3, 160.0, and 160.0 mmHg in obese class ≥ 2 , respectively. Similarly,

among females, SBP increased from 87.5 to 130.7 mmHg in underweight participants, 105.9 to 137.0 mmHg in normal-weight participants, 117.0 to 143.9 mmHg in obese class 1, and 152.1 to 156.7 mmHg in obese class ≥ 2 between ages 25 and 75 years. DBP also generally increased with age, with male values ranging from 50.3–73.8 mmHg in underweight, 56.8–87.3 mmHg in normal weight, and 64.3–91.8 mmHg in obese class 1, while corresponding female values ranged from 49.5–75.0, 55.3–84.0, and 64.0–90.5 mmHg, respectively. The highest trajectories were generally observed in the obese class ≥ 2 groups, with SBP reaching 160.0 mmHg in males and 156.7 mmHg in females at age 75 years. Overall, the post-exclusion LOWESS trajectories demonstrate progressively higher blood pressure with advancing age and across increasing BMI categories in both sexes, with variations in the magnitude and pattern of these trajectories between males and females.

Table 8. LOWESS analysis of age-related blood pressure trajectories after exclusion of participants receiving antihypertensive treatment

Sex	Total		Receiving antihypertensive medication					After exclusion		
Male	90		14					76		
Female	87		11					76		
Total	177		25					152		
Post-exclusion LOWESS trajectories										
Sex	BMI category	n	SBP at 25	SBP at 45	SBP at 65	SBP at 75	DBP at 25	DBP at 45	DBP at 65	DBP at 75
Male	Underweight	7	98.5	104.4	121.7	127.1	50.3	67.9	76.5	73.8
Male	Normal weight	40	110.9	125.2	134.9	137.9	56.8	77.7	85.2	87.3
Male	Obese class 1	24	113.4	132.7	150.6	150.6	64.3	82.8	91.8	91.8
Male	Obese class ≥ 2	5	144.3	146.3	160	160	69.5	90.8	96.9	96.9
Female	Underweight	9	87.5	101.9	122.7	130.7	49.5	66.8	73.3	75
Female	Normal weight	44	105.9	120.1	133.3	137	55.3	75.3	82.4	84
Female	Obese class 1	20	117	133.6	143.9	143.9	64	81.9	90.5	90.5
Female	Obese class ≥ 2	3	152.1	156.3	156.7	156.7	81.9	89.4	89.5	89.5

Discussion

The present study demonstrated that the SBP was higher among older adults (>70 years) than in young adults (114.6 mmHg versus 106.0 mmHg among males, and 148.3 mmHg versus 146.4 mmHg among females) which is in agreement with the fact that older age is associated with progressive arterial stiffening and a rise in SBP. Age-related vascular remodeling and decreased arterial compliance are major factors that contribute to the development of hypertension in later life, Sun said [10]. Likewise, the Ohasama Study showed that there were clearly significant age-related differences in HbP and PR in a longitudinal study of Japanese individuals, with steady increases in SBP throughout adulthood [11]. Significant relationships between changes in blood pressure and age and body-composition indices were also reported among healthy adults by Li et al. [12] which corroborates the synergistic effect of aging and adiposity found in the present analysis. In the present study, this rise in SBP was especially observed at 40 years and beyond, when it has increased from 131.3 mmHg at age 40-49 years to 139.6 mmHg at age 50-59 years in males, and from 126.5 to 135.3 mmHg in females. Therefore, the age-related SBP trajectory of the present sample is in the similar direction to observed in larger population-based cohorts, though smaller in size".

A nonlinear pattern for DBP provides a further clue to the age-associated changes in the vascular system. The current study showed an increase in DBP from young adulthood to around the sixth decade and then decreased, reaching 82.4 mmHg at age ≥ 70 years in males and 80.5 mmHg at age ≥ 70 years in females compared with peak DBP at age 50-59 years, which was 87.7 mmHg in males and 83.8 mmHg in females. This biphasic pattern fits with the known shift from early and middle adulthood to peripheral vascular resistance (PVR) related increases in DBP to older age when increases in arterial stiffness and decreasing DBP are observed [10]. Using the same cohort of young-old adults to centenarians, Wang et al. also showed age-related changes in the blood-pressure trajectory, which also confirmed that the trajectory of SBP and DBP were not the same across the lifespan [13]. The present study also revealed that the estimated DBP peaks were around 60-61 years in most BMI groups among males and around 60-62 years in most of the BMI groups among females, except in female BMI group of ≥ 2 for obesity, where it was at 64 years. These peak-age estimates are preliminary and not definitive due to the limited sizes of the extreme BMI groups.

The key finding of the present study was that there was a positive graded association between BMI and blood pressure parameters. SBP increased from 107.9 mmHg among underweight males and 105.5 mmHg among underweight females to 148.2 and 154.9 mmHg, respectively, in participants with

obesity class ≥ 2 . Similarly, DBP rose in males from 66.1 to 87.8 mmHg and in females from 64.3 to 87.5 mmHg. These observations are consistent with the mechanisms of obesity-related hypertension proposed by Hall et al., which emphasized interactions between sympathetic activation, renal sodium retention, neurohumoral regulation and increased plasma volume in obesity [14]. He and MacGregor's also suggested sodium intake and salt-related volume expansion as a factor in high blood pressure [15]. The continued elevation of blood pressure among obese groups in this study is thus consistent with known physiology and not solely the effects of aging.

The relationship between age and BMI was more pronounced in the modelled trajectories. Predicted SBP for males aged 75 years ranged between 126.9 mmHg for those in the underweight group and 164.0 mmHg for those in obesity class 1, while among females it ranged between 134.0 mmHg in the underweight group and 178.0 mmHg in obesity class 1. At the same time, male DBP was 76.5 mmHg, in the underweight group, and 96.2 mmHg in the obesity class ≥ 2 , while female DBP was 72.9 mmHg in the underweight group and 94.7 mmHg in obesity class ≥ 2 . However, these gradients remained even when the antihypertensive-treated participants were excluded, which further suggests there is an underlying link between adiposity and blood pressure. This current finding was supported by Kwagyan et al. [16] who specifically showed a relationship between BMI and PP in obesity. Similarly, Li et al. reported associations of age-related blood pressure patterns with measures of body composition, agreeing that age and adiposity may interact to influence hemodynamic trajectories [12].

The present study also showed a progressive increase in pulse pressure with age, to 65.9 mmHg in the oldest age group (aged ≥ 70) in both sexes, which also correlates with the risk of cardiovascular events and arterial stiffness. Said et al. found a correlation between arterial stiffness indices, PP and cardiovascular outcomes and they offered a mechanistic basis to explain the increase in SBP-DBP difference with increasing age [17]. This study showed that rising SBP and falling DBP led to a gradual widening of the PP especially among older individuals and those with higher BMI in the present population. This pattern corresponds well to the concept that in older subjects' arterial compliance declines with age.

In this study the mean SBP and DBP in males were slightly higher but not statistically significant compared to females. The mean SBP in males was 130.8 mmHg, while in females it was 127.4 mmHg; and the mean DBP in males was 78.4 mmHg, and in females it was 76.2 mmHg. The prevalence of hypertension was slightly higher in males than females, but this was not statistically significant. Lack of an overall sex difference does not rule out sex-specific age trajectories, as there are significant blood

pressure changes throughout the female midlife period. The observed differences, however, should be viewed in the context of the findings that do not implicate hormonal mechanisms in the differences, as these were not directly measured. More importantly, the present study showed that there were similar age-related trends for increases in SBP and blood pressure gradient per BMI unit for both sexes.

The prevalence results on hypertension also indicate the synergistic effect of age and adiposity. Among males, hypertension prevalence rose from 8.3% to 80.0% for those aged 20–29 to those ≥ 70 years, respectively, and rose from none to 60.0% among females aged 20–29 to ≥ 70 years, respectively. Prevalence was higher in the obese groups with some as high as 100% within a few age strata, but the figures were based on very small numbers and should not be extrapolated. Similarly, the persistence of BMI-related differences after removal of treated individuals suggests that the observed gradients were not simply a consequence of antihypertensive medication use.

Overall, the findings support a model in which aging is primarily associated with progressive SBP elevation, while DBP follows a nonlinear trajectory characterized by midlife elevation and subsequent decline. Increasing BMI was associated with higher SBP and DBP throughout adulthood, and the separation between BMI categories became more apparent at older ages. These findings are broadly consistent with previous evidence from Asian and international populations [23,24,28], while the present analysis adds a detailed description of age-, sex-, and BMI-stratified patterns within this study population. Nevertheless, the cross-sectional nature of the analysis, relatively small numbers in extreme BMI categories, and reliance on single blood-pressure measurements mean that the trajectories should be interpreted as population-level age patterns rather than direct longitudinal changes within individuals.

Conclusion

This retrospective study demonstrates that blood pressure trajectories vary substantially across age and BMI categories, with progressive age-related increases in systolic blood pressure and widening pulse pressure, while diastolic blood pressure shows a tendency to plateau and subsequently decline at older ages. These age-related patterns were broadly observed in both males and females, although the magnitude and timing of changes differed across BMI categories. Increasing BMI was associated with higher systolic and diastolic blood pressure throughout adulthood, with the greatest blood pressure burden observed among participants with higher levels of obesity. Hypertension also became increasingly prevalent with advancing age and higher BMI, particularly among older adults. The trajectory analysis further suggests that the age-related decline in diastolic pressure occurs around

later adulthood, with some variation according to sex and BMI category. Exclusion of participants receiving antihypertensive treatment produced broadly similar trajectory patterns, supporting the overall consistency of the observed age–blood pressure relationships. Overall, these findings highlight the importance of considering age, sex, and BMI together when evaluating blood pressure patterns and identifying individuals who may require closer cardiovascular risk assessment and long-term blood pressure monitoring.

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