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Trends in the global, regional, and national burden of cardiovascular diseases attributed to high systolic blood pressure from 1990 to 2021 and projections to 2045: a systematic analysis based on GBD 2021 data

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Abstract

Background Cardiovascular disease (CVD) remains the leading cause of death and disability worldwide, and high systolic blood pressure (HSBP) is considered among its most critical modifiable risk factors. This study analyzed the temporal trends of the global burden of CVD attributed to HSBP from 1990 to 2021, examined its relationships with age, period, and birth cohort, and projected future trends to 2045.

Methods The study employed a joinpoint regression model to evaluate the temporal trends of CVD burden attributed to HSBP from 1990 to 2021 and used an Age-Period-Cohort (APC) model to analyze the effects of age, period, and cohort. Additionally, a Bayesian Age-Period-Cohort (BAPC) model was applied to project the disease burden trends up to 2045.

Results From 1990 to 2021, the absolute number of deaths and DALYs (disability-adjusted life years) of CVD attributed to HSBP increased significantly. However, the age-standardized mortality rate (ASMR) and age-standardized DALY rate (ASDR) showed a consistent declining trend. The study highlights significant regional differences, with the disease burden increasing most markedly in regions with a middle Socio-Demographic Index (SDI) and decreasing most significantly in high SDI regions. Additionally, the study revealed gender differences, with the decline in ASMR and ASDR was more pronounced in females, while males exhibited a higher overall disease burden than females. Projections from the BAPC model indicate that from 2022 to 2045, the absolute number of deaths and DALYs will continue to rise, while ASMR and ASDR will decline further.

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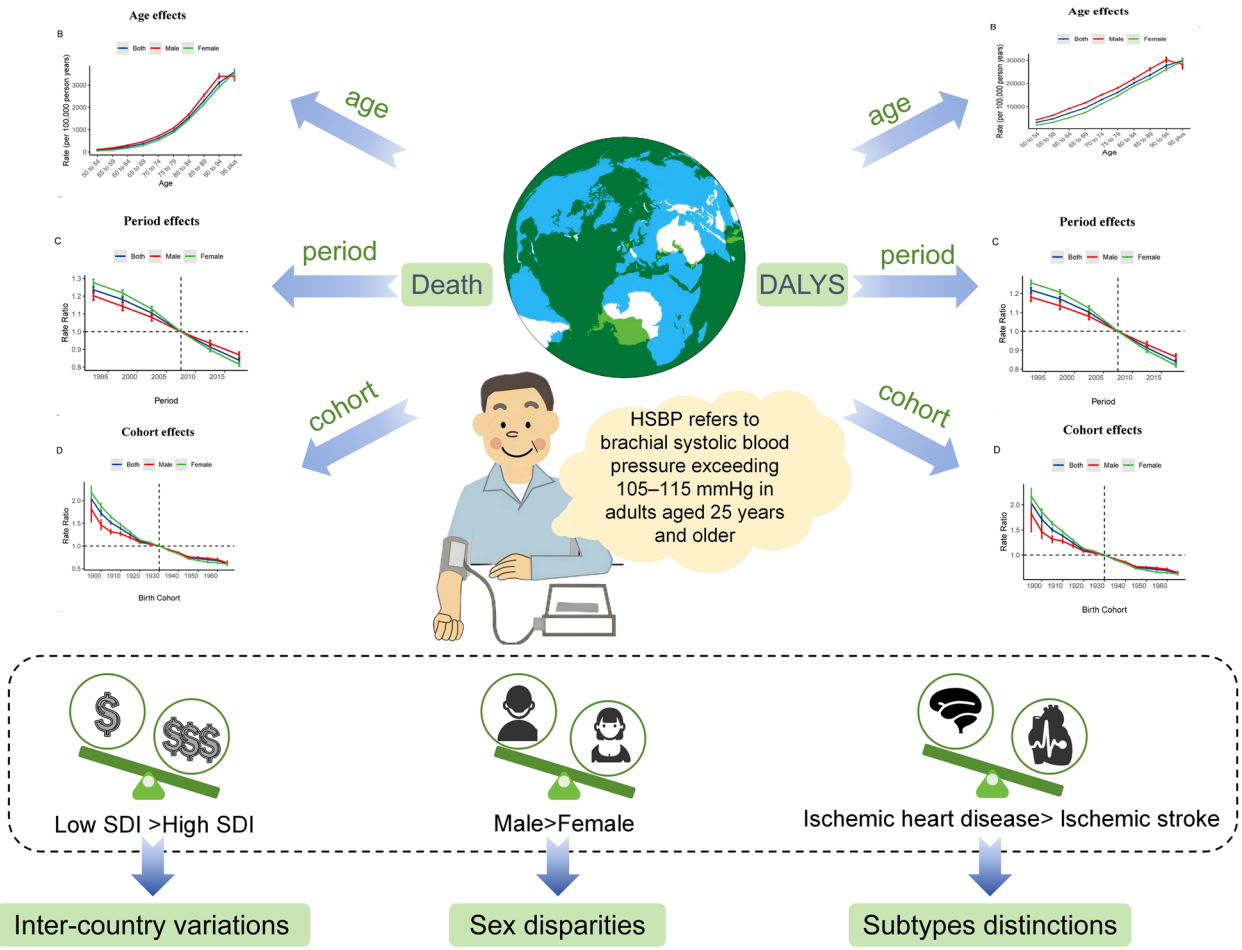
Conclusions This study conducted a comprehensive analysis of CVD attributed to HSBP globally, highlighting significant sex, age, and regional differences in disease burden as well as their temporal trends. The findings underscore the importance of targeted prevention strategies, particularly for high-risk populations. This study provides valuable insights for policymakers to formulate effective interventions to reduce the global disease burden.

Keywords Cardiovascular disease, High systolic blood pressure, Age-period-cohort analysis, Projection, Global burden

Graphical Abstract



Key learning points

What is already known:

- CVD remains the leading cause of death and disability worldwide.
- HSBP is a critical modifiable risk factor for CVD.
- Effective control of HSBP reduces the risk of developing CVD, but a significant portion of the global population remains unaware of their hypertension or fails to manage it effectively.
- There is currently a lack of research detailing the global burden and temporal trends of CVD and its subtypes attribute to HSBP.

What this study adds:

- This study explores the relationships between different genders, ages, SDI, regions, and the global CVD mortality and DALYs caused by HSBP.

- We examined the impact of HSBP on the burden of CVD and systematically analyzed the temporal trends in the burden attribute to HSBP using an age-period-cohort model.
- The BAPC model was used to predict trends in the burden of CVD through 2045.

Introduction

Cardiovascular disease (CVD) has become the leading cause of death and disability among the global population, posing a major public health challenge worldwide [1, 2]. Over the past 32 years, the global burden of CVD has significantly increased due to population growth, accelerated aging, and lifestyle changes. It is predicted that the global mortality and disability-adjusted life years (DALYs) associated with CVD will continue to rise, further intensifying the disease burden [3]. Among the various subtypes of CVD, ischemic heart disease (IHD) and ischemic stroke (IS) are the leading causes of CVD-related mortality [4]. Furthermore, the prevalence of CVD is closely linked to the socioeconomic development level of a region. Low- and middle-income countries bear significant economic and health burdens due to limited access to medical resources [5, 6]. Understanding these contributing factors is essential for developing effective strategies to reduce the burden of CVD. Studies have shown that risk factors such as high systolic blood pressure (HSBP), low physical activity, dietary risks, and abnormal levels of high or low-density lipoprotein cholesterol are closely associated with CVD, among which HSBP is considered one of the most critical modifiable risk factors [4]. HSBP refers to brachial systolic blood pressure exceeding 105–115 mmHg in adults aged 25 years and older [7]. Current research indicates that prolonged HSBP significantly increases the risk of developing CVD, while effective control of HSBP can substantially reduce this risk [8–10]. Nearly half of the global population is unaware that they have hypertension, and approximately 80% of patients fail to control their blood pressure effectively [11]. This underscores the importance of timely prevention and intervention, which play a decisive role in alleviating the overall burden of CVD. Although recent studies have comprehensively analyzed the global burden of cardiovascular diseases (CVD) and their risk factors, most of these studies have analyzed all attributable risk factors as a whole, lacking in-depth exploration of individual key risk factors. As one of the most important and modifiable risk factors for CVD, high systolic blood pressure (SBP) has yet to be studied in detail regarding the long-term trends and projections of its contribution to the CVD burden at the global, regional, and national levels.

This study is based on the GBD 2021 database, which covers 371 diseases and injuries and 88 risk factors across 204 countries and regions, providing comprehensive global health data support [12]. We examined the impact of HSBP on the burden of CVD and systematically analyzed the temporal trends in the burden attributable to HSBP using an Age-Period-Cohort (APC) model. Additionally, we employed the Bayesian Age-Period-Cohort (BAPC) model to predict trends in the burden of CVD through 2045. This study aims to provide essential theoretical and data support for formulating CVD prevention strategies and reducing the health burden in high-risk populations.

Method

Data source

GBD 2021 conducted a comprehensive assessment of 371 diseases and injuries, as well as 88 risk factors related to disease burden, across 204 countries and regions. We collected data on CVD caused by HSBP and their subtypes, including mortality rates, DALYs, Age-standardized mortality Rate (ASMR), Age-standardized DALY Rate (ASDR), and the corresponding 95% uncertainty intervals (UI). These data are stratified by age, sex, region, and country. The methodology for using GBD 2021 data has been described in previous studies [12, 13]. Additionally, we utilized the SDI, a composite indicator used to measure the development level of a region, which is calculated based on the geometric mean of fertility rates for those under 25, education levels for adults over 15, and per capita income [14]. The SDI ranges from 0 to 1, with higher values indicating higher levels of development. Based on SDI values, the 204 countries and regions were divided into five quintiles from high to low. The data for this study is publicly accessible through the Global Health Data Exchange (GHDx) query tool (http://ghdx.healthdata.org/gbd-results-tool) and does not require ethical approval.

Statistical analysis

The APC model is used to explain the impact of age, period, and cohort on the burden of CVD attributable to HSBP. The age effect refers to differences in outcome variables across different age groups. The period effect illustrates the changes in the burden of CVD attributable to HSBP across all age groups over time. The cohort effect reflects differences among groups of individuals with the same birth year. The APC model generates two primary output parameters: net drift reflects the time trend of mortality and DALYs across all age groups. Local drift reflects the time trend of mortality and DALYs for each age group at specific time points. In this model, the age and period intervals must be equal, with data at

consecutive 5-year intervals. For period and cohort intervals, the midpoint incidence rates and population counts are selected to represent specific periods instead of using 5-year averages. Age is divided into 10 age groups (50–54, 55–59, …, 95 +). Periods are divided into 6 groups (1992–1996, 1997–2001, …, 2017–2021). Birth cohorts are divided into 17 groups (1898–1902, 1903–1907, …, 1963–1967).

The Joinpoint regression model is used to analyze the time trend of the burden of CVD attributable to HSBP from 1990 to 2021. The annual percent change and average annual percent change (AAPC) for each time period, along with their 95% confidence intervals (CI), are calculated. If the annual percent change and its 95% CI are both >0, it indicates a significant upward trend in that time period. Conversely, if both are <0, it indicates a significant downward trend.

This study uses the Bayesian Age-Period-Cohort (BAPC) model to project the burden of CVD attributable to HSBP from 2022 to 2045. The model applies Bayesian statistical methods to the traditional APC model, demonstrating excellent predictive performance [15, 16]. All analyses were conducted using R software (Version 4.3.1), with a *P*-value <0.05 considered statistically significant.

Results

The burden and trends of CVD attributable to high systolic blood pressure globally

Globally, in 2021, the cases of deaths and DALYs of CVD attributable to HSBP were approximately 6,782,688.77 (95% UI: 5,370,932.76 to 8,090,099.96) and 135,019,809.48 (95% UI:106,718,820.24 to 160,988,651.37), representing an increase of 117.62% (95% UI: 96.56 to 140.57) and 115.01% (95% UI: 93.63 to 138.23) compared to 1990, respectively (Tables 1 and 2). Despite the significant increase in the absolute number of cases, in 2021, ASMR and ASDR for CVD attributable to HSBP were 82.3 per 100,000 (95% UI: 64.94 to 98.24) and 1587.1 per 100,000 (95% UI: 1255.42 to 1892.76), respectively, representing decreases of 74.15% (95% UI: 82.29 to 65.07) and 64.82% (95% UI: 73.72 to 55.25) compared to 1990 (Tables 1 and 2). A similar trend is observed across different CVD subtypes, with the cases of deaths and DALYs attribute to HSBP in 2021 for IHD being 2.25 and 2.29 times higher than for IS, respectively. Correspondingly, the ASMR and ASDR for IHD are 2.22 and 2.27 times those of IS (Tables S1 and S2) In terms of gender, over the past 32 years, the increase in death cases and DALYs among males has been significantly higher than among females, and the percentage decline in ASMR and ASDR for females has been higher than for males. The APC model estimated the global net drift of ASMR and ASDR for CVD attributable to HSBP to be −1.23% per year (95% CI: −1.29 to −1.17) and −1.16 per year (−1.2 to −1.12), respectively. In terms of gender, the global net drift for ASMR and ASDR in males was −1.03% per year (95% CI: −1.11 to −0.94) and −0.96% per year (95% CI: −1.03 to −0.9), respectively. For females, the global net drift for ASMR and ASDR was −1.48% per year (95% CI: −1.56 to −1.4) and −1.39% per year (95% CI: −1.43 to −1.35), respectively (Tables 1 and 2). This reflects that over the past 32 years, the improvement in reducing the burden of CVD attribute to HSBP has been less pronounced in males than in females.

In summary, although the global cases of deaths and DALYs of CVD and its subtypes attributable to HSBP have increased significantly over the past 32 years, the corresponding ASMR and ASDR have continued to decline.

The burden of CVD caused by high systolic blood pressure across different SDI regions globally

The global burden of CVD attributable to HSBP shows significant regional differences, with the most pronounced increases in deaths and DALYs observed in the Middle SDI region, rising by 365.73% (95% UI:298.72 to 440.45) and 312.6% (95% UI: 254.25 to 380.7) compared to 1990. The most significant decreases were observed in the High SDI region, with reductions of 58.82% (95% UI: 70.82 to 49.46) and 61.87% (95% UI: 70.95 to 53.27) compared to 1990 (Table 1 and Table 2). However, ASMR and ASDR increased most significantly in the Low-middle SDI region and declined most significantly in the High SDI region (Table 1 and Table 2).

From 1990 to 2021, across the 21 GBD regions, we observed an inverted U-shaped pattern between the ASMR of CVD attributed to HSBP and SDI values. A similar relationship was also observed between the ASDR of CVD and SDI values (Fig. 1). ASMR and ASDR increased in regions where SDI was below 0.47, then plateaued until the SDI value reached 0.72, and finally decreased as the SDI value continued to rise. During this period, ASMR and ASDR were higher than expected in Eastern Europe, Central Asia, North Africa, the Middle East, and Central Europe. In contrast, the burden was lower than expected in the Caribbean, East Asia, Southeast Asia, Andean Latin America, Central Latin America, Southern Latin America, and Oceania. In 2021, when the SDI was below 0.5, the EAPC of ASMR and ASDR for CVD attributable to HSBP remained relatively stable. However, when the SDI exceeded 0.5, there was an overall downward trend (Fig. 1). Over the past 32 years, most of the analyzed GBD super-regions showed an upward trend in ASMR and ASDR, with EAPC values above 0. A similar pattern in the relationship between ASMR, ASDR, their EAPC, and SDI values was observed among cardiovascular subtypes (Figures S1 and S2).

Table 1 The trends in CVD deaths attributable to high systolic blood pressure by global, sex, SDI, and WHO regions from 1990 to 2021

	Deaths		All-age mortality		Age-standardized mortality		
	Number in 2021, n	Change of numbers 1990–2021, %	Rate in 2021, per 100,000	Percent change 1990–2021, %	Rate in 2021, per 100,000	Percent change 1990–2021, %	Net drift of mortality, % per year
Global	6,782,688.77 (5,370,932.76 to 8,090,099.96)	117.62 (96.56 to 140.57)	85.95 (68.06 to 102.52)	14.67 (0.44 to 30.18)	82.3 (64.94 to 98.24)	−74.15 (−82.29 to −65.07)	−1.23 (−1.29 to −1.17)
Sex							
Female	3,225,694.71 (2,514,562.42 to 3,849,592.35)	87.59 (65.65 to 112.72)	82.04 (63.95 to 97.91)	−6.33 (−21.11 to 10.59)	68.75 (53.64 to 82.03)	−84.27 (−92.61 to −74.73)	−1.48 (−1.56 to −1.4)
Male	3,556,994.06 (2,781,671.87 to 4,297,342.13)	154.06 (118.92 to 192.09)	89.84 (70.26 to 108.54)	40.17 (16.33 to 65.96)	98.27 (76.68 to 118.7)	−62.01 (−74.64 to −47.82)	−1.03 (−1.11 to −0.94)
SDI							
High SDI	969,047.39 (731,499.75 to 1,181,362.9)	−58.82 (−70.82 to −49.46)	88.57 (66.86 to 107.98)	−86.5 (−96.15 to −78.98)	39.28 (29.91 to 47.7)	−137.48 (−141.81 to −133.72)	−3.73 (−3.86 to −3.6)
High-middle SDI	2,040,063.18 (1,609,455.97 to 2,454,979.38)	77.5 (53.67 to 104.53)	156.44 (123.42 to 188.26)	26.32 (6.88 to 48.37)	105.48 (82.94 to 127.18)	−83.04 (−92.42 to −72.14)	−2.02 (−2.19 to −1.85)
Middle SDI	2,141,966.76 (1,678,561.34 to 2,577,051.02)	365.73 (298.72 to 440.45)	87.48 (68.55 to 105.25)	198.07 (150.92 to 250.65)	91.44 (71.42 to 109.8)	−13.2 (−34 to 10.56)	−0.14 (−0.2 to −0.09)
Low-middle SDI	1,289,247.06 (1,024,120.25 to 1,539,605.02)	317.77 (268.03 to 378.6)	67.11 (53.31 to 80.14)	113.02 (82.95 to 149.79)	103.87 (82.65 to 124.1)	3.81 (−15.61 to 27.01)	0.31 (0.24 to 0.39)
Low SDI	334,779.02 (255,095.17 to 414,696.04)	241.08 (192.61 to 298.39)	29.96 (22.83 to 37.11)	−2.12 (−23.86 to 23.6)	84.26 (64.28 to 103.94)	−6.69 (−26.87 to 16.82)	−0.12 (−0.21 to −0.03)
WHO regions							
African Region	340,626.16 (266,859.9 to 412,830.87)	271.51 (218.8 to 335.37)	29.48 (23.09 to 35.73)	7.83 (−15.4 to 35.98)	91.68 (71.88 to 110.45)	11.93 (−10.65 to 39.27)	0.07 (−0.05 to 0.19)
Eastern Mediterranean Region	559,551.69 (432,061.22 to 683,217.09)	243.05 (190.97 to 304.16)	74.31 (57.38 to 90.73)	21.06 (−4.92 to 51.55)	155.55 (120.68 to 189.35)	−20.32 (−40.13 to 3.39)	−0.25 (−0.31 to −0.19)
European Region	1,621,627.93 (1,269,806.4 to 1,911,034.99)	−41.54 (−50.16 to −33.83)	173.73 (136.04 to 204.73)	−54.29 (−62.22 to −47.21)	87.31 (68.99 to 102.77)	−111.03 (−115.13 to −106.93)	−2.91 (−3.15 to −2.68)
Region of the Americas	694,078.11 (524,525.02 to 836,241.87)	26.09 (10.71 to 40.34)	67.59 (51.08 to 81.44)	−42.32 (−53.05 to −32.38)	50.07 (37.85 to 60.31)	−105.52 (−111.69 to −99.74)	−2.45 (−2.56 to −2.35)
South-East Asia Region	1,510,410.11 (1,197,271.09 to 1,817,461)	381.36 (316.1 to 461.73)	73.19 (58.02 to 88.07)	167.13 (125.92 to 217.89)	95.99 (75.92 to 115.69)	4.72 (−17.32 to 32.29)	0.14 (0.05 to 0.23)
Western Pacific Region	2,035,607.26 (1,533,832.54 to 2,581,413.18)	396.45 (291.14 to 528.83)	105.73 (79.67 to 134.08)	277.56 (193.24 to 383.55)	75.03 (56.31 to 95.38)	−18.28 (−48.27 to 18.87)	0.15 (0.06 to 0.25)

Abbreviation: *CVD* cardiovascular disease, *SDI* socio-demographic index

CVD burden attributable to high systolic blood pressure in different countries around the world

In 2021, China, India, and the Russian Federation had the highest cases of CVD deaths and DALYs due to HSBP, while Tokelau, Niue, and Nauru had the lowest number of CVD deaths and DALYs (Table S3). In 2021, the ASMR for CVD due to HSBP was the highest in Nauru, Ukraine, and Egypt, and the lowest in Japan, San Marino, and Singapore. The ASDR were highest in Nauru, Egypt, and Turkmenistan, and lowest in San Marino, South Korea, and Switzerland (Table S3). In most countries, the ASMR

Table 2 The trends in CVD DALYs attributable to high systolic blood pressure by global, sex, SDI, and WHO regions from 1990 to 2021

	DALYs		All-age DALYs		Age-standardized DALYs		
	Number in 2021, n	Change of numbers 1990–2021, %	Rate in 2021, per 100,000	Percent change 1990–2021, %	Rate in 2021, per 100,000	Percent change 1990–2021, %	Net drift of mortality, % per year
Global	135,019,809.48 (106,718,820.24 to 160,988,651.37)	115.01 (93.63 to 138.23)	1710.98 (1352.35 to 2040.06)	12.91 (−1.54 to 28.6)	1587.1 (1255.42 to 1892.76)	−64.82 (−73.72 to −55.25)	−1.16 (−1.2 to −1.12)
Sex							
Female	57,493,118.1 (45,361,320.47 to 68,817,764.83)	87.61 (66.83 to 111.8)	1462.2 (1153.66 to 1750.21)	−6.32 (−20.31 to 9.98)	1237.95 (977.32 to 1482.16)	−75.17 (−84.19 to −64.92)	−1.39 (−1.43 to −1.35)
Male	77,526,691.39 (60,387,260.9 to 93,415,617.92)	142.45 (109.82 to 178.8)	1958.05 (1525.17 to 2359.34)	32.29 (10.16 to 56.95)	1971.97 (1537.06 to 2379.38)	−54.83 (−67.88 to −40.57)	−0.96 (−1.03 to −0.9)
SDI							
High SDI	16,187,132.58 (12,465,955 to 19,551,132.59)	−61.87 (−70.95 to −53.27)	1479.56 (1139.43 to 1787.05)	−88.95 (−96.26 to −82.04)	739.79 (573.61 to 893.21)	−130.61 (−135.14 to −126.46)	−3.52 (−3.59 to −3.45)
High-middle SDI	36,809,567.69 (29,165,851.23 to 44,096,962.69)	59.65 (37.29 to 84.48)	2822.75 (2236.59 to 3381.59)	11.77 (−6.47 to 32.02)	1874.5 (1483.59 to 2246.36)	−79.3 (−89.4 to −67.99)	−1.89 (−1.99 to −1.8)
Middle SDI	44,295,721.23 (34,604,766.6 to 53,646,514.99)	312.6 (254.25 to 380.7)	1809.06 (1413.28 to 2190.96)	160.69 (119.63 to 208.61)	1724.44 (1351.96 to 2086.23)	−13.88 (−34.09 to 9.23)	−0.09 (−0.14 to −0.04)
Low-middle SDI	29,601,801.27 (23,340,142.41 to 35,511,426.19)	292.26 (244.21 to 349.54)	1540.87 (1214.93 to 1848.48)	97.6 (68.55 to 132.22)	2118.95 (1679.45 to 2538.46)	2.87 (−16.27 to 24.82)	0.33 (0.26 to 0.39)
Low SDI	7,984,516.89 (6,121,610.08 to 9,849,911.31)	228.15 (178.95 to 281.86)	714.57 (547.85 to 881.52)	−7.91 (−29.99 to 16.18)	1679.29 (1283.96 to 2070.88)	−10.9 (−30.89 to 12.04)	−0.09 (−0.17 to −0.02)
WHO regions							
African Region	7,693,527.81 (6,026,347.46 to 9,333,399.42)	262.84 (213.31 to 324.46)	665.82 (521.54 to 807.74)	4.01 (−17.82 to 31.18)	1705.17 (1344.16 to 2056.48)	5.24 (−16.35 to 31.14)	0.1 (0.03 to 0.17)
Eastern Mediterranean Region	13,237,214.95 (10,130,286.01 to 16,275,208.11)	250.33 (196.04 to 313.03)	1757.87 (1345.27 to 2161.3)	24.7 (−2.39 to 55.98)	3063.18 (2362.86 to 3750.75)	−21.13 (−41.73 to 2.64)	−0.22 (−0.28 to −0.17)
European Region	27,971,447.29 (22,410,379.22 to 32,728,777.1)	−50.4 (−57.8 to −43.22)	2996.62 (2400.85 to 3506.28)	−62.44 (−69.25 to −55.84)	1637.24 (1312.41 to 1916.97)	−106.92 (−111.37 to −102.43)	−2.79 (−2.92 to −2.67)
Region of the Americas	12,792,855.1 (9,951,774.16 to 15,380,506.24)	24.44 (12.37 to 36.68)	1245.81 (969.13 to 1497.8)	−43.47 (−51.89 to −34.94)	945.94 (735.74 to 1137.13)	−101.1 (−106.47 to −95.87)	−2.39 (−2.45 to −2.32)
South-East Asia Region	34,772,025.91 (27,450,927.04 to 42,007,046.93)	326.31 (271.39 to 394.53)	1685.01 (1330.24 to 2035.61)	132.37 (97.69 to 175.45)	1966.9 (1558.46 to 2367.93)	−1.76 (−22.43 to 23.99)	0.15 (0.07 to 0.24)
Western Pacific Region	38,143,900.43 (28,564,006.65 to 48,354,398.15)	327.91 (232.25 to 439.97)	1981.21 (1483.63 to 2511.55)	222.68 (146.09 to 312.41)	1366.28 (1021.12 to 1730.95)	−11.38 (−43.58 to 27.4)	0.23 (0.15 to 0.3)

Abbreviation: *CVD* cardiovascular disease, *SDI* socio-demographic index

and ASDR for CVD due to HSBP showed a declining trend, with the largest decreases observed in the United Kingdom, South Korea, and Singapore (Fig. 2 and Table S3). A similar pattern was observed in the ASMR and ASDR of IHD and IS across different countries (Figures S3 and S4).

The burden of CVD attributable to high systolic blood pressure by sex and age globally

Age-specific CVD deaths and DALYs attributable to HSBP increased with age, except for DALYs in individuals aged over 80. This pattern was similar across CVD subtypes (Fig. 3). Notably, the proportion of deaths was

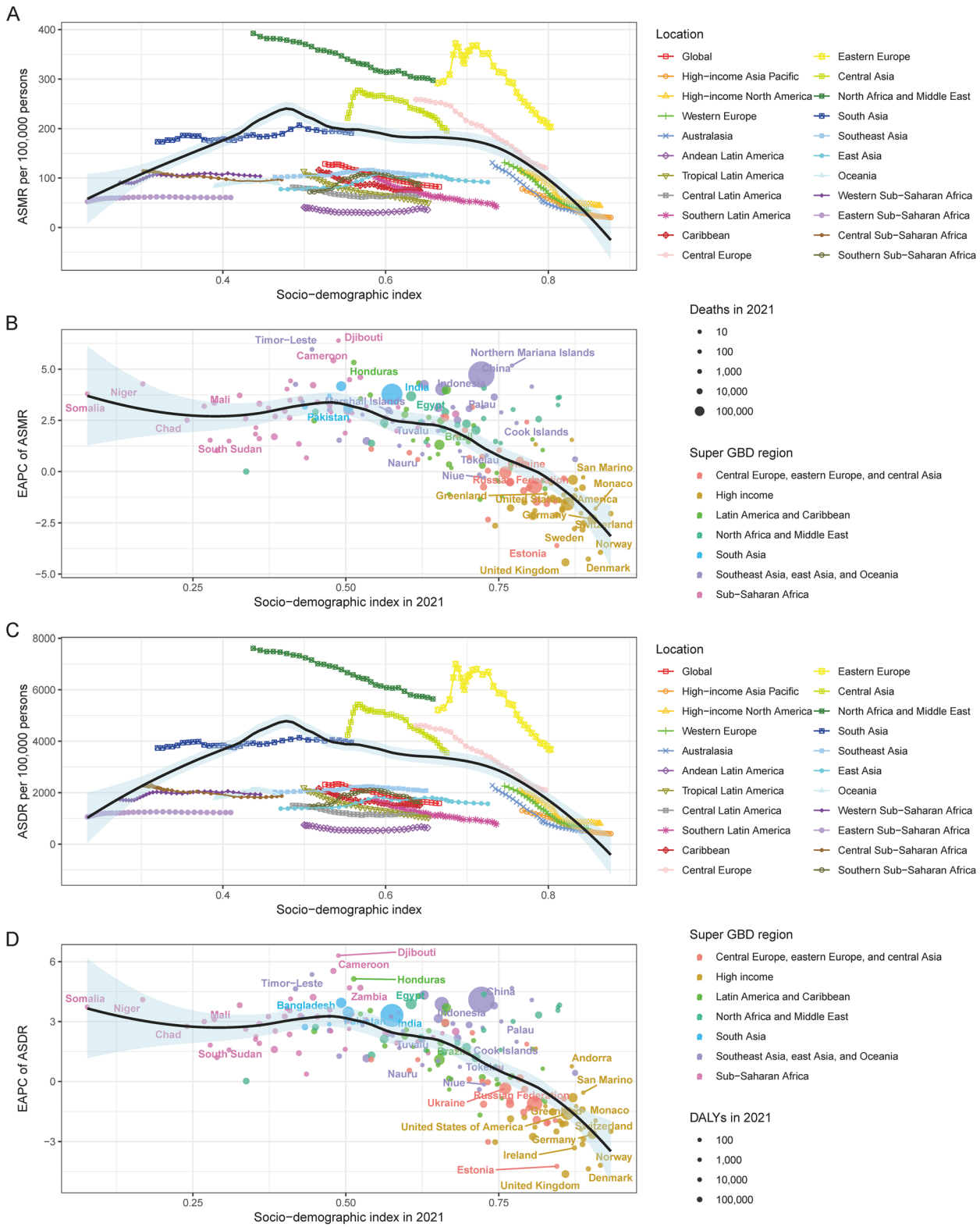


Fig. 1 **A** The global relationship between SDI levels and the ASMR for CVD attributable to HSBP from 1990 to 2021 (**B**) The EAPC of ASMR from 1990 to 2021 across seven super GBD regions (**C**) The global relationship between SDI levels and the ASDR for CVD attributable to HSBP from 1990 to 2021 (**D**) The EAPC of ASDR from 1990 to 2021 across seven super GBD regions

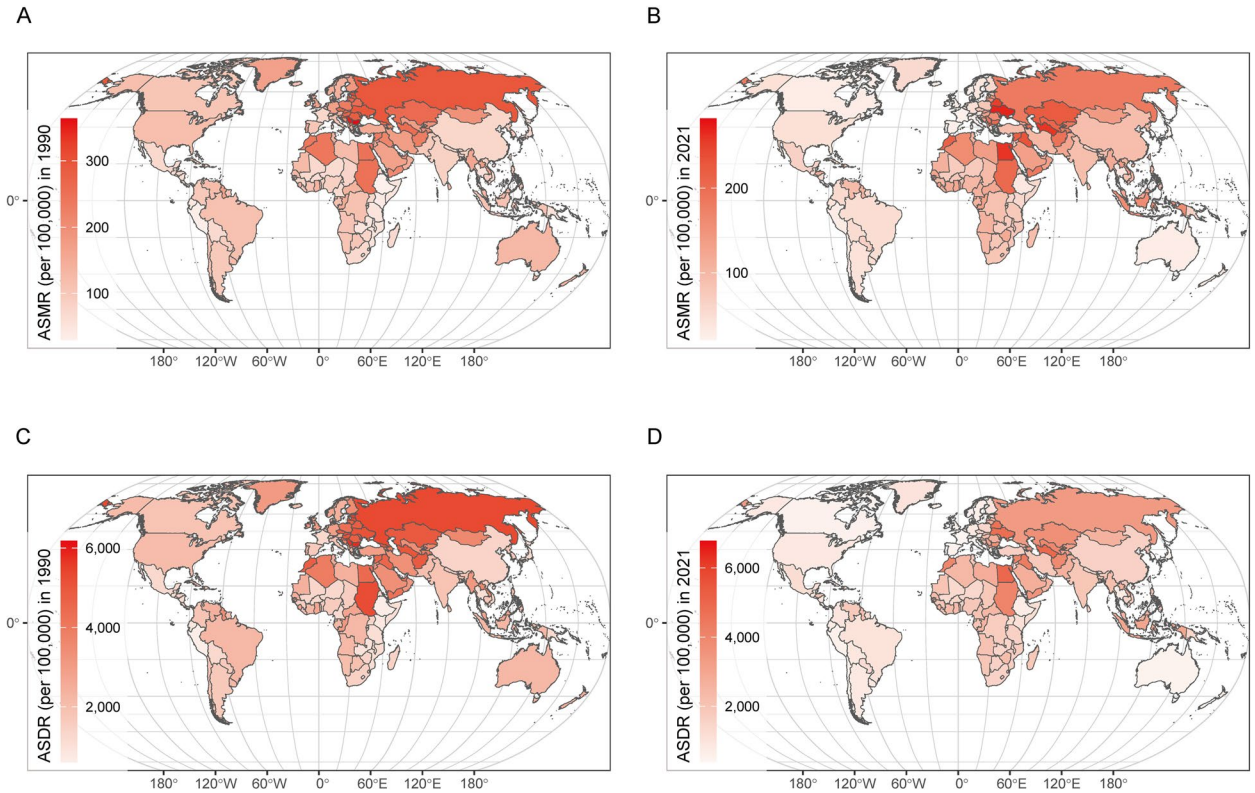


Fig. 2 World map of ASMR and ASDR to CVD attributable to HSBP in 1990 and 2021, and the change of ASMR and ASDR globally from 1990 to 2021. **A** ASMR of CVD attributable to HSBP in 1990. **B** ASMR of CVD attributable to HSBP in 2021. **C** ASDR of CVD attributable to HSBP in 1990. **D** ASDR of CVD attributable to HSBP in 2021

highest in the 80 and above age group, while the proportion of DALYs was highest in the 70–79 age group. Regarding gender, in 1990, the peak number of deaths for females occurred in the 80 and above age group, accounting for 47.1%, while for males, the peak was in the 70–79 age group, accounting for 31.1%. In 2021, the deaths peak for both males and females waas in the 80 and above age group, accounting for 52.5% and 34.5%, respectively (Figure S5). In 1990, the DALYs peak for females was in the 70–79 age group, accounting for 32.0%, while the peak for males was in the 60–69 age group, accounting for 29.6%. In 2021, the DALYs peak for females was in the 80 and above age group, accounting for 32.2%, while the peak for males was in the 70–79 age group, accounting for 25.3% (Figure S7). Overall, age-specific DALYs and deaths from CVD attributable to HSBP showed an aging trend.

From 1990 to 2021, regardless of age group and CVD subtype differences, the global deaths rate and DALYs rate of CVD attribute to HSBP declined, with the most significant decrease observed in the elderly population (Fig. 3). In terms of gender, the decline in death rates and DALYs rates was greater for females than for males. From 1990, when the death rates and DALYs rates of females aged 80 and above were higher than those of males, it shifted by 2021, with the mortality rate and DALYs rate of males surpassing those of females (Figures S6 and S8). Over the past 32 years, the deaths rate for males was higher than for females in most age groups. Additionally, from 1990 to 2021, the ASMR and ASDR of CVD attributable to HSBP showed a downward trend in the 50 and above age groups with fluctuations being more pronounced among females (Figs. 4 and 5).

Local drift, age, period, and cohort effects on the Burden of CVD due to high systolic blood pressure

After controlling for period and cohort effects, the age effect results for the CVD burden attributable to HSBP indicate that ASMR and ASDR increase with age (Figs. 4 and 5). In males, ASMR and ASDR increased with age up to the 90–94 age group, and then decreased in the 95 and above age group. In females, ASMR and ASDR showed a continuous upward trend with age. A similar age effect was observed across cardiovascular subtypes (Figs. 4 and 5).

For the period effect, the rate ratio (RR) for both sexes showed a downward trend over time. Before 2010, the RR

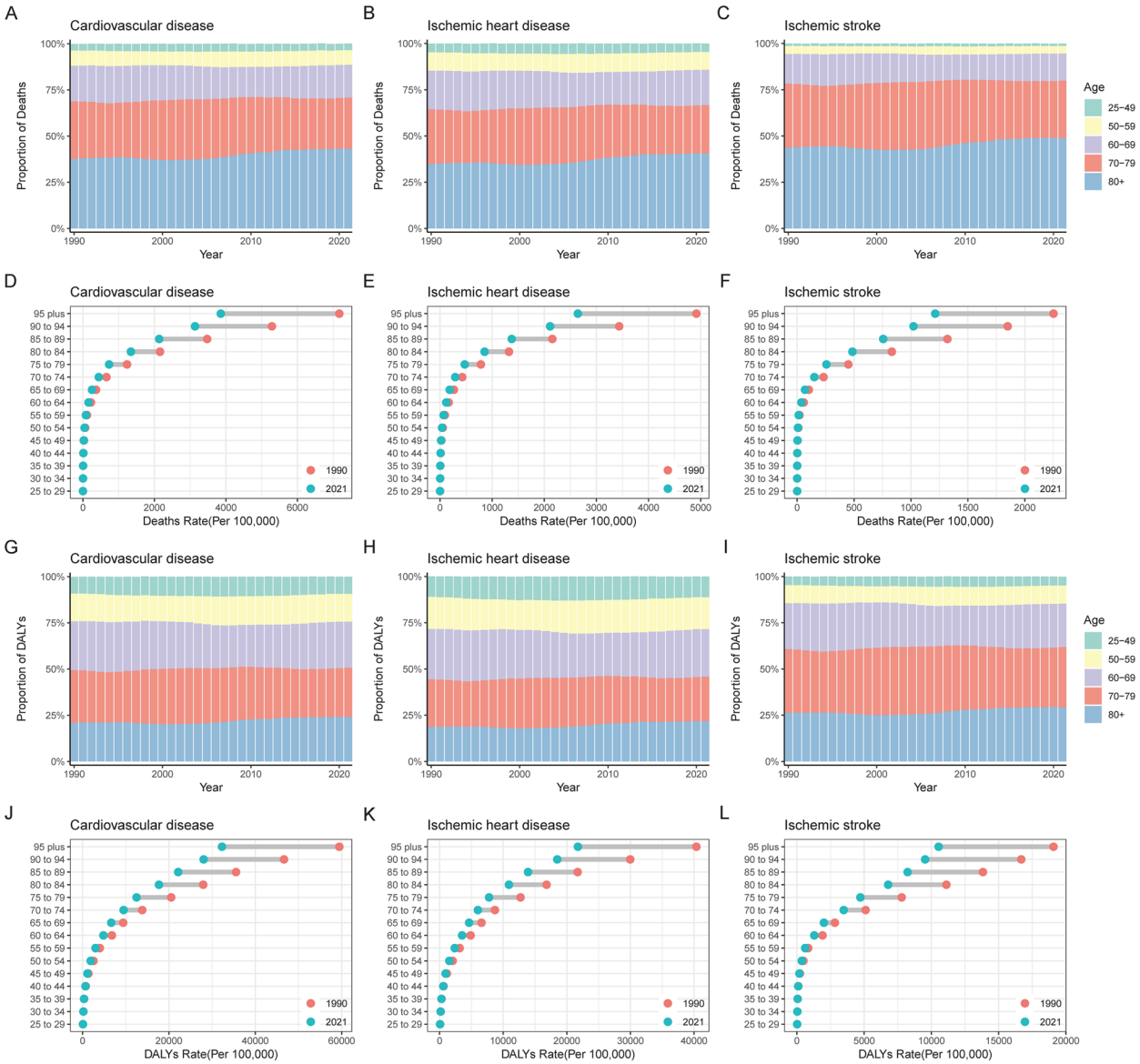


Fig. 3 Temporal changes in CVD-related mortality and DALYs attributed to HSBP across all age groups globally from 1990 to 2021. **A**-**C** The relative proportion of CVD-related mortality, (D)(E)(F) the temporal changes in the mortality rate of CVD, (**G**-**I**) The relative proportion of CVD-related DALYs, **J**-**L** The temporal changes in the DALYs rate of CVD

for males was lower than for females, but as the decline in females was faster, the RR for females became lower than that for males after 2010 (Figs. 4 and 5). A similar period effect was observed across cardiovascular subtypes.

For the cohort effect, the RR of death rates and DALYs rates from CVD and its subtypes due to HSBP are higher in earlier birth cohorts compared to later birth cohorts. With increasing birth years, the RR of death rates and DALYs rates for CVD and its subtypes due to HSBP gradually decrease (Figs. 4 and 5). Before the 1930 birth cohort, the decline in RR was greater for females. after the 1930 birth cohort, the rate of decline in RR became similar for both males and females.

Joinpoint regression analysis of the global CVD burden attributable to high systolic blood pressure

The joinpoint regression analysis results indicate that over the past 32 years, the ASMR and ASDR of CVD attributable to HSBP have shown an overall declining trend (Figs. 6 and 7). The AAPC for ASMR and ASDR

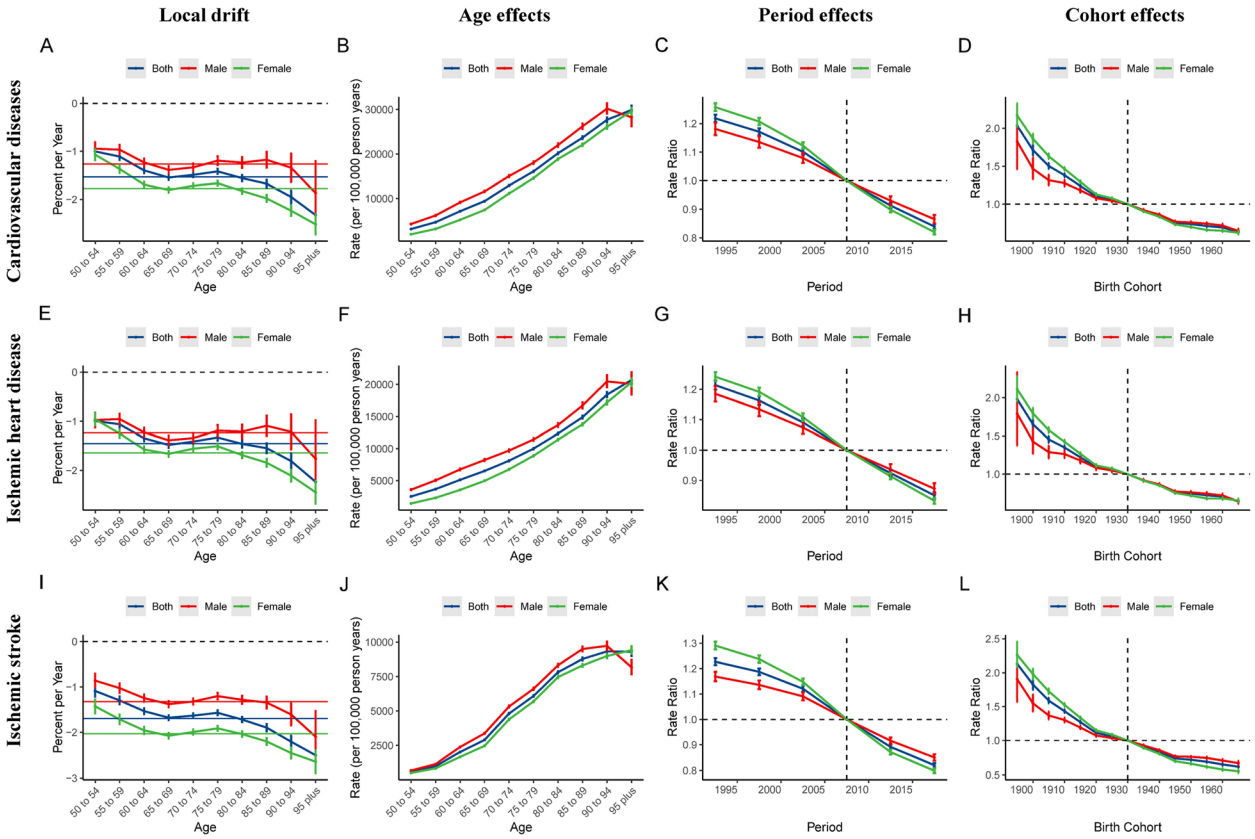


Fig. 4 The local drifts, age effects, period effects, and cohort effects of CVD-related mortality attributable to HSBP worldwide from 1990 to 2021

were −1.43% (95% CI: −1.64 to −1.22) and −1.19% (95% CI: −1.35 to −1.03), respectively. The most significant decline occurred from 2003 to 2007, with APCs of −2.56% (95% CI: −3.38 to −1.72) and −2.18% (95% CI: −2.88 to −1.47), respectively (Table 3). Cardiovascular subtypes showed a similar trend. The AAPC of ASMR and ASDR for IHD attributable to HSBP were −1.31% (95% CI: −1.5 to −1.12) and −1.15% (95% CI: −1.31 to −0.98), respectively. The most significant decrease in ASMR occurred from 1994 to 1998, with an annual percent change of −2.13% (95% CI: −2.89 to −1.37). The most significant decrease in ASDR occurred from 2004 to 2007, with an annual percent change of −3.21% (95% CI: −4.46 to −1.93). The AAPC of ASMR and ASDR for IS attributable to HSBP were −1.15% (95% CI: −1.31 to −0.98) and −1.35% (95% CI: −1.54 to −1.17), respectively. The most significant decrease in ASMR occurred from 2003 to 2007, with an annual percent change of −3.21% (95% CI: −4.02 to −2.4). The most significant decrease in ASDR occurred from 2004 to 2007, with an annual percent change of −3.21% (95% CI: −4.46 to −1.93) (Table 3). In terms of gender, over the past 32 years, the ASMR and ASDR of CVD and its subtypes attributable to HSBP have declined for both males and females (Figures S9 and S10).

Prediction of the Burden of CVD attribute to high systolic blood pressure from 2022 to 2025

The BAPC model was used to predict the burden of CVD attributed to HSBP from 2022 to 2045.It is projected that from 2022 to 2045, global cases of CVD deaths and DALYs attributed to HSBP will continue to increase, reaching approximately 12,870,828.11 (95% CI: 0 to 26,622,683.15) and 243,097,568.34 (95% CI: 918,560.74 to 487,506,838.82) by 2045.Meanwhile, ASMR and ASDR are projected to show a continuous downward trend, reaching approximately 137.99 per 100,000 (95% CI: 0 to 285.45) and 2890.63 per 100,000 (95% CI: 10.13 to 5805.96) by 2045 (Figs. 8 and 9). It is predicted that the increase in male deaths and DALYs from 2022 to 2045 will be significantly higher than those for females, while the reduction in ASMR and ASDR for females will be significantly greater than those for males (Figures S11 and S12). By 2045, the burden of CVD attributed to HSBP will remain greater for men than for women.

Discussion

This study is the first to comprehensively analyze the global burden of CVD attribute to HSBP from 1990 to 2021, along with its temporal trends, and predict future

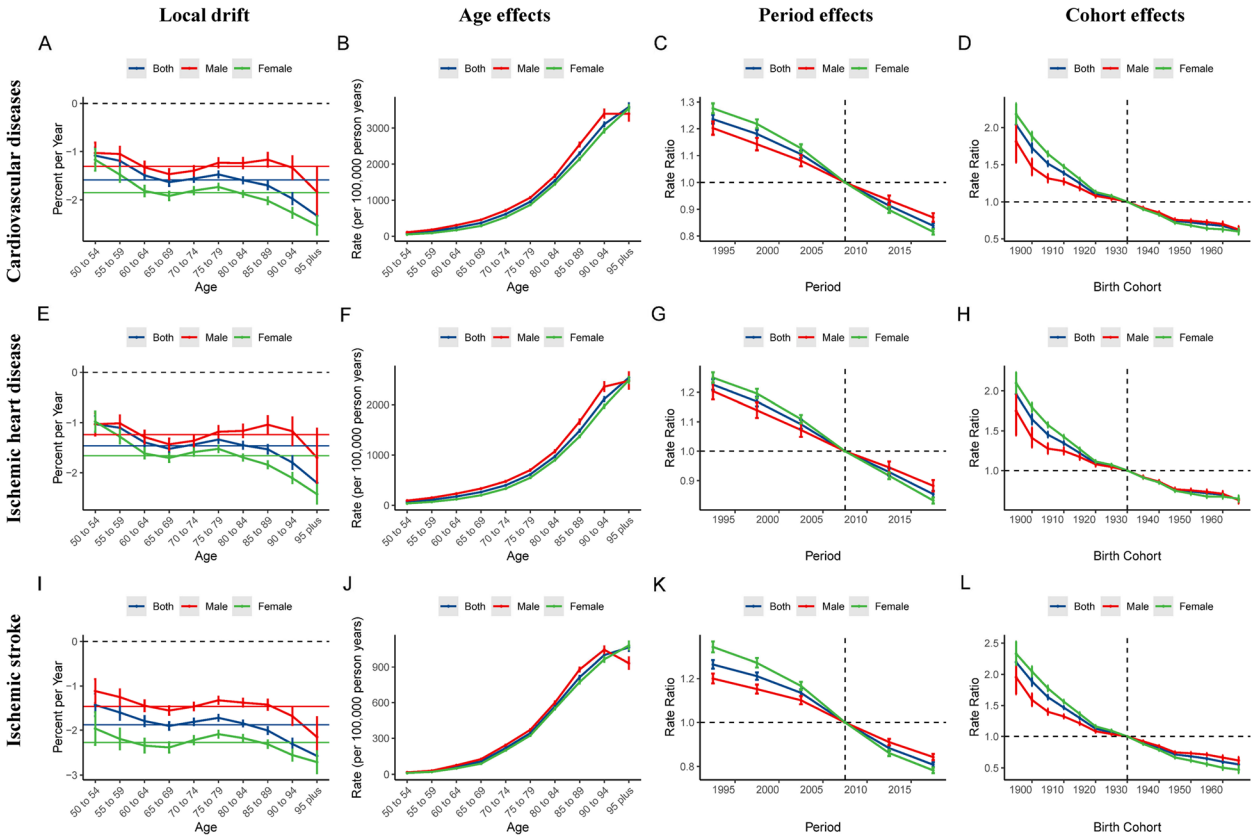


Fig. 5 The local drifts, age effects, period effects, and cohort effects of CVD-related DALYs attributable to HSBP worldwide from 1990 to 2021

patterns. Over the past 32 years, the ASMR and ASDR attribute to HSBP have generally decreased, indicating relative progress in the treatment and prevention of CVD over time. The number of deaths and DALYs attributable to CVD caused by HSBP has more than doubled, potentially driven by population growth and aging. There are significant differences in the CVD burden across different age groups, genders, CVD subtypes, and GBD regions and countries. According to predictions using the BAPC model, the number of death and DALYs is expected to continue increasing, while ASDR and ASMR are anticipated to keep declining. The findings of this study highlight the critical role of HSBP in the global burden of CVD and provide a theoretical basis for formulating intervention strategies.

HSBP is a key risk factor for CVD. Hypertension leads to arterial stiffness by affecting the balance of elastin and collagen, oxidative stress, inflammatory responses, vascular smooth muscle cell phenotype changes, and endothelial dysfunction [17]. This pathological process increases the risk of CVD. The PURE study indicates that sodium intake is positively correlated with blood pressure, which may increase the risk of hypertension [18]. Some prospective cohort studies and meta-analyses of randomized trials suggest a U-shaped relationship between sodium intake and cardiovascular risk, where both low and high sodium intake are associated with higher risks [19]. Therefore, reducing sodium intake is considered a cost-effective strategy for preventing hypertension and CVD, thereby reducing the disease burden they cause.

The burden of CVD attribute to HSBP varies significantly across different SDI regions and countries. The middle-SDI regions experienced the largest increase in mortality and DALYs, while high-SDI regions showed the greatest decline. Low-middle SDI regions observed the most notable rise in ASDR and ASMR, whereas high-SDI regions demonstrated a significant decrease. This contrast highlights the profound impact of socioeconomic development on health outcomes [20, 21]. Although high-SDI regions have more CVD risk factors, their more robust healthcare systems and higher-quality medical services significantly alleviate the burden of CVD [22, 23].

In contrast, middle-SDI regions, such as China, India, and the Russian Federation, experienced the largest increase in mortality and DALYs, which could be attributed to their large population bases [24, 25]. Middle-SDI

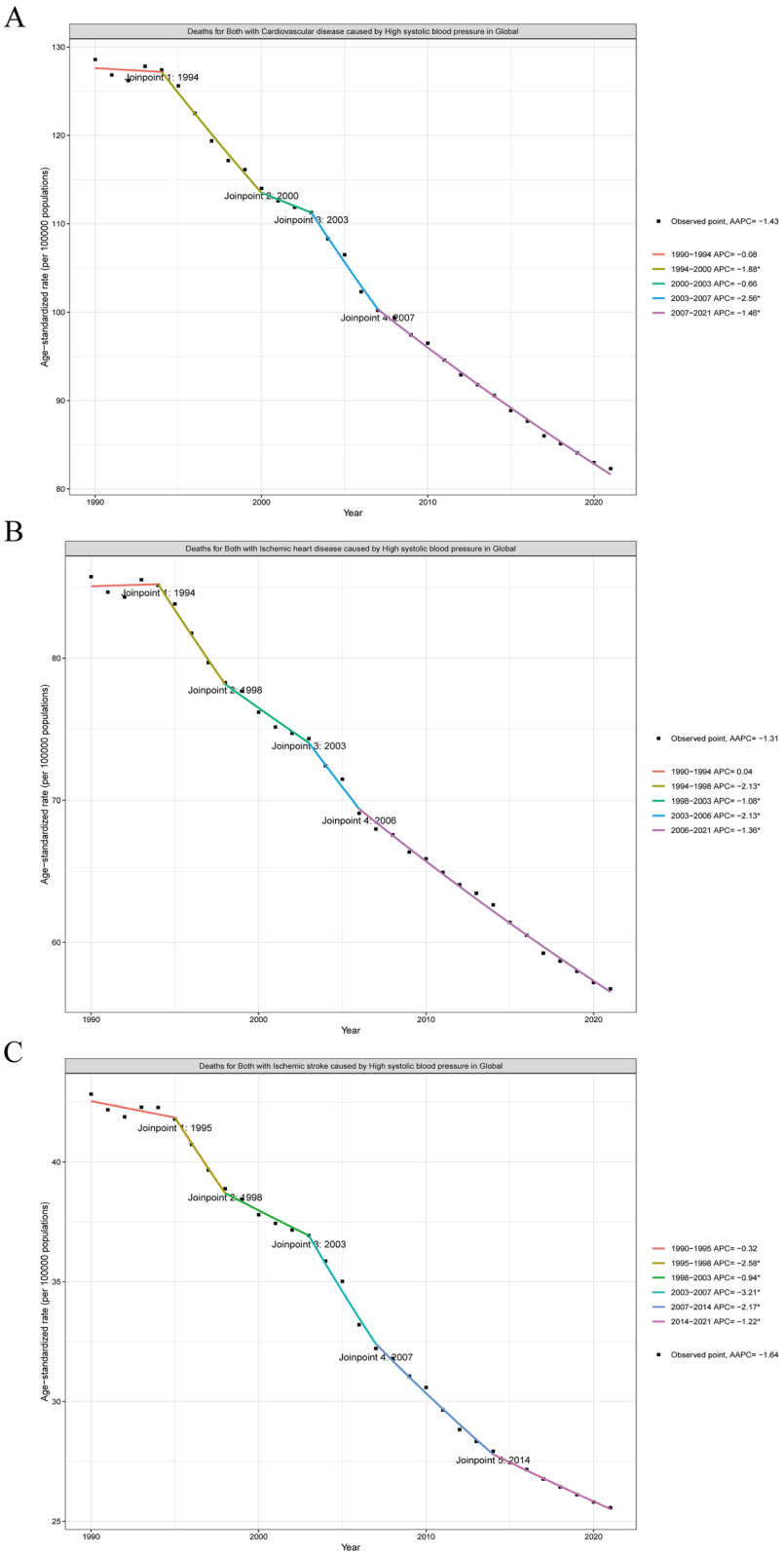


Fig. 6 The joinpoint regression analysis of the age -standardized death rate for CVD attributable to HSBP in global from 1990 to 2021. **A** The joinpoint regression analysis of the age -standardized death rate for CVD, **B** The joinpoint regression analysis of the age -standardized death rate for ischemic heart disease, **C** The joinpoint regression analysis of the age -standardized death rate for ischemic stroke

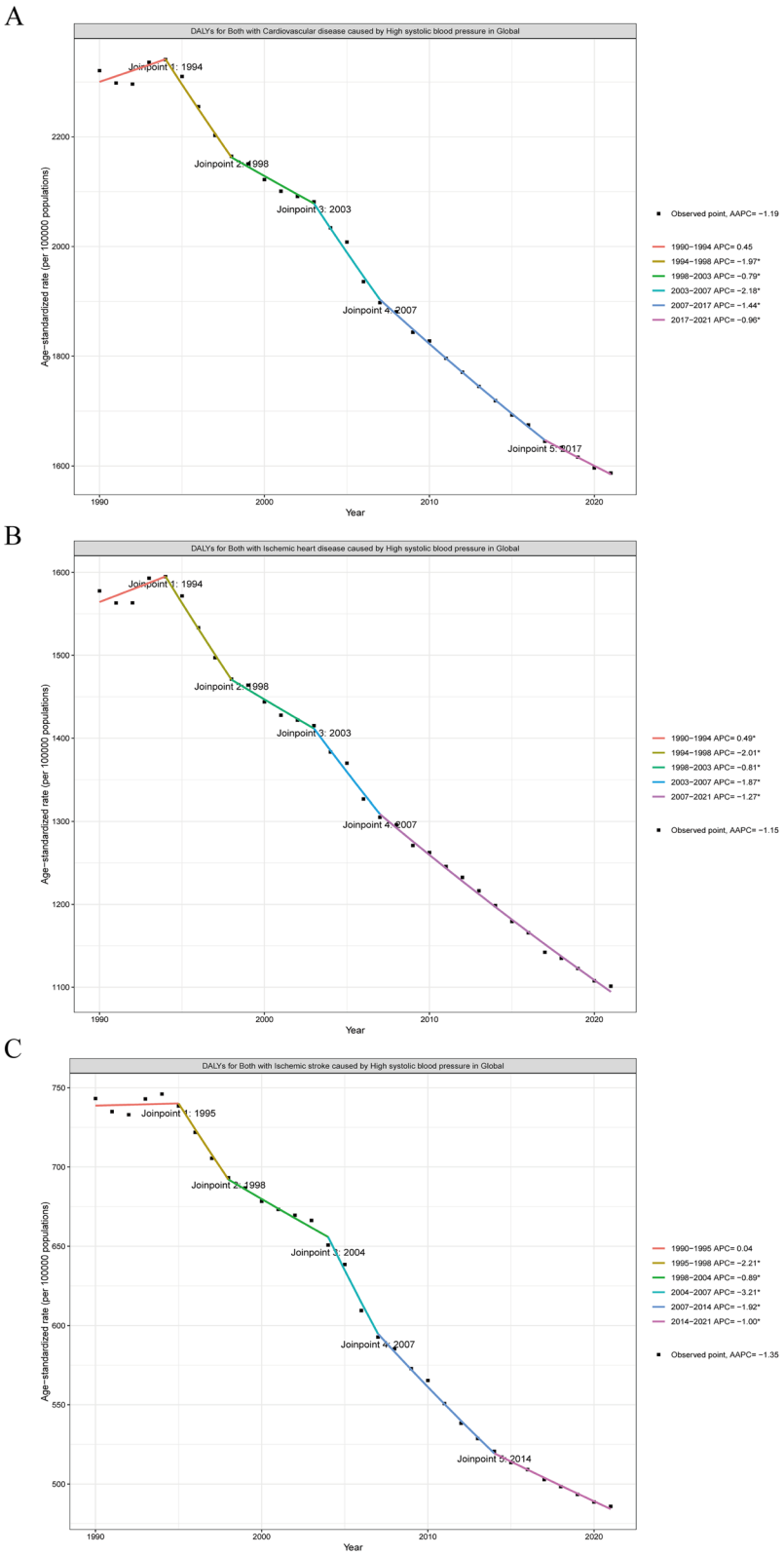


Fig. 7 The joinpoint regression analysis of the age -standardized DALYs rate for CVD attributable to HSBP in global from 1990 to 2021. **A** The joinpoint regression analysis of the age -standardized DALYs rate for CVD, **B** The joinpoint regression analysis of the age -standardized DALYs rate for ischemic heart disease, **C** The joinpoint regression analysis of the age -standardized DALYs rate for ischemic stroke

Table 3 The results of the AAPC, showing the trends in age-standardized Deaths and DALYs rates (per 100,000 persons) for CVD attributable to High Systolic Blood Pressure by Sex and CVD Subtype in the Global from 1990 to 2021

Deaths				Dalys			
Sex	**Period**	**AAPC (95% CI)**	***P* value**	**Sex**	**Period**	**AAPC (95% CI)**	***P* value**
Cardiovascular disease				Cardiovascular disease			
Both	1990–2021	−1.43 (−1.64 to −1.22)	< 0.001	Both	1990–2021	−1.19 (−1.35 to −1.03)	< 0.001
Male	1990–2021	−1.15 (−1.33 to −0.98)	< 0.001	Male	1990–2021	−1.01 (−1.19 to −0.83)	< 0.001
Female	1990–2021	−1.67 (−1.89 to −1.45)	< 0.001	Female	1990–2021	−1.46 (−1.63 to −1.29)	< 0.001
Ischemic heart disease				Ischemic heart disease			
Both	1990–2021	−1.31 (−1.5 to −1.12)	< 0.001	Both	1990–2021	−1.15 (−1.31 to −0.98)	< 0.001
Male	1990–2021	−1.09 (−1.3 to −0.88)	< 0.001	Male	1990–2021	−1 (−1.14 to −0.85)	< 0.001
Female	1990–2021	−1.54 (−1.77 to −1.32)	< 0.001	Female	1990–2021	−1.37 (−1.53 to −1.21)	< 0.001
Ischemic stroke				Ischemic stroke			
Both	1990–2021	−1.64 (−1.85 to −1.42)	< 0.001	Both	1990–2021	−1.35 (−1.54 to −1.17)	< 0.001
Male	1990–2021	−1.26 (−1.45 to −1.07)	< 0.001	Male	1990–2021	−1.05 (−1.23 to −0.86)	< 0.001
Female	1990–2021	−1.94 (−2.16 to −1.72)	< 0.001	Female	1990–2021	−1.62 (−1.82 to −1.42)	< 0.001

regions are still undergoing socioeconomic transitions and development, characterized by uneven distribution of healthcare resources, limited access to medical services, and low rates of health education dissemination [26]. These factors may prevent patients with high SBP from accessing timely and high-quality medical services, including blood pressure monitoring, pharmacological treatment, and complication management, thereby increasing the disease burden [27]. Additionally, low education levels, limited access to health information, and a lack of public health campaigns are prevalent in middle-SDI regions [28, 29]. These issues contribute to insufficient public awareness of HSBP and associated cardiovascular risk factors, hindering effective prevention and self-management measures. Therefore, policymakers in middle-SDI regions should dedicate more effort to resource allocation, healthcare system development, and disease prevention to mitigate the CVD burden attribute to HSBP.

Based on age analysis, our results indicate that with increasing age, the number of deaths and DALYs attribute to HSBP significantly increases, with a shift in deaths and DALYs towards the elderly population for both men and women. This is similar to previous studies. The pace of population aging is accelerating rapidly, and by 2050, the global population aged 60 and above is expected to reach approximately 2 billion, accounting for 18% of the total global population [30]. The extension of life expectancy and population aging increase the number of adults suffering from CVD [31]. With age, changes in arterial structure and function increase the risk of CVD [32]. The burden of coronary artery plaque also increases with age [33]. In addition, elderly people often suffer from multiple diseases such as diabetes, hypertension, and hyperlipidemia, which significantly increase the risk of CVD [34]. Therefore, governments need to develop tailored healthcare strategies for different age groups, especially the elderly population, to effectively reduce the burden of CVD.

The gender differences in CVD burden attribute to HSBP are significant, which is critical for disease management and prevention strategies. Our study shows that the CVD burden is generally higher in men compared to women. Physiological factors play an important role in gender differences, as estrogen exerts protective effects on CVD by regulating lipid metabolism, promoting endothelial function, preventing atherosclerosis, and countering myocardial ischemia [35, 36]. However, this protective effect significantly weakens after menopause in women. With the significant decline in estrogen levels after menopause, the CVD burden in women rises substantially. Additionally, unhealthy lifestyles in men, such as smoking, excessive alcohol consumption, unhealthy

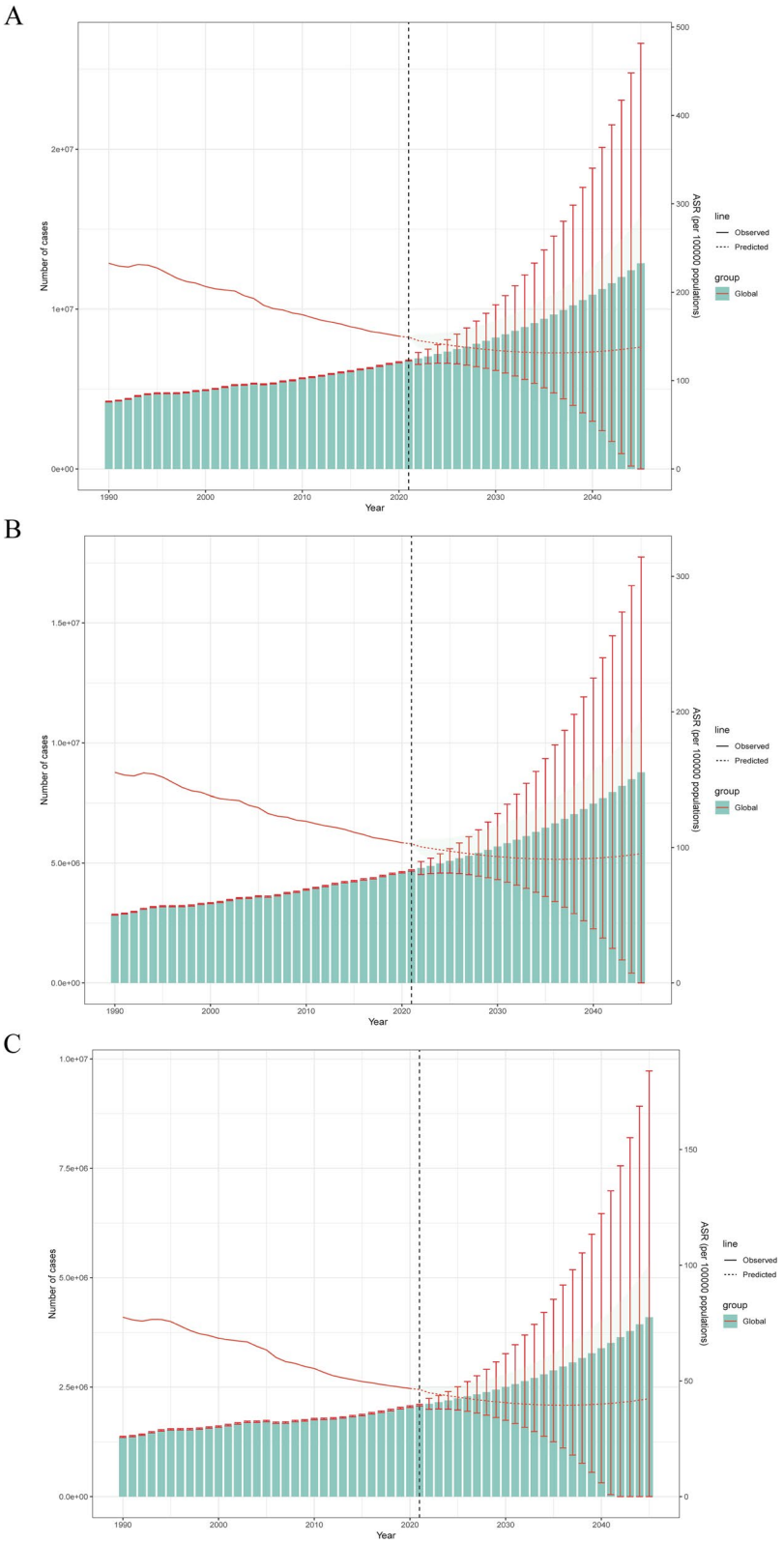


Fig. 8 Temporal trend in the number of deaths and ASMR for CVD from 1990 to 2045. **A** Temporal trend in the number of deaths and ASMR for CVD from 1990 to 2045, **B** Temporal trend in the number of deaths and ASMR for ischemic heart disease from 1990 to 2045, **C** Temporal trend in the number of deaths and ASMR for ischemic stroke from 1990 to 2045. Solid lines represent observed ASMR, and dashed lines represent ASMR predicted by the BAPC model

diets, and lack of exercise, also significantly increase the CVD burden. Men are more likely to ignore early symptoms and delay seeking medical attention until the disease progresses to more severe stages, thereby increasing the disease burden [37]. Developing differentiated management and prevention strategies targeting gender differences is key to improving cardiovascular health.

The joinpoint regression model indicates that the ASMR and ASDR of CVD caused by HSBP for both males and females have an AAPC of less than 0. The APC model estimates that their net drift values are less than 0. These two findings collectively demonstrate that the ASMR and ASDR for both males and females showed a decreasing trend from 1990 to 2021. This indicates that the burden of CVD attribute to HSBP has significantly improved. This change is mainly attributed to the following aspects. Firstly, modern medicine has made significant advances in the diagnosis and treatment of CVD. For example, the widespread use of early diagnostic tools for hypertension and antihypertensive medications has made blood pressure management more effective [38]. Secondly, many countries have actively promoted healthy lifestyles through public health policies, such as limiting high-salt diets, raising awareness of the dangers of hypertension, encouraging exercise, and promoting smoking cessation. Thirdly, with enhanced accessibility to medical services, more people can receive standardized hypertension management, especially in low- and middle-income countries [27].

Period effects indicate that the risk of CVD caused by HSBP has declined over time. Period effects are usually influenced by a combination of historical events and environmental factors. Therefore, improvements in healthcare, rapid economic development, and lifestyle changes may be the reasons for the decline in risk.

Birth cohort analysis indicates that individuals born in earlier cohorts have a higher relative risk compared to those born in later cohorts. Before the 1930 birth cohort, the decline in relative risk was more pronounced for females, while after the 1930 cohort, the decline was similar for both males and females. Individuals in earlier birth cohorts may have experienced wars, which not only worsened living and sanitary conditions but also directly threatened life and health. With socioeconomic development and improved education levels, younger generations have acquired more comprehensive health knowledge and better access to medical resources, which may be associated with the reduction in relative risk [39]. Before the nineteenth century, women generally had lower social status, and the allocation of medical resources often favored men, resulting in women facing inequities in the healthcare field. Around the twentieth century, with socioeconomic development and the rise of the women's movement, awareness of women's rights gradually strengthened. Some advanced countries began focusing on women's health issues and took steps to improve their status and treatment in the healthcare field [40]. This may explain the significant changes in the relative risk of female birth cohorts around 1930.

According to the BAPC prediction model, the global burden of CVD caused by HSBP from 2022 to 2045 will follow the current trend. The increase in male deaths and DALYs is significantly higher than that of females, while the decline in female ASMR and ASDR is significantly greater than that of males. By 2045, the burden of CVD caused by HSBP in males will still be higher than in females. This trend calls for greater attention to the risks of the CVD burden caused by HSBP, especially among men, and the formulation of targeted prevention and treatment policies to reduce the disease burden.

This study has the following limitations. First, the GBD study itself has certain limitations. The accuracy of the GBD database is limited by the quality and quantity of the original data. Although various statistical methods were used to correct data uncertainties, some low and low-middle SDI regions may have underreporting and undiagnosed cases due to insufficient screening, lack of diagnostic tools, and limited medical services, thus underestimating the burden of CVD. Secondly, the results of the APC model study only reflect overall trends at the global and regional levels, and are inevitably subject to ecological fallacy, making them inapplicable to individuals directly. Therefore, large-scale cohort studies based on data at the national level are needed for further verification. Third, this study is based on national-level data and lacks analysis of local differences. Finally, this study only analyzes the risk factor of HSBP. Other risk factors may also contribute to the burden of cardiovascular disease, further increasing data uncertainty.

(See figure on next page.)

Fig. 9 Temporal trend in the number of DALYs and ASDR for CVD from 1990 to 2045. **A** Temporal trend in the number of DALYs and ASDR for CVD from 1990 to 2045, **B** Temporal trend in the number of DALYs and ASDR for ischemic heart disease from 1990 to 2045, **C** Temporal trend in the number of DALYs and ASDR for ischemic stroke from 1990 to 2045. Solid lines represent observed ASDR, and dashed lines represent ASDR predicted by the BAPC model. Abbreviations: CVD, cardiovascular disease. SDI, socio-demographic index. ASMR, age-standardized mortality rate. ASDR, age-standardized DALYs rate. EAPC, estimated annual percentage change. AAPC, average annual percent change. Solid lines represent observed ASDR, and dashed lines represent ASDR predicted by the BAPC model

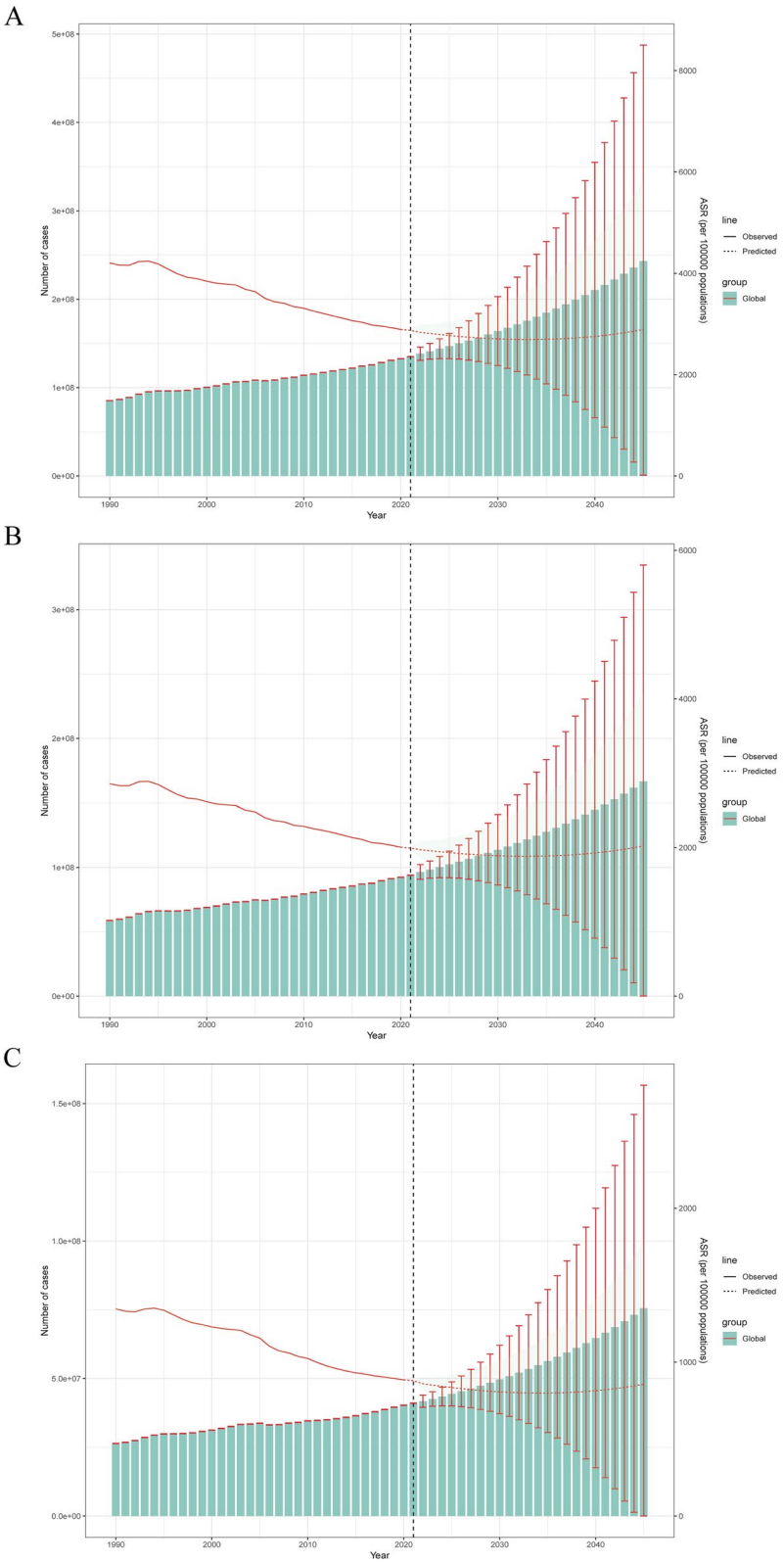


Fig. 9 (See legend on previous page.)

Conclusion

In conclusion, from 1990 to 2021, the absolute numbers of CVD mortality and DALYs caused by HSBP globally continued to rise. However, after age standardization, both sexes showed a downward trend in mortality and DALYs, with the decline being more pronounced in women. This trend is projected to continue until 2045. The increase in CVD burden caused by HSBP is primarily observed in older adults and low-middle SDI regions. This underscores the urgent need to develop targeted public health measures and policies to better protect specific populations and reduce the disease burden.

Abbreviations

APC	Age-Period-Cohort
BAPC	Bayesian age-period-cohort
ASDR	Age-standardized DALY Rate
ASMR	Age-standardized mortality Rate
CI	Uncertainty Interval
CVD	Cardiovascular Disease
DALYs	Disability-Adjusted Life Years
AAPC	Average Annual Percentage Change
GBD	Global Burden of Disease
IHD	Ischemic Heart Disease
IS	Ischemic Stroke
YLLs	Years of Life Lost
YLDs	Years Lived with Disability
HSBP	High Systolic Blood Pressure

Supplementary Information

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Supplementary Material 1

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Authors' contributions

All authors have made substantial contributions to the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. The manuscript, including figures and tables has not been previously published and that the manuscript is not under consideration elsewhere. Conceptualization and methodology–Zhiqiang Zhang, Xinyue Yang, Yanyan Du, Tenglong Hu and Xiqing Wei. Investigation and data curation–Zhiqiang Zhang, Xinyue Yang, Yanyan Du,Tenglong Hu, Yangyu Zhao, Lei Chen, Xinyue Yang, Na Sun, Qiang Sun, Wenyan Liang and Xiqing Wei. Supervision–Zhiqiang Zhang, Tenglong Hu, Xinyue Yang, Yanyan Du, Lei Chen, Xinyue Yang, Yangyu Zhao, Na Sun, Qiang Sun, Wenyan Liang and Xiqing Wei. Validation–Zhiqiang Zhang, Tenglong Hu and Xiqing Wei. Formal analysis–Zhiqiang Zhang, Xinyue Yang, Yanyan Du, Tenglong Hu and Xiqing Wei. Project Administration, Resources and Software–Zhiqiang Zhang, Tenglong Hu, Xinyue Yang, Yanyan Du and Xiqing Wei. Visualisation and writing, original draft–Zhiqiang Zhang, Tenglong Hu, Xinyue Yang, Yanyan Du and Xiqing Wei. Writing, preparation, review and editing–Zhiqiang Zhang, Tenglong Hu, Xinyue Yang, Yanyan Du, Lei Chen, Xinyue Yang, Yangyu Zhao, Na Sun, Qiang Sun, Wenyan Liang and Xiqing Wei.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

An ethics approval and the consent to participate was not necessary.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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