Original research

Global burden of disease study highlights the global, regional and national trends of stroke

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ABSTRACT

Background Stroke remains a significant global health challenge, especially in low- and middle-income countries, despite advances in treatment and prevention. Understanding stroke trends is crucial for guiding prevention and healthcare strategies.

Methods We analysed global data from the Global Burden of Disease Study 2021 on stroke incidence, prevalence, disability-adjusted life years and mortality from 1990 to 2021. The study focused on the major subtypes of stroke—ischaemic stroke (IS), intracerebral haemorrhage and subarachnoid haemorrhage—examining the effects of age, sex and sociodemographic index (SDI) on stroke outcomes. Decomposition analysis assessed the contributions of population growth, ageing and other factors to stroke burden. The Nordpred Prediction Model was used to forecast stroke trends from 2022 to 2046.

Results From 1990 to 2021, global stroke incidence and deaths increased by 70.20% and 32.17%, respectively, driven by population ageing (45.3%) and growth (29.1%). However, age-standardised incidence and mortality rates declined by 21.78% and 39.10%, reflecting improvements in healthcare and risk factor control. IS saw the largest increase in crude incidence (87.97%), with regional disparities, especially in low-SDI countries. By 2046, global stroke incidence and mortality are projected to rise by 20.3% and 35.7%, primarily in low- and middle-SDI countries.

Conclusions The global stroke burden is rising, particularly in low-SDI regions, due to ageing and population growth. Declines in age-standardised rates emphasise the importance of healthcare improvements. Region-specific strategies are needed to address the rising burden and reduce disparities in stroke outcomes.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Despite advances in stroke prevention and treatment, stroke remains a leading global cause of death and disability. Prior studies have shown a decline in age-standardised stroke rates, but global crude incidence and mortality continue to rise, especially in low- and middle-income countries. Comprehensive, subtype-specific and regionally stratified long-term evaluations are still lacking.

INTRODUCTION

Global health patterns are evolving, with significant shifts in disease distribution, life expectancy, mortality rates and risk factors for non-communicable diseases. Stroke has emerged as a major public health concern, exerting a growing burden on healthcare systems, economies and social structures worldwide. In 2021, stroke was the second leading cause of death and the third leading cause of both death and disability globally. While age-standardised mortality rates (ASMR) have declined, stroke incidence has only decreased modestly, suggesting that progress in prevention has lagged behind advances in acute treatment and secondary care.[1 2] The rising stroke burden is attributable to several modifiable and non-modifiable risk factors, including hypertension, smoking, dietary risks and population ageing, underscoring the need for multifaceted and context-specific strategies for prevention, early intervention and long-term management.[3] The WHO emphasises addressing upstream determinants such as hypertension, diabetes, tobacco use and sedentary lifestyles to reduce stroke risk.[4]

This study adopts a conceptual framework grounded in sociodemographic development to analyse global stroke burden across different contexts. Specifically, countries were stratified using the sociodemographic index (SDI), a composite indicator incorporating income per capita, educational attainment and fertility rate, to reflect health system capacity, epidemiological transition stages and population risk profiles. Using data from 1990 to 2021, we examined stroke burden across sex, region, country and stroke subtype (ischaemic stroke (IS), intracerebral haemorrhage (ICH) and subarachnoid haemorrhage (SAH)), based on estimates from the Global Burden of Disease (GBD) study encompassing 204 countries and territories.[1 5]

To disentangle the complex drivers of stroke burden, we employed three complementary analytical methods: decomposition analysis, to quantify the relative contributions of population growth, ageing and epidemiological changes; frontier analysis, to assess efficiency gaps in stroke burden relative to socioeconomic development; and the age-period-cohort (APC) model, to examine temporal trends and generational patterns in incidence and mortality. By integrating these approaches within the SDI framework, this study aims to elucidate how demographic and epidemiological dynamics shape global stroke trends and to inform the design of tailored, evidence-based interventions.

> **WHAT THIS STUDY ADDS**
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> ⇒ This study provides the most recent and comprehensive assessment of global stroke burden using Global Burden of Disease 2021 data. From 1990 to 2021, global stroke incidence and deaths increased by 70.2% and 44.0%, respectively, primarily driven by population growth and ageing. Age-standardised rates declined significantly across all stroke subtypes. Decomposition and frontier analyses revealed striking disparities by region and sociodemographic index (SDI), with high stroke burden and inefficiency gaps concentrated in low-SDI countries. Forecasting with the Nordpred and Bayesian age–period–cohort (BAPC) models suggests that although age-standardised burden will continue to decline, the absolute number of stroke cases, deaths and disability-adjusted life years (DALYs) will rise substantially by 2046. An age-standardised risk assessment estimated population-attributable fraction (PAF) and population-preventable fraction (PPF, for protective exposures) for DALYs and deaths, identifying high systolic blood pressure as the dominant preventable driver across all SDI quintiles, with additional contributions from ambient particulate matter, smoking, dietary sodium, high low-density lipoprotein (LDL) cholesterol and fasting glucose, and diet-related gains especially in low-SDI settings.
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> **HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY**
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> ⇒ By combining 1990–2021 trends, SDI-stratified analyses, decomposition, frontier benchmarking and forecasts to 2046, this study offers a practical roadmap for priority-setting. Age-standardised PAF/PPF rankings pinpoint high systolic blood pressure as the dominant, cross-SDI target, followed by ambient particulate matter, smoking, dietary sodium, high LDL cholesterol and fasting glucose, with protective dietary gains—supporting SDI-tailored, cost-effective packages (eg, blood pressure (BP) detection-to-control at scale, tobacco control, salt reduction, air-quality/clean-cooking measures and affordable lipid/diabetes care in primary care). Frontier results highlight addressable efficiency gaps in low-SDI settings, while projections show rising absolute DALYs and deaths despite declining age-standardised rates, underscoring the need to expand prevention alongside organised acute stroke care and rehabilitation and to monitor policy impact over time.

METHODS

Study data

Annual data on stroke incidence and age-standardised incidence rates (ASIR) from 1990 to 2021, stratified by sex, region, country and subtype (IS, ICH, SAH), were retrieved from the GBD Results Tool (http://ghdx.healthdata.org/gbd-results-tool).[1 6] Data from 204 countries and territories were categorised by SDI into five groups: low, low-middle, middle, high-middle and high.[7] Countries were also grouped into 21 regions globally, such as East Asia (online supplemental table 1). The GBD 2021 methodology and disease burden estimation have been described in previous studies.[2 6] Stroke was defined by the WHO as rapid-onset clinical symptoms of focal or global brain dysfunction lasting more than 24 hours or leading to death.[8] IS is characterised by neurological dysfunction due to brain infarction,[9] ICH by non-traumatic focal bleeding within the brain and SAH by bleeding into the brain's subarachnoid space. In regions lacking neuroimaging, the GBD methods for determining stroke and its subtype have been previously detailed.[8]

Stroke burden

Stroke burden was measured at global, regional and national levels using incidence, prevalence, stroke-related deaths and disability-adjusted life years (DALYs). Mortality was estimated using the Cause of Death Ensemble Model from the GBD study. DALYs were the sum of years lived with disability (YLDs) and years of life lost (YLLs). YLDs reflect the duration of stroke-related disabilities, weighted by severity, while YLLs represent years lost to premature stroke-related death. These metrics were estimated by age, sex and location, reported as raw counts, rates per 100 000 population and age-standardised rates based on the WHO's standard population.

Social demographic index (SDI)

In this analysis, countries were categorised into five distinct groups based on the quintiles of the 2021 SDI (online supplemental table 1).[10] SDI is a composite indicator ranging from 0 to 1, used to measure the level of socioeconomic development of a country or region. It incorporates three key components: per capita income, educational attainment and total fertility rate. A higher SDI value indicates a higher level of socioeconomic development. To facilitate comparisons, SDI is standardised for analysis across different regions and time periods.

Decomposition analysis

To gain a deeper understanding of the key factors driving changes in the stroke burden, a decomposition analysis will be conducted for the period from 1990 to 2021. This analysis aims to quantitatively evaluate the independent contributions of population growth, population ageing and epidemiological changes to variations in stroke burden.[11] The analysis will focus on stroke incidence, mortality and DALYs. Variables will first be defined, and the contribution of each factor to changes in the stroke burden will be calculated while holding the other two factors constant. This approach allows for separate evaluation of the burden increase attributable to population growth, the impact of population ageing on stroke incidence and the effects of epidemiological changes on stroke mortality.

Frontier analysis

To assess the relationship between stroke burden and sociodemographic development, this study conducted a Frontier Analysis. Stroke-related data, including age-standardised DALY rates (ASDR), were collected for various countries and regions, alongside corresponding SDI data. A non-parametric data envelopment analysis method was employed to construct a non-linear frontier model, identifying the minimum achievable stroke burden at different levels of development. By comparing the observed DALY rates with the minimum achievable DALY rates estimated by the frontier model, efficiency gaps were calculated to represent unrealised health gains based on current development levels. Statistical software was then used to analyse the results and generate visual maps, providing an intuitive depiction of the relationship between stroke burden and sociodemographic development across countries and regions. These findings aim to inform public health policy development for stroke prevention and management.[12 13]

Age-period-cohort (APC) analysis

This study employed the APC method to analyse dynamic changes in stroke incidence, prevalence, mortality and DALYs. The APC model, based on the Poisson distribution, captures trends across age groups, time periods and birth cohorts. We used the R-based online tool from the National Cancer Institute (http://analysistools.nci.nih.gov/apc/), which estimates APC parameters and generates relationships between disease rates and age, period and cohort.[14] Stroke incidence and mortality data from 1992 to 2021, stratified by 5 year age groups, along with annual population estimates, were extracted from the GBD database. Age groups were defined as 10–14, 15–19, 20–24, …, 95–100 years, with age group 0 representing those under 5 years old. Total incidence and mortality cases, as well as cumulative rates, were calculated for each age group over successive 5-year periods (eg, 1992–1996, 1997–2001).

The APC tool performed Wald tests to assess rate differences across age, time and cohorts. Key metrics, including net drift (annual percentage change) and local drift (age-specific estimated annual percentage change (EAPC)), were computed. Model fitting was performed using the Epi package in R (V.2.56),[15] with the best-fitting model determined by residual deviance and Akaike Information Criterion values. This analysis offers valuable epidemiological insights to inform public health strategies.

Nordpred prediction model

The Nordpred prediction model, based on the APC framework, effectively forecasts future trends in disease incidence, mortality and DALY rates. This model incorporates relationships between temporal trends and demographic factors, including population structure changes, disease trajectories and generational effects.[16 17] To predict future trends in stroke burden, the Nordpred APC model was used to project ASIR, ASMR and ASDR from 2022 to 2046, with calculations stratified by sex. The Nordpred package (V.1.1)[18] was employed to integrate dynamic changes in incidence, mortality, DALY rates and population structure. To ensure the reliability of the predictions, additional analyses were performed using the BAPC[19] and INLA[20] packages in R software. These tools provided cross-validation of the results, enhancing the robustness of the projections.

Risk-attributable analysis for stroke disability-adjusted life years (DALYs and deaths

We conducted an additional cross-sectional comparative risk assessment using GBD 2021 summary results (Global Health Data Exchange) to quantify the population-attributable fraction (PAF) and population-preventable fraction (PPF) for stroke burden. For the calendar year 2021, we downloaded two harmonised datasets with identical specifications: (i) risk-attributable burden and (ii) total non-risk-attributed burden. Analyses were performed for both sexes at the global level and across SDI quintiles (low, low-middle, middle, high-middle, high SDI) for overall stroke and subtypes (IS, ICH, SAH). The primary estimand was PAF based on age-standardised rates (ASR, per 100 000): PAFrate=risk-attributable age-standardised rate/total age-standardised rate, computed separately for DALYs and deaths with perfectly matched measure, age (age-standardised) and metric (rate). PAFrate represents the proportion of burden preventable if exposure were reduced to the theoretical minimum risk exposure level. As a secondary scale measure, we repeated calculations using all-ages counts (age=all ages, metric=number) and reported attributable numbers alongside rates. Negative attributable values, when 95% uncertainty intervals (UIs) crossed zero, were truncated to zero and PAFs bounded to [0,1]; because GBD applies joint attribution, PAFs are not additive across risks. Uncertainty was propagated using GBD draws when available; otherwise, we fitted log-normal distributions to reported 95% UIs for numerators and denominators and generated 5000 Monte-Carlo samples of the ratio, reporting means and 95% UIs. Risks were ranked by PAFrate globally and within SDI strata.

RESULTS

Global stroke burden

In 2021, the global stroke incidence was 11 946 273.94 (95% UI: 10 772 079.55–13 219 841.45), a 70.20% increase from 1990. The incidence rates for IS, ICH and SAH were 7 804 449.40, 3 444 338.05 and 697 486.49, respectively, reflecting increases of 87.97%, 46.05% and 37.09% since 1990. The stroke incidence per 100 000 increased from 131.60 (UI: 118.97–146.13) in 1990 to 151.38 (UI: 136.50–167.52) in 2021. The incidence rates per 100 000 for IS, ICH and SAH were 98.90 (UI: 85.15–113.34), 43.65 (UI: 38.69–48.31) and 8.84 (UI: 7.78–10.08), respectively. From 1990 to 2021, the ASIR per 100 000 decreased from 180.97 (UI: 163.98–200.62) to 141.55 (UI: 127.97–155.81) for stroke. For IS, ICH and SAH, the ASIRs declined from 109.79 (UI: 93.56–127.62) to 92.39 (UI: 79.84–105.82), from 59.49 (UI: 51.41–66.64) to 40.83 (UI: 36.20–45.21) and from 11.69 (UI: 10.22–13.50) to 8.33 (UI: 7.34–9.48), respectively (online supplemental tables 1 and online supplemental figure 1).

Stroke prevalence in 2021

In 2021, there were 93 816 414.10 prevalent stroke cases worldwide, including 69 944 884.82 IS, 16 603 836.26 ICH and 7,852,792.32 SAH cases. Compared with 1990, this represented increases of 86.09%, 101.76%, 48.59% and 60.21%, respectively. The prevalence per 100 000 population rose from 945.24 (UI: 896.08–997.96) in 1990 to 1188.85 (UI: 1128.20–1258.79) in 2021, with IS, ICH and SAH prevalences increasing from 649.99 to 886.35, 209.51 to 210.41 and 91.90 to 99.51, respectively. However, the age-standardised prevalence rate (ASPR) per 100 000 decreased from 1201.11 (UI: 1137.99–1271.32) in 1990 to 1099.31 (UI: 1044.17–1162.11) in 2021. ASPR for IS, ICH and SAH decreased from 849.49 to 819.47, from 250.23 to 194.51 and from 109.90 to 92.17, respectively (online supplemental table 2).

Stroke-related disability-adjusted life years (DALYs) in 2021

In 2021, the global stroke burden in DALYs was 121 405 471.72 (95% UI: 114 722 212.95–127 625 131.78), including 70 357 911.88 DALYs for IS, 79 457 426.84 for ICH and 10 641 881.91 for SAH. This represents increases of 32.17% for IS, 52.37% for ICH and 25.73% for stroke overall, while SAH decreased by 11.55%. The DALY rate per 100 000 population for stroke was 2033.32 (UI: 1872.70–2175.07) in 2021, with IS at 891.58, ICH at 1006.89 and SAH at 134.85. Compared with 1990, these rates showed a 10.67% decrease for stroke overall, a 2.98% increase for ICH, a 15.02% reduction for IS and a 40.22% decrease for SAH. The ASDR per 100 000 decreased from 3078.95 (UI: 2893.58–3237.34) in 1990 to 1886.20 (UI: 1738.99–2017.90) in 2021. The ASDR for IS, ICH and SAH decreased from 1286.31 to 837.36, from 1286.31 to 923.64 and from 275.85 to 125.20, respectively (online supplemental table 3).

In 1990, stroke-related deaths globally were 5 033 557.89 (95% UI: 4 712 391.53–5 296 054.77), rising to 7 252 675.54

(UI: 6 566 884.21–7 808 179.59) in 2021. Deaths from IS increased from 2 317 112.28 to 3 591 498.62 and from ICH from 2 341 558.14 to 3 308 366.70. SAH deaths slightly decreased from 374 887.47 to 352 810.22. In 2021, the crude mortality rates per 100 000 population were 91.91 for stroke, 45.51 for IS, 41.92 for ICH and 4.47 for SAH. Compared with 1990, crude mortality rates for stroke, ICH and SAH decreased by 2.61%, 4.51% and 36.39%, respectively, while IS increased by 4.76%. The ASMR per 100 000 in 2021 were 87.45 for stroke, 44.18 for IS, 39.09 for ICH and 4.18 for SAH, reflecting decreases of 39.10%, 39.60%, 36.58% and 56.12%, respectively, compared with 1990 (online supplemental table 4).

Global variations in age-standardised incidence rate (ASIR) of stroke

There was significant geographic variation in the ASIR of stroke in 2021. The highest ASIR was observed in the Solomon Islands at 355.00 per 100 000, followed by Kiribati and North Macedonia (figure 1A). China and India accounted for the largest share of new stroke cases, contributing 34.27% (4.09 million cases) and 10.48% (1.25 million cases) of the global total, respectively. Globally, new stroke cases increased by 70.25% (95% CI 69.67% to 70.68%) from 1990 to 2021, with the United Arab Emirates seeing the largest increase of 582.68% (95% CI 559.72% to 606.42%) (figure 1B). The global annual average percent change (EAPC) in ASIR was 0.34% (95% CI 0.22% to 0.45%). Lesotho showed the largest increase in ASIR (EAPC=1.14), followed by the Philippines and Zimbabwe (figure 1C). In contrast, the largest reductions in ASIR were seen in Portugal (EAPC = −2.15), followed by Korea and Singapore (figure 1B,C).

Stroke epidemiology in 2021 by age and sociodemographic index (SDI) levels

Stroke prevalence per 100 000 population showed a consistent upward trend across age groups in both high- and low-SDI countries, with the steepest increase in high-SDI countries. In individuals aged >80 years, prevalence was highest across all SDI quintiles (online supplemental figure 2A). However, in high-middle and middle-SDI countries, stroke prevalence started to decline in the >80 years group. Stroke incidence was highest in high-middle and middle-SDI countries, while low in high-SDI countries (online supplemental figure 2B). Stroke incidence showed a continuous increase with age across all SDI quintiles, while stroke mortality and DALY rates remained lowest in high-SDI countries across age groups (online supplemental figure 2C,D). The trends for IS, ICH and SAH were generally similar, as detailed in online supplemental figure 3.

To explore the global age distribution of stroke by SDI quintile, we constructed age distribution charts. In low-SDI countries, strokes were more prevalent in younger age groups, peaking early in the 55–59 years group. In contrast, high-SDI countries showed a later and higher peak in the 70–74 years age group. Across all SDI quintiles, the percentage of stroke cases declined sharply after the peak age. The patterns for stroke incidence, DALYs and mortality were similar, with slight variations in the peak ages.

Trends in stroke age-standardised incidence rate (ASIR) across regions based on sociodemographic index (SDI)

Figure 2 illustrates the relationship between stroke ASIR and SDI, highlighting regional trends. Regions like North Africa and the Middle East, Western Europe, High-Income Asia Pacific, High-Income North America and Australasia closely followed expected ASIR trends. In mid-to-high SDI regions, ASIR showed significant variability, with some regions consistently below expected levels, while others had fluctuating ASIR levels well above expectations (figure 2A). At the country level, a strong negative correlation between stroke ASIR and SDI was observed in 2021, with higher SDI countries generally having lower ASIR (figure 2B). The trends for IS ASIR mirrored those of overall stroke ASIR (online supplemental figure 4). For ICH, ASIR declined across all SDI ranges, particularly in low-SDI and low-middle-SDI countries, though some regions had ASIR above expectations (online supplemental figure 5). SAH ASIR fluctuated along the SDI gradient, initially increasing, then decreasing and rising again at higher SDI levels.

Decomposition analysis of age-standardised disability-adjusted life year (DALY) rates

To explore the contributions of population growth, ageing and epidemiological changes to the evolving epidemiology of stroke over the past 32 years, we conducted a decomposition analysis of DALYs based on population size, age structure and age- and population-standardised prevalence and mortality rates (referred to as epidemiological changes in this study). Globally, DALYs attributable to stroke increased significantly during this period, with the most pronounced growth observed in regions within the middle-SDI quintile (online supplemental figure 6). Population ageing and growth accounted for 47.43% and 88.40% of the global DALY increase, respectively. The impact of ageing was most prominent in the high-SDI quintile, contributing 136.29% to DALY growth, while population growth had the greatest contribution in the low-SDI quintile, accounting for 162.58%. In contrast, epidemiological changes negatively contributed to DALY growth globally (−35.83%), with the most substantial impact observed in the high-SDI quintile (−191.41%). The contributions of demographic factors and epidemiological changes to DALY trends varied significantly across countries and regions. Over the past 32 years, global epidemiological changes, reflected by reductions in age- and population-standardised stroke prevalence and mortality rates, contributed to a decline in DALYs. This decline was most significant in the high-SDI quintile and least evident in the low-SDI quintile (online supplemental figure 6).

Decomposition analysis by stroke subtypes

We performed a decomposition analysis of the three stroke subtypes (IS, ICH and SAH) without age and population standardisation. From 1990 to 2021, the reduction in ICH was the primary contributor to the decrease in stroke DALYs globally and in countries with low, low-middle and middle SDI (online supplemental figure 6). Globally, ICH and IS contributed 64.69% and 19.19%, respectively, to the overall reduction in stroke DALYs. Except in high-middle SDI countries, where the reduction in IS contributed the most to the overall decrease in DALYs (68.30%), changes in ICH were the largest contributor to DALY changes across other SDI quintiles. Notably, in high-SDI countries, stroke DALYs increased overall, with the growth in ICH contributing the most to the increase (106.34%) (online supplemental figure 7).

Annual age-standardised disability-adjusted life year (DALY) rate (ASDR) of stroke across sociodemographic index (SDI) quintiles

The ASDR of stroke decreases progressively with higher SDI quintiles, with the highest DALY rate in the low SDI quintile (2463.45, UI=2198.34–2736.75) and the lowest in the high SDI quintile

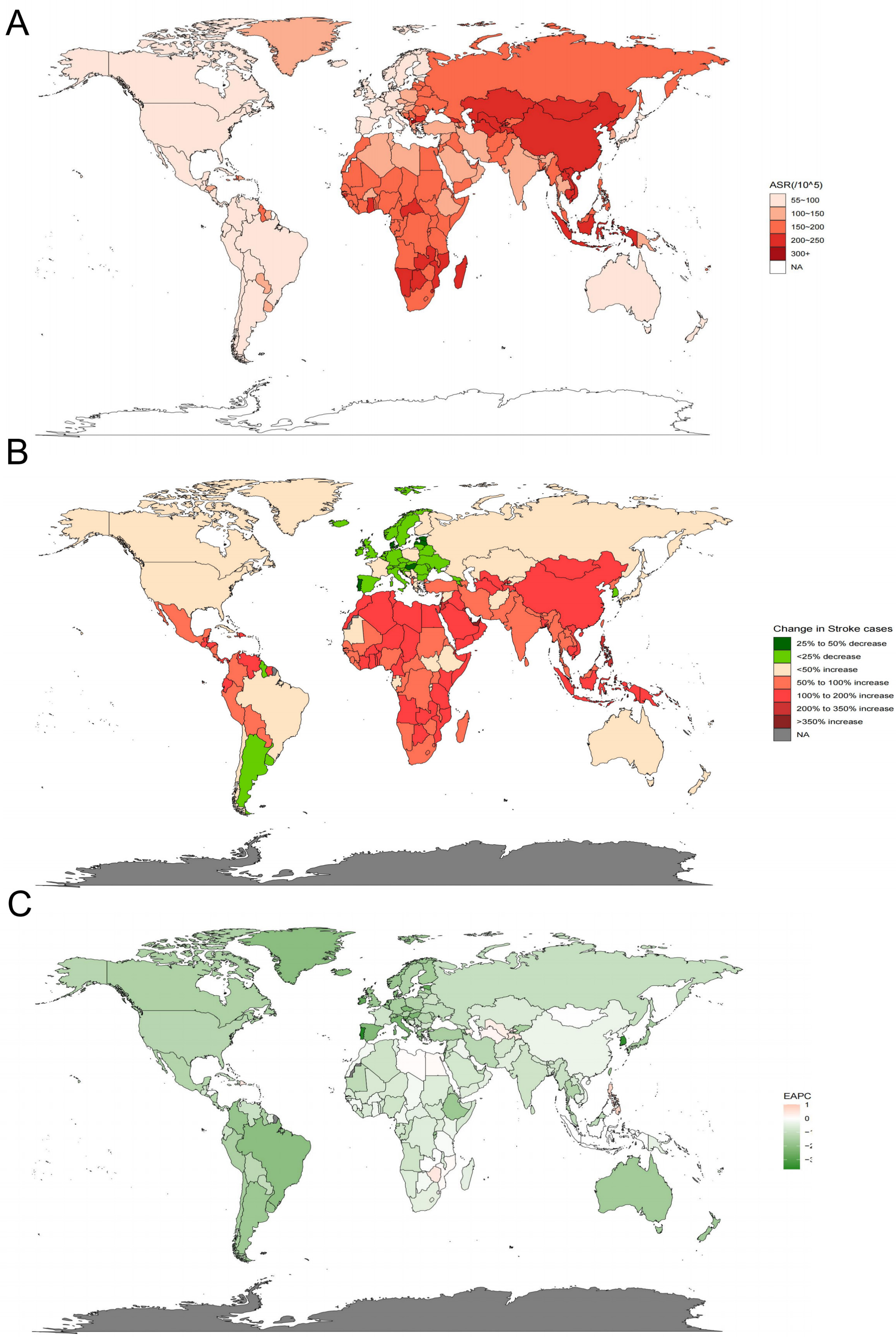

Figure 1 Stroke disease burden in 204 countries and regions worldwide. (A) Age-standardised incidence rate (ASIR) of stroke in 2021. (B) Relative change in stroke incident cases from 1990 to 2021. (C) Estimated annual percentage change (EAPC) in stroke ASIR from 1990 to 2021. Countries with significant case numbers or trends are labelled.

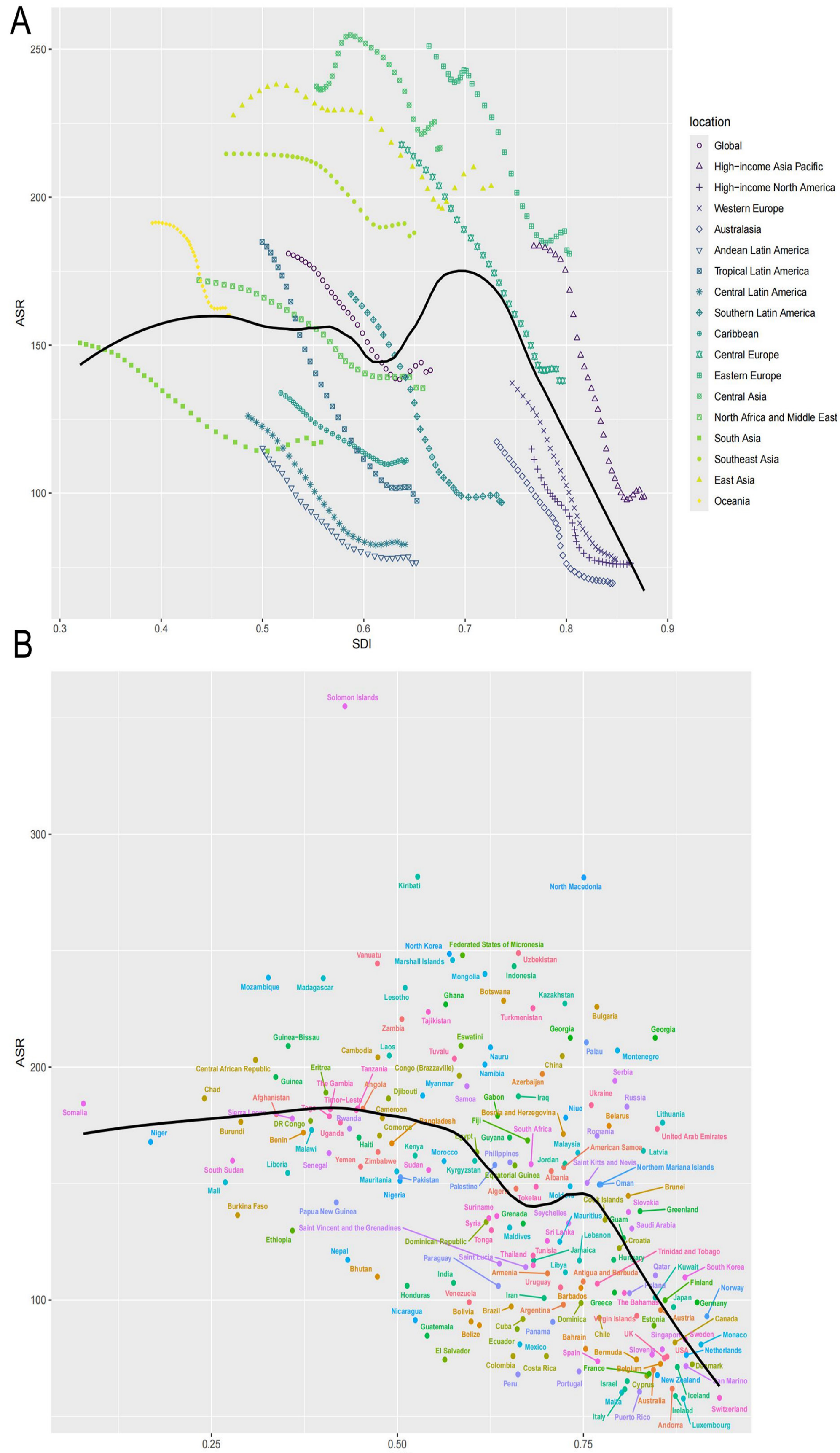

Figure 2 Trends in age-standardised incidence rate (ASIR) of stroke from 1990 to 2021 across different sociodemographic index (SDI) levels. (A) 21 regions from the Global Burden of Disease Study; (B) Shows 204 countries and regions. The black line represents the expected values of the SDI and disease incidence rate based on all regions.

(786.87, UI=665.87–786.87). To assess the minimum achievable DALY rate at different SDI levels, we performed a frontier analysis using data from 1990 to 2021 (figure 3A). The analysis identifies the lowest DALY rates for countries at each SDI level, representing optimal performance. The efficiency gap, the difference between actual DALY rates and these minimum values, indicates potential for improvement through enhanced socioeconomic development. Based on the 2021 DALY rate and SDI value, countries with the largest efficiency gaps, such as Somalia, Niger and Chad, had significantly higher stroke DALY rates than nations with similar socioeconomic levels. In contrast, countries like Switzerland, Ireland and South Korea, with smaller gaps, had lower DALY rates, reflecting better health outcomes at similar SDI levels. The unachieved health gains for countries between 1990 and 2021 are shown in figure 3A. Figure 3B further details the DALY burden and efficiency gaps for countries at various SDI levels in 2021. As socioeconomic development advances, efficiency gaps generally narrow, highlighting potential for burden reduction in lower SDI regions. Similar trends were observed for IS, ICH and SAH ASDR (online supplemental figure 8).

Age-period-cohort (APC) analysis

Figure 4A and online supplemental figure 9A show trends in stroke incidence and mortality across age groups from 1992 to 2017. For individuals aged 0 to 45 years, changes in incidence and mortality were minimal, but after age 40, incidence increased gradually. Both incidence and mortality rose with age, with no significant differences below 45. Figure 4B and online supplemental figure 9B show temporal trends in stroke incidence and mortality. Incidence rates generally declined over time across most age groups, and mortality followed a similar downward trend, with higher rates observed in older adults. Trends for stroke subtypes followed similar patterns. Figure 4C and online supplemental figure 9C depict cohort-based changes in incidence and mortality. Both rates decreased with later birth cohorts. Age, period and cohort-specific trends for IS, ICH and SAH are shown in online supplemental figures 10-12. For IS, ICH and SAH, age-related trends in incidence and mortality, as well as rising IS mortality, mirrored overall stroke trends. However, ICH mortality declined in the oldest age groups (>90 years).

The full model, including age, period and cohort, best reflects the individual effects compared with models considering only two factors. Online supplemental figure 13 shows the effects of age, period and cohort on stroke incidence and mortality. For stroke incidence, the age effect shows a decline before age 10, followed by a rapid increase, levelling off after age 85. The period effect trends upward, while the cohort effect shows a continuous reduction in incidence risk from early to later birth cohorts. The effects on stroke mortality are similar to those for incidence. The age, period and cohort effects on IS, ICH and SAH incidence and mortality are shown in online supplemental figures 14–16.

Predicted global stroke age-standardised disability-adjusted life year rate (ASDR data

By 2046, the global total incidence of stroke is projected to rise by 92.5%, reaching 22 962 866 cases. The ASIR per 100 000 is predicted to increase by 5.9%, from 143.71 in 2021 to 152.2 in 2046 (figure 5A). The total incidence of IS is projected to increase by 103.4% to 15 854 040, with the ASIR rising by 9.5%, reaching 102.7 per 100 000 (online supplemental figure 17A). ICH incidence is expected to grow by 81.8%, from 3 437 578 in 2021 to 6 247 817 in 2046, with the ASIR increasing by 2.7% (online supplemental figure 18A). For SAH, the total incidence is predicted to increase by 56.1%, with the ASIR rising slightly by 0.4% (online supplemental figure 19A).

Global total mortality from stroke is expected to reach 13 402 784 by 2046, an 84.8% increase compared with 2021 (figure 5B). However, the ASMR per 100 000 is projected to decrease by 9.7%, reaching 80.0 in 2046. For IS, total mortality is projected to increase by 111.6%, reaching 7 599 136 in 2046, while the ASMR is expected to decrease by 5.3% (online supplemental figure 17B). For ICH, total mortality is projected to increase by 62.9%, while the ASMR is expected to decline by 12.8% (online supplemental figure 18B). For SAH, total mortality is expected to grow by 57.3%, while the ASMR is projected to decrease by 11.8% (online supplemental figure 19B).

According to the BAPC model, the total global DALYs for stroke are projected to increase by 105.4% from 2021 to 2046, reaching 255 921 207 years. However, the model predicts that the ASDR per 100 000 population will decrease by 9.6%, from 1908.8 in 2021 to 1726.3 in 2046 (figure 5C). The total DALYs for IS are expected to increase by 90.3%, from 70 357 912 in 2021 to 133 860 598 in 2046. However, the ASDR per 100 000 for IS is projected to decrease by 2.4% during this period (online supplemental figure 17C). For ICH, the total DALYs are projected to increase by 41.4%, while the ASDR is expected to decrease by 13.1%, reaching 811.65 in 2046 (online supplemental figure 18C). The total DALYs for SAH are anticipated to grow by 34.0%, reaching 14 255 027 in 2046, while the ASDR is expected to decrease by 11.7%, from 127.6 in 2021 (online supplemental figure 19C).

Risk-attributable stroke burden by age-standardised rate (Global Burden of Disease (GBD) 2021)

Using ASR, high systolic blood pressure accounted for by far the largest share of preventable global stroke burden in 2021 for both DALYs and deaths, with PAFs around one-half and consistently highest across all five SDI quintiles. A second tier of risks—ambient particulate matter pollution, smoking, high LDL cholesterol, household air pollution from solid fuels, diet high in sodium, high fasting plasma glucose, kidney dysfunction, lead exposure and low fruit intake—each contributed more modest PAFs (roughly 5%–20%), with clear gradients by development: household air pollution declined steeply with increasing SDI, whereas ambient particulate matter and smoking varied less across SDI. Subtype contrasts were coherent with underlying pathophysiology. For IS, after high blood pressure, high LDL cholesterol and high fasting plasma glucose rose in rank and magnitude, while household air pollution became less prominent, indicating a more metabolic risk profile. ICH mirrored the overall stroke pattern but assigned relatively greater weight to smoking and high sodium intake and less to LDL cholesterol. SAH again placed high blood pressure first, with smoking and ambient particulate matter among the leading risks and LDL cholesterol typically not appearing in the top 10; behavioural risks such as low fruit intake were more prominent (online supplemental figures 20 and 21). online supplemental figure 21Sensitivity analyses based on all-ages counts yielded the same ranking structure and SDI gradients, reinforcing the primacy of blood-pressure control alongside tobacco and air-pollution mitigation and dietary–metabolic interventions as global prevention priorities (online supplemental figures 22 and 23).

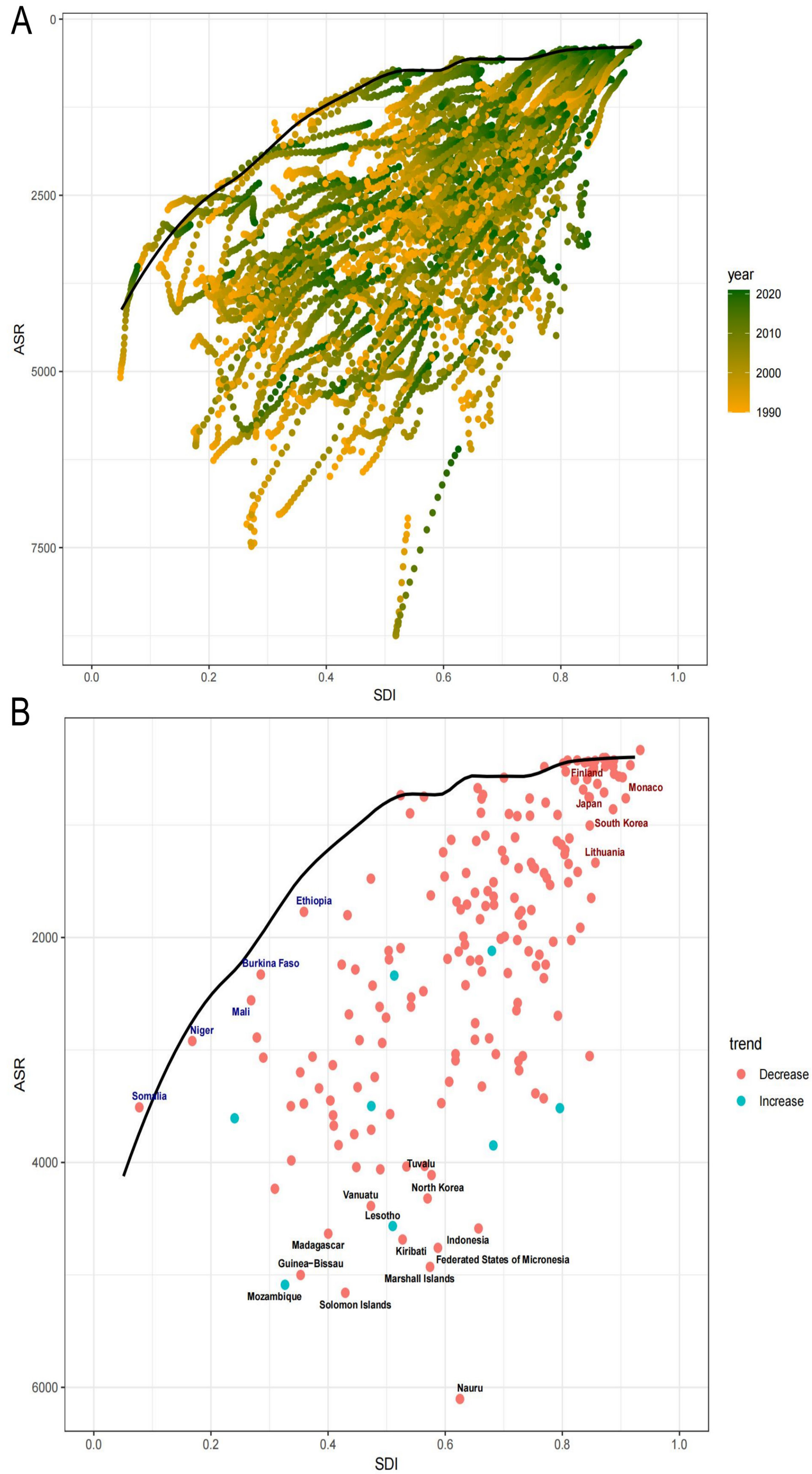

Figure 3 Frontier analysis based on SDI and age-standardised stroke disability-adjusted life years (ASDR) in 2021. The frontier is outlined by the black solid line, with countries and regions represented by dots. The top 15 countries with the largest effective DALY gap (ie, the maximum difference between stroke DALYs and the frontier) are marked in black. Countries with low SDI (<0.5) and small effective DALY gaps are marked in blue (eg, Somalia, Niger, Mali, Burkina Faso, Ethiopia). Countries with high SDI (>0.85) but relatively large DALY effective gaps compared with their development level are marked in red (eg, South Korea, Lithuania, Japan, Finland, Monaco). Red dots represent countries where stroke ASDR increased from 1990 to 2021, while blue dots indicate countries where stroke ASDR decreased during this period. DALYs, disability-adjusted life years; SDI, sociodemographic index.

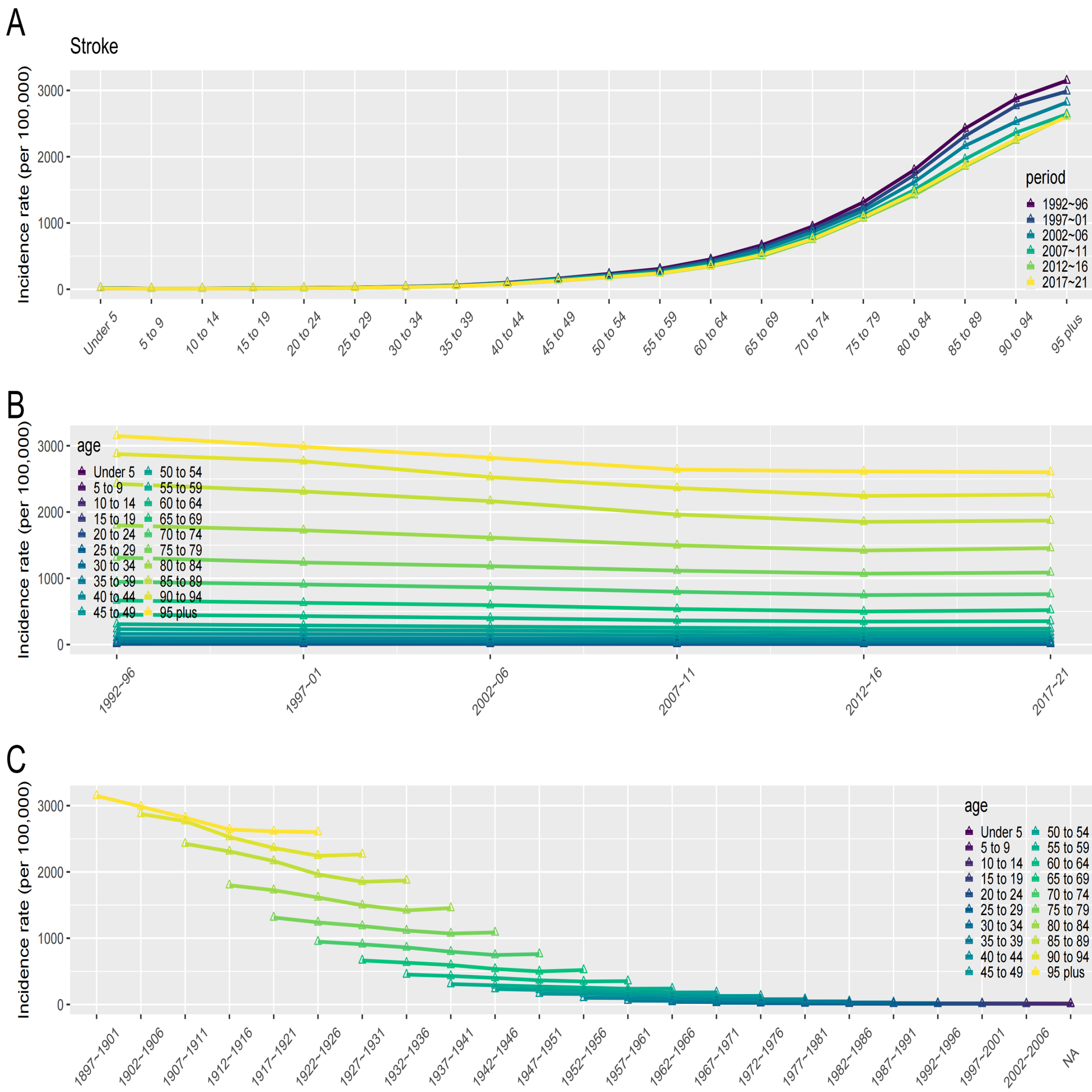

Figure 4 Global stroke incidence. (A) Age-specific stroke incidence rates for different periods; each line connects the age-specific incidence rates for a 5-year period. (B) Age-specific stroke incidence rates for different birth cohorts; each line connects the age-specific incidence rates for a 5-year birth cohort. (C) Birth cohort-specific stroke incidence rates for different age groups; each line connects the birth cohort-specific incidence rates for a 5-year age group.

DISCUSSION

This study systematically examined global trends in stroke burden and its major subtypes—IS, ICH and SAH—from 1990 to 2021, using a SDI framework. Globally, the increasing crude prevalence and incidence of stroke reflect demographic shifts, particularly population growth and ageing.[21] However, the declines in age-standardised prevalence, incidence and DALY rates point to progress in prevention, early detection and treatment.[22] These improvements are attributable to better hypertension control, antithrombotic therapies and organised acute stroke management.

Stroke subtypes demonstrated distinct epidemiological patterns driven by variations in pathophysiology, modifiable risk factor distribution and health system accessibility. IS exhibited the greatest rise in absolute numbers of cases and deaths, especially in low- and middle-income countries (LMICs), where population ageing and delayed epidemiological transitions compound the burden.[23 24] However, widespread adoption of anticoagulants, antiplatelet agents and reperfusion therapies (eg, thrombolysis, mechanical thrombectomy), along with public health measures (eg, statin use, tobacco control), has likely mitigated age-standardised rates.[25–29]

For ICH, a modest rise in absolute case numbers contrasts with pronounced reductions in age-standardised incidence, mortality and DALYs—likely due to improved hypertension screening, pharmacologic control and public awareness campaigns, particularly in East and Southeast Asia. Progress in acute-phase interventions (eg, blood pressure management, neurosurgery, neurocritical care) has contributed to better outcomes.[30] In individuals over 90, declining ICH mortality may reflect palliative care integration.[31] SAH showed the steepest age-standardised decline, largely due to enhanced

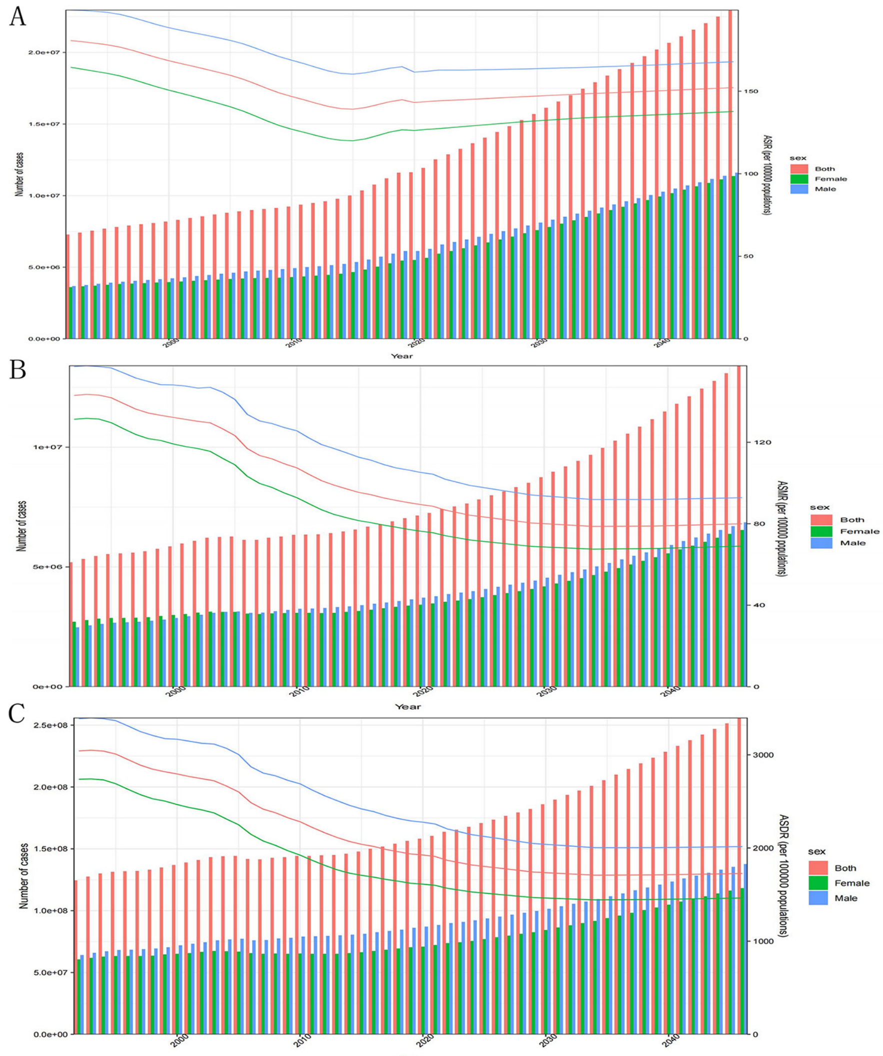

Figure 5 Projections of global stroke (A) age-standardised incidence rate (ASIR), (B) age-standardised mortality rate (ASMR) and (C) age-standardised disability-adjusted life year (DALY) rate (ASDR) from 2021 to 2046 for both sexes and overall.

detection and intervention for aneurysms and declining smoking prevalence.[32]

Using age-standardised PAF/PPF estimates as a policy lens, our findings prioritise blood pressure control as the single most powerful lever to reduce stroke burden globally, with consistently highest fractions across all SDI quintiles for both DALYs and deaths. Importantly, the PAFs also identify where non-medical, system-level investments can yield the greatest, low-cost gains. In low-SDI settings, a large preventable share is attributable to household air pollution from solid fuels; clean-cooking transitions (clean stoves/fuels, supply-chain subsidies and microfinance) therefore represent a high-yield, non-clinical intervention with broad co-benefits. Across the SDI spectrum, tobacco taxation and comprehensive smoke-free policies and population salt reduction (mandatory reformulation targets, front-of-pack labelling, salt-standard procurement in public catering) address risks that rank in the top tier for stroke and its subtypes, particularly smoking for SAH and sodium for ICH. Ambient particulate matter pollution—another leading PAF—supports investments in air-quality standards and enforcement (industrial/ transport emissions) with cardiovascular co-benefits. For IS, the prominence of high LDL cholesterol and hyperglycaemia argues for scaled statin access and diabetes control within primary care, ideally via task-sharing, standardised treatment protocols and fixed-dose combinations to improve the detection-to-control cascade at low unit cost. Additional actionable risks include lead exposure (paint/battery regulation) and low fruit intake (healthy-food procurement and produce subsidies in schools/ social protection). Because GBD uses joint attribution, PAFs are not additive; nevertheless, they can be translated into potential health gains by multiplying each PAF by the current burden in a given setting (eg, DALYs or deaths), thereby providing an explicit, SDI-specific value-for-money map to guide incremental budgeting in both HICs and LMICs.

Our SDI-stratified and decomposition analyses illuminate the heterogeneity in stroke trends over time and across regions. Stroke burden evolves differently between LMICs and high-income countries (HICs), driven by variable demographic structures, health infrastructure and disease epidemiology.[33] High-SDI countries are characterised by slower population growth and advanced ageing, where burden reduction is supported by well-developed care systems. In contrast, LMICs face faster population expansion, premature stroke onset and under-resourced health systems.[34]

Our analytical framework accounted for both temporal and regional variations. Decomposition models separated the effects of population growth, ageing and epidemiological changes on DALYs, and SDI-based stratification captured disparities in care capacity and risk profiles. These approaches allowed us to contextualise global trends within development-specific realities and produce policy-relevant insights. From a policy perspective, it is crucial to recognise that LMICs are unlikely to implement the same standard of stroke prevention and care as HICs. The latter—with the exception of the USA—generally enjoy more equitable and affordable healthcare access. Therefore, it is insufficient to offer only general recommendations (eg, 'quit smoking', 'reduce salt and alcohol intake'). Instead, interventions must be feasible within the context of available resources, infrastructure and workforce. For example, task-shifting to community health workers, low-cost antihypertensive access and mobile screening may yield high returns in LMICs.[35] Meanwhile, system-level comparisons (eg, Canada vs USA) illustrate how structural design affects stroke outcomes even among similarly wealthy nations. Frontier analysis in our study revealed efficiency gaps in low-SDI settings, emphasising the unrealised potential to reduce DALYs through strategic policy alignment.

The benefits of epidemiological transitions were more prominent in high-SDI countries, with DALY reductions reflecting mature healthcare systems, strong public health institutions and broad implementation of preventive strategies. In contrast, LMICs displayed stagnation in epidemiological gains, highlighting a need for greater investment and adaptation of global best practices to local contexts. Countries like Somalia and Chad—with DALY burdens exceeding expectation—exemplify the intersection of weak governance, limited funding and poor service delivery. Disparities among nations with similar SDIs further underscore the role of health system performance, not just socioeconomic status.[36]

Our APC model further clarified the temporal evolution of stroke burden. Stroke incidence and mortality increase substantially after age 40, with subtype-specific divergences. Declines in ICH mortality among those over 90 may indicate evolving end-of-life care norms. Longitudinally, incidence and mortality rates declined across nearly all age groups from 1992 to 2021, due to improved prevention and acute management. Cohort effects suggested reduced stroke risk among later birth cohorts, potentially due to favourable early-life exposures and better healthcare access. These findings reinforce the value of life-course approaches to prevention. Forecasts from the Bayesian APC model indicate that although total DALYs and mortality will increase due to demographic expansion, age-standardised rates (ASDR, ASIR, ASMR) will decline modestly. These trends reflect the dual impact of population ageing and continuing healthcare improvements, with IS expected to contribute most substantially to future burden.

Although we did not conduct a formal analysis of between-country inequality trends over time (eg, Gini coefficient, Theil index or inter-country ASDR dispersion), this decision was informed by two key considerations. First, a prior study has already provided detailed assessments of national-level inequality in stroke burden using these metrics.[37] Second, given the scope of our paper, we focused on SDI and regional levels of aggregation, which align more closely with practical policymaking and offer better interpretability in light of data quality variation across 204 countries. Nevertheless, our results are consistent with earlier findings, affirming persistent and sometimes widening disparities in global stroke burden.

This study has limitations. It relies on model-based GBD estimates, particularly in data-sparse regions. Behavioural, cultural and environmental factors were not explicitly modelled, and risk factors were not decomposed in detail by subtype. Future research should incorporate granular regional data and longitudinal designs and examine the impact of structural health reforms. Integrating molecular epidemiology could also improve understanding of stroke heterogeneity and guide precision prevention.

In summary, this study offers a comprehensive, SDI-informed analysis of stroke burden trends from 1990 to 2021. While global stroke burden continues to rise in absolute terms, reductions in age-standardised metrics reflect genuine progress. Persistent cross-national disparities, however, demand that future interventions be tailored to demographic realities, system capacities and regional needs—especially in LMICs. Equitable and efficient allocation of global health resources remains imperative for closing the stroke burden gap.

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Contributors All listed authors meet the ICMJE criteria for authorship. SY, MD, JZ and YT conceived and designed the study. SY, MD, XR, ZK, JCL and GH were responsible for data collection. SY, ZK, FW, HY and XX performed the data analysis and interpretation. SY, MD, XR, JZ, YT, JL and YLC drafted and revised the manuscript. All authors reviewed and approved the final version of the manuscript. YT and JZ are the guarantors of this work. They had full access to all the data in the study and take full responsibility for the integrity of the data and the accuracy of the data analysis.

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