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ABSTRACT

Introduction China faces the dual challenge of high air pollution and an increasing burden of cardiovascular disease (CVD). We aimed to estimate the healthcare costs associated with CVD and the quality-adjusted life years (QALYs) under scenarios of improved air quality in China.

Methods A health prediction model was developed to estimate 10-year CVD-related costs and QALY associated with PM2.5 levels in 2015, as well as two hypothetical improved air quality scenarios: (1) the China national PM2.5 target of 35 µg/m³, and (2) the World Health Organization's (WHO) PM2.5 guideline of 5 µg/m³. Population CVD risks were estimated from the 2015 China Health and Retirement Longitudinal Study. Hazard ratios from WHO risk curves were subsequently applied to baseline cardiovascular risks to predict national 10-year estimates of ischaemic stroke and coronary heart disease-related healthcare expenditures and QALYs for individuals aged 45–85 under the three air quality scenarios.

Results Under PM2.5 levels in 2015, we estimated a cumulative 10-year incidence of 35.40 million CVD events, resulting in healthcare costs of US$96.12 billion and 4.44 billion QALYs. Under the national target of 35 µg/m³, the projected 10-year CVD incidence was 31.92 million cases, resulting in cost savings of US$9.29 billion and 3.43 million QALY gains compared with 2015 levels. If PM2.5 concentration levels meet the WHO's guideline of 5 µg/m³, the projected number of CVD events would decrease to 24.18 million, translating to cost savings of approximately US$30.10 billion and gains of 11.29 million QALYs.

Conclusion Our findings indicate that achieving the WHO recommended PM2.5 concentration level of 5 µg/m³ could lead to over threefold greater health and economic benefits than those achievable under national standards of 35 µg/m³. This underscores the potential need for stricter future national PM2.5 standards. Our findings also inform other low- and middle-income countries in establishing effective long-term PM2.5 targets.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Ambient fine particulate matter (PM2.5) is a major risk factor for cardiovascular disease (CVD) globally.

⇒ China faces both elevated PM2.5 concentrations and an increasing health and economic burden associated with CVD.

⇒ Despite significant efforts to reduce national ambient air pollution concentrations, pollution levels remain nearly 10-fold higher than the standards set by the WHO.

WHAT THIS STUDY ADDS

⇒ A significant additional cost savings of US$20.81 billion and an increase of 7.86 million quality-adjusted life years (QALYs) could be realised nationally for individuals aged 45–85 if annual PM2.5 concentrations were reduced further to meet the WHO's target of 5 µg/m³.

⇒ Achieving the national target of 35 µg/m³ for ambient air pollution is projected to reduce the 10-year incidence of CVD among individuals aged 45–85 to 31.92 million cases.

⇒ This improvement would result in cost savings of US$9.29 billion and an increase of 3.43 million QALYs compared to 2015 levels.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The findings underscore the substantial health and economic benefits achievable under improved air quality scenarios and emphasise the need for the future implementation of more stringent national air quality standards in China.

INTRODUCTION

Ambient air pollution poses a significant environmental health challenge globally. In 2019, the WHO reported that over 4.2 million premature deaths worldwide were attributable to exposure to outdoor air pollution.[1] Among the growing health challenges, an increasing concern is the rising risk of associated cardiovascular disease (CVD). Recent evidence from the Global Burden of Diseases (GBD) 2021 study indicates that exposure to ambient air pollution was the second leading risk factor contributing to the global burden of disease, accounting for approximately 8% of total disability-adjusted life years (DALYs).[2] Additionally, estimates from the GBD 2019 suggest that approximately half of the disease burden resulting from exposure to ambient air pollution is associated with ischaemic heart disease and stroke, which represents the highest proportion in comparison to other health conditions.[3] While conventional cardiovascular risk factors remain predominant in determining populational risk, mounting evidence suggests that short- and long-term exposure to elevated levels of ambient air pollution can increase the risks of cardiovascular events, such as stroke, acute myocardial infarction (AMI) and heart failure, and potentially contribute to their onset.[4,5] Existing evidence is particularly strong in relation to the effects of PM2.5, with several proposed pathophysiological mechanisms delineating the biological process by which exposure to ambient PM2.5 induces CVD.[6,7] Collectively, exposure to both short- and long-term ambient PM2.5 significantly contributes to the overall health and economic burden on societies, encompassing increased mortality and morbidity, direct medical costs and indirect costs such as loss of productivity.[3,8,9] Therefore, there is an imperative need to address this environmental health challenge. Existing studies have suggested that lowering PM2.5 exposure can be more effective in reducing cardiovascular risks compared with conventional modifiable risk reduction strategies such as targeting smoking rates, diabetes mellitus and hypertension.[10,11] This is particularly the case for low- and middle-income countries (LMICs), where higher exposure to particulate matter, inadequate healthcare infrastructure and limited access to healthcare facilities collectively contribute to an increased disease burden.[12]

China grapples with the dual challenge of combating heightened ambient air pollution and managing the escalating burden of CVD. Estimates show that approximately 5.09 million CVD-related deaths occurred in 2019, of which 0.92 million deaths were attributable to exposure to particulate matter.[3,13,14] In 2016, the annual average PM2.5 concentration levels in 210 cities in China ranged from 11 to 128 $\mu g/m^3$, with only 1.4% of cities meeting the national standards of 35 $\mu g/m^3$, and were 2–25 times higher than the WHO's recommended annual PM2.5 concentration guideline of 5 $\mu g/m^3$.[3,15,16] Recognising the substantial implications on human well-being and the health system, the national government has made concerted efforts to reduce PM2.5 concentrations and has introduced a series of national quality standards, such as the National Air Quality Action Plan (NAQAP) and the 13th Five-year Action Plan.[17,18] Specifically, the NAQAP encompassed a range of measures designed to improve air quality and mitigate pollution, including optimising industry structure, promoting cleaner technologies, reducing energy consumption, and improving regulatory and monitoring frameworks.[19] Additionally, it stipulated national targets for PM2.5 concentrations.[20] Annual average PM2.5 concentrations in 74 major cities consequently reduced by 33.3%, from 72.2 $\mu g/m^3$ to 47.0 $\mu g/m^3$ between 2013 and 2017.[21] However, despite these concerted efforts, the current national PM2.5 targets in China still exceed the recommended levels established by the WHO and regulatory standards set by other regions, such as the USA and EU.[16,22]

While numerous studies have examined the CVD burden associated with exposure to PM2.5 in China,[23–28] limited studies have modelled potential cardiovascular health and economic outcomes from improved air quality at the national level. Huang *et al* estimated the potential life-years gained from reduced cardiovascular mortality as a result of lower PM2.5 concentrations between 2017 and 2030 and compared the magnitude of potential health gains against conventional risk reduction strategies.[29] Other studies have also projected reductions in mortality burden that were attributable to future air quality improvements and changes in population demographics.[30–32] Understanding the economic and health impacts of such improvements is essential for effective policymaking and designing future environmental interventions. Employing an economic health prediction model, we aimed to estimate the 10-year cardiovascular health and economic outcomes, and quantify potential cost savings and QALY gains, associated with improved air quality.

METHODS

Study population and time horizon

Using the 2015 wave of the China Health and Retirement Longitudinal Study (CHARLS) data as the baseline, we modelled the 10-year cumulative ischaemic stroke and coronary heart disease (CHD) incidences, total healthcare expenditure, and accrued QALYs for individuals aged 45–85 years across the following three PM2.5 concentration levels:

1. National average PM2.5 concentration levels in 2015.
2. Annual average PM2.5 concentration of 35 $\mu g/m^3$ set by the NAQAP.
3. The stricter annual average PM2.5 concentration of 5 $\mu g/m^3$ set by the WHO's Air Quality Guidelines.

Additionally, we compared the cumulative ischaemic stroke and CHD incidences, healthcare costs and QALYs associated with the NAQAP and WHO targets against the 2015 baseline scenario.

CHARLS is a nationally representative sample of over 17 500 individuals aged 45 and above from 10 000 households across China. Specifically, the national baseline survey was conducted between 2011 and 2012, involving 17 708 individuals through a multistage probability sampling method. Participants were followed biennially through face-to-face computer-assisted personal interviews.[33] Physical measurements were taken at each 2-year follow-up, while blood samples were collected once every two follow-up periods. The 2015 wave was chosen for its representation of CVD risks at background PM2.5 levels and includes data on key cardiovascular risk factors.

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Air quality data

Air quality monitoring data between 1 January and 31 December 2015 were obtained from the China National Environmental Monitoring Center (https://air.cnemc.cn:18007/), which contains hourly PM2.5 concentrations collected from 1497 monitoring sites in 338 Chinese cities at the prefectural level and above. We computed annual average PM2.5 concentrations derived from 24-hour moving averages for over 100 cities. Annual averages, assuming sufficient duration of exposure, were employed to represent long-term individual exposure.

Risk prediction

A cardiovascular risk equation[34] was used to calculate the 10-year age- and sex-specific event probabilities of atherosclerotic CVD (ASCVD), including ischaemic stroke and coronary events, for the 2015 CHARLS population. Specifically, equations 1 and 2 present the 10-year integrated cardiovascular risk equation for males and females where SBP represents systolic blood pressure, TC represents total cholesterol, BMI represents body mass index, I() is the indicator function, and smoking and diabetes is an indicator variable.

$$\begin{aligned}&\text{10-year integrated ASCVD risk for males} = 1-0.9835^{\sum \beta_i X_i},\\ &\text{where } \textstyle\sum \beta_i X_i = 0.0656\times \text{Age}_i - 0.5488\times I(\text{SBP}_i<120)\\ &+0.4011\times I(130\le \text{SBP}_i\le 139)+0.8073\times I(139<\text{SBP}_i\le 159)\\ &+1.7041\times I(159<\text{SBP}_i\le 179)+2.5327\times I(\text{SBP}_i>179)\\ &+0.2864\times I(\text{BMI}_i\ge 24)-0.007\times I(3.62\le \text{TC}_i\le 5.17)\\ &+0.304\times I(\text{TC}_i\ge 5.17)+0.7082\times \text{Smoking}_i+0.0651\times \text{Diabetes}_i\\ &-3.5951\end{aligned} \tag{1}$$

$$\begin{aligned}&\text{10-year integrated ASCVD risk for females} = 1-0.9948^{\sum \beta_i X_i},\\ &\text{where } \textstyle\sum \beta_i X_i = 0.0851\times \text{Age}_i - 0.8267\times I(\text{SBP}_i<120)\\ &+0.2294\times I(130\le \text{SBP}_i\le 139)+0.7970\times I(139<\text{SBP}_i\le 159)\\ &+1.3674\times I(159<\text{SBP}_i\le 179)+1.8483\times I(\text{SBP}_i>179)\\ &+0.6762\times I(\text{BMI}_i\ge 24)-0.0866\times I(3.62\le \text{TC}_i\le 5.17)\\ &+0.2654\times I(\text{TC}_i\ge 5.17)+0.4699\times \text{Smoking}_i+0.9599\times \text{Diabetes}_i\\ &-3.8780\end{aligned} \tag{2}$$

We estimated individual 10-year ASCVD event probabilities by inputting individual cardiovascular risk factors into equations 1 and 2. Further, we linked individual demographic data with annual PM2.5 concentration levels based on their reported county or city. Adjusted 10-year ischaemic stroke and CHD event probabilities associated with PM2.5 exposure were then computed using relative risks derived from the WHO's integrated response functions for the modelled air quality scenarios.[35] Yearly equivalent age- and sex-specific probabilities were derived assuming a continuous rate of probability (online supplemental equation 1). One-year probabilities of CHD and ischaemic stroke events were then estimated by adjusting the 1-year integrated ASCVD probability by relative CHD and ischaemic stroke incidence rates (online supplemental table 1).

Outcomes

Our primary outcome was to quantify 10-year ischaemic stroke and CHD incidences, healthcare costs, as well as accrued QALYs, for individuals aged 45–85 years in China across the three air quality scenarios. Total CVD-related healthcare costs and QALY associated with the NAQAP and WHO targets, were compared against the baseline 2015 scenario. Cost and QALYs were chosen as our primary outcomes as they are widely used in economic evaluations of health interventions.[36] Moreover, several economic studies have shown that stroke and CHD primarily contribute to the overall CVD burden.[37 38] Annual average health expenditures, encompassing both direct medical costs, out-of-pocket expenses and indirect costs, associated with ischaemic stroke and CHD events, were sourced from prior national level economic burden studies.[39 40] QALYs were calculated from age- and sex-specific health state utilities for the Chinese population.[41] One-month and long-term disutility values of stroke and CHD events were obtained from an economic modelling study conducted in Beijing.[42] Summaries of the costs, utility and disutility parameters are provided in online supplemental tables 2–4.

Model

We extrapolated age- and sex-specific adjusted estimates of ischaemic stroke and CHD event probabilities derived from the CHARLS cohort onto the national Chinese population for individuals aged 45–85 years. Annually, we estimated the expected incidences of ischaemic stroke and CHD for the three modelled air quality scenarios by applying the adjusted annual event probabilities associated with each PM2.5 scenario to the projected national population. Demographic data at the national level in 2015 were sourced from the UN World Population Prospects database, which offers age- and sex-stratified demographic estimates (online supplemental table 5).[43] Subsequently, on an annual basis, we quantified the healthcare expenditures associated with ischaemic stroke and CHD events using the healthcare expenditure estimates described above. Additionally, annual expected QALYs were estimated using the adjusted ischaemic stroke and CHD event probabilities with baseline age- and sex-specific utility and disability values presented earlier, where individuals were assumed to experience four states (ischaemic stroke event, CHD event, experience both ischaemic stroke and CHD events, and no event). For individuals experiencing a CVD event, it was assumed that the event occurred at the end of the year. Both cost and QALY were accrued on a yearly basis at a rate of 5%, consistent with current economic modelling guidelines for China.[44]Age-and-sex stratified baseline survival probabilities were derived from central mortality estimates from the UN Population Prospects database.[43] The UN database was chosen for its provision of mortality estimates at each individual aged between 45 and 85 years, which allowed the projection of mortality annually over the modelled period, assuming events occurred at the end of the year. Additionally, to account for improvements in air quality, we adjusted baseline survival probabilities using 28-day excess mortality rates associated with stroke and AMI, as sourced from a previous economic evaluation study (online supplemental table 6).[45] Specifically, the increased survival likelihood was quantified by accounting for the difference in the probability of cardiovascular events and their associated mortality probabilities under improved air quality scenarios, compared with the baseline. Online supplemental tables 7–12 present the baseline and adjusted survival probabilities stratified by age and sex for the three modelled scenarios. Key assumptions that form the basis for our modelling are summarised in online supplemental table 13.

Sensitivity analysis

To ensure the robustness of our findings, we performed one-way sensitivity analyses on costs and discount factor parameters. Additionally, we accounted for the variability in the health effects of air pollution on CVD using the WHO's lower and upper bound relative risk estimates. One-way sensitivity analyses and parameter inputs are presented in online supplemental table 14.

All statistical analysis was performed using R Statistical Software (V.4.4.1).

RESULTS

Table 1 presents the baseline age- and sex-stratified cardiovascular risk factors for the CHARLS cohort. We observed similar trends for males and females across BMI and SBP. Additionally, the prevalence of self-reported diabetes mellitus was relatively comparable between male and female respondents, with 419 cases in males and 541 in females, respectively. Conversely, smoking prevalence was significantly higher among males, with 3221 reporting smoking compared with 427 females. Further, the average annual population weighted PM2.5 in 2015 was 57.31 µg/m^3 for the CHARLS cohort, higher than the national average of 50 µg/m^3. Annual average PM2.5 concentrations in 2015 ranged between 18 µg/m^3 and 100 µg/m^3 with 92% of respondents experiencing PM2.5 levels higher than the NAQAP standard.

Table 2 presents the estimated age- and sex-specific incidence of ischaemic stroke and CHD events under the modelled PM2.5 concentration levels. For the 10-year period, the cumulative ASCVD events projected under the 2015 PM2.5 concentration levels were approximately 35.40 million cases, including 25.46 million ischaemic stroke events and 9.94 million CHD events. Using the same population assumptions, we estimated approximately 31.92 million ASCVD events, comprising 22.69 million ischaemic stroke events and 9.23 million CHD events, under the NAQAP's current PM2.5 target of 35 µg/m³. Furthermore, adjusting the annual average PM2.5 concentration to the WHO's recommended level of 5 µg/m³, our model predicted a decrease in total ASCVD events of 11.22 million. Additionally, for sex-specific results, we reported that the estimated total ASCVD incidences for male individuals in the baseline scenario were 19.04 million. Under the improved NAQAP and WHO targets, cumulative ischaemic stroke and CHD events decreased to 17.11 million and 12.75 million, respectively. For female individuals, the estimated incidences corresponded to 16.36 million, 14.81 million and 11.43 million, respectively.

Table 1 China Health and Retirement Longitudinal Study cohort baseline cardiovascular risk factors according to age and sex

(n=10 555)	Male	Female
Age		
45–54	1582	1958
55–64	1731	1932
65–74	1251	1213
75–84	446	417
85+	9	16
SBP mean (mm Hg)		
45–54	125.6	121.3
55–64	129.9	127.3
65–74	132.7	133.1
75–84	135.4	140.2
TC mean (mmol/L)		
45–54	4.63	4.69
55–64	4.61	4.99
65–74	4.60	5.00
75–84	4.55	4.91
BMI mean (kg/m^2)		
45–54	24.41	24.90
55–64	23.63	24.45
65–74	23.08	23.96
75–84	21.89	22.78
Smoking	3221	427
Diabetes mellitus	419	541

BMI, body mass index; SBP, systolic blood pressure; TC, total cholesterol.

Table 3 illustrates the projected 10-year total healthcare expenditure and accrued QALY attributable to ambient PM2.5 for the three concentration levels. For the baseline, we estimated that the cumulative costs of ASCVD for both male and female individuals were approximately US$51.89 billion and US$44.23 billion, respectively, resulting in a combined total of US$96.12 billion. This encompassed $63.87 billion in ischaemic stroke-related expenses and US$32.25 billion in costs associated with CHD. In this context, total QALYs were estimated at 4.44 billion, with 2.22 billion attributed to males and 2.23 billion to females. Additionally, when modelling under NAQAP standards, we identified a decrease in total healthcare costs of US$9.29 billion, with US$5.18 billion

Table 2 Projected incidence of ischaemic stroke and CHD events under three air quality improvement scenarios*

Age	2015 levels			NAQAP 35 μg/m³ scenario				WHO 5 μg/m³ scenario			
	Stroke	CHD	Total	Stroke	CHD	Total	Excess	Stroke	CHD	Total	Excess
Male											
45–49	1.27	0.53	1.80	1.07	0.47	1.54		0.69	0.33	1.02	
50–54	1.38	0.57	1.95	1.18	0.52	1.70		0.79	0.37	1.16	
55–59	1.80	0.75	2.55	1.57	0.69	2.26		1.09	0.50	1.59	
60–64	2.37	0.99	3.36	2.09	0.91	3.00		1.50	0.69	2.19	
65–69	2.11	0.88	2.99	1.89	0.82	2.71		1.41	0.64	2.05	
70–74	1.87	0.78	2.65	1.68	0.73	2.41		1.30	0.58	1.88	
75–79	1.67	0.70	2.37	1.53	0.66	2.19		1.22	0.55	1.77	
80–85	0.97	0.40	1.37	0.91	0.39	1.30		0.76	0.33	1.09	
Total_m	13.44	5.60	19.04	11.92	5.19	17.11	1.93	8.76	3.99	12.75	6.29
Female											
45–49	0.46	0.17	0.63	0.39	0.15	0.54		0.25	0.10	0.35	
50–54	0.65	0.23	0.88	0.56	0.21	0.77		0.38	0.15	0.53	
55–59	0.92	0.33	1.25	0.79	0.30	1.09		0.55	0.22	0.77	
60–64	1.67	0.60	2.27	1.46	0.55	2.01		1.05	0.42	1.47	
65–69	1.77	0.64	2.41	1.57	0.59	2.16		1.17	0.46	1.63	
70–74	2.23	0.81	3.04	2.03	0.76	2.79		1.58	0.61	2.19	
75–79	2.27	0.82	3.09	2.07	0.77	2.84		1.66	0.64	2.30	
80–85	2.05	0.74	2.79	1.90	0.71	2.61		1.58	0.61	2.19	
Total_f	12.02	4.34	16.36	10.77	4.04	14.81	1.55	8.22	3.21	11.43	4.93
Total	25.46	9.94	35.40	22.69	9.23	31.92	3.48	16.98	7.20	24.18	11.22

*Figures presented in millions.
CHD, coronary heart disease; NAQAP, National Air Quality Action Plan.

reductions attributed to males and US$4.11 billion attributed to females. Total QALY improvement was estimated at 3.43 million, of which 1.88 million resulted from males and 1.56 million from females. Compared with the baseline scenario, at the 5 μg/m³ level, the estimated reductions in healthcare costs amounted to US$30.10 billion. Subsequently, total QALY gains corresponded to 11.29 million, with male and female individuals experiencing estimated gains of 6.27 million and 5.02 million, respectively. In terms of the average 10-year ASCVD costs per person under baseline and improved air quality scenarios of 35 μg/m³ and 5 μg/m³, the estimates per person were US$191.03, US$172.54 and US$131.25, respectively. The corresponding 10-year average QALYs per person were 8.93 years, 8.94 years and 8.95 years, respectively.

Figures 1 and 2 present the results of our sensitivity analyses. We observed that variations in the discount rate and per capita CVD costs had a similar effect on the overall estimate of cumulative 10-year CVD healthcare costs. For a 15% reduction in annual per capita ischaemic stroke and CHD costs, the projected cumulative 10-year healthcare costs were US$72.10 billion, US$65.15 billion and US$49.50 billion, respectively, for the three scenarios. These estimates increased to US$87.06 billion, US$78.66 billion and US$59.76 billion, respectively, assuming a 3% annual discount rate. Conversely, for a 15% increase in annual costs, the total estimated cost of the outcomes was US$110.56 billion, US$99.89 billion and US$75.91 billion, respectively. However, under an 8% discount rate, the cumulative 10-year healthcare costs were US$111.75 billion, US$100.98 billion and US$76.75 billion, respectively. Additionally, when modelling under the lower and upper risk curve boundaries to account for variations in the impact of air pollution on cardiovascular health, our analysis suggested that the results are comparable to those at baseline.

DISCUSSION

The findings of our study indicate that reducing national PM2.5 concentration levels could yield significant economic and health benefits associated with CVD. Based on 2015 concentration levels, the projected cumulative 10-year healthcare costs for ischaemic stroke and CHD among individuals aged 45–85 years were approximately US$96.12 billion. This significantly reduced to US$86.83 billion and US$66.02 billion under the national and international regulatory guidelines, respectively. For accrued QALY, estimates corresponding to

Table 3 Estimated cost savings and QALY gains for ischaemic stroke and CHD under three air quality improvement scenarios*†

Age	2015 levels				35 µg/m³ scenario		5 µg/m³ scenario	
	Stroke costs	CHD costs	Total cost	Total QALY	Excess cost	Excess QALY	Excess cost	Excess QALY
Male								
45–49	3.15	1.70	4.85	619.53	0.70	201 960	2.08	623 890
50–54	3.41	1.84	5.25	479.61	0.67	200 485	2.07	641 431
55–59	4.45	2.40	6.85	360.42	0.77	231 902	2.54	780 871
60–64	5.90	3.18	9.08	326.65	0.95	321 745	3.13	1 081 190
65–69	5.29	2.85	8.14	203.68	0.76	274 702	2.55	954 309
70–74	4.71	2.54	7.25	119.03	0.64	295 349	2.06	959 314
75–79	4.27	2.30	6.57	72.27	0.50	258 289	1.65	860 951
80–85	2.53	1.37	3.90	36.46	0.19	91 870	0.79	367 098
Total_m	33.71	18.18	51.89	2.22	5.18	1 876 302	16.87	6 269 053
Female								
45–49	1.13	0.53	1.66	586.21	0.23	59 837	0.71	187 112
50–54	1.60	0.75	2.35	464.73	0.28	73 737	0.94	248 214
55–59	2.26	1.05	3.31	347.58	0.40	110 749	1.25	343 172
60–64	4.12	1.92	6.04	332.85	0.65	199 154	2.09	645 058
65–69	4.41	2.06	6.47	212.94	0.67	219 488	2.09	701 926
70–74	5.63	2.63	8.26	134.64	0.73	322 909	2.35	1 036 641
75–79	5.73	2.67	8.40	91.10	0.66	334 481	2.13	1 078 845
80–85	5.28	2.46	7.74	57.08	0.49	235 120	1.67	780 282
Total_f	30.16	14.07	44.23	2.23	4.11	1 555 474	13.23	5 021 250
Total	63.87	32.25	96.12	4.44	9.29	3 431 776	30.10	11 290 303

*Cost figures presented in billions.
†2015 QALY figures reported in millions, other QALY figures presented per unit.
CHD, coronary heart disease; QALY, quality-adjusted life year.

the three modelled scenarios amounted to 4.44 billion years, 4.49 billion years and 4.50 billion years, respectively. These findings suggest that potential cost savings related to cardiovascular health and gains in QALY under the WHO's PM2.5 target could exceed threefold the outcomes achievable under the existing NAQAP's target.

Our findings corroborate existing literature underscoring the potential cardiovascular benefits of reducing ambient PM2.5 air pollution in China.[29–31] Following the 2021 revision of the WHO air quality guidelines, which now recommend annual mean PM2.5 concentrations not exceeding 5 µg/m³, updated epidemiological evidence

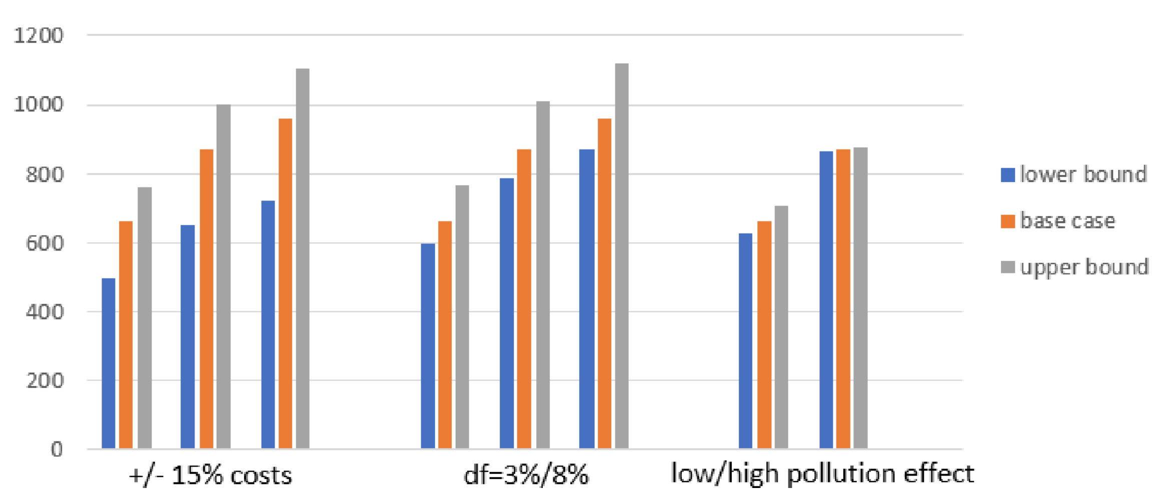

Figure 1 One-way sensitivity analyses for healthcare costs.

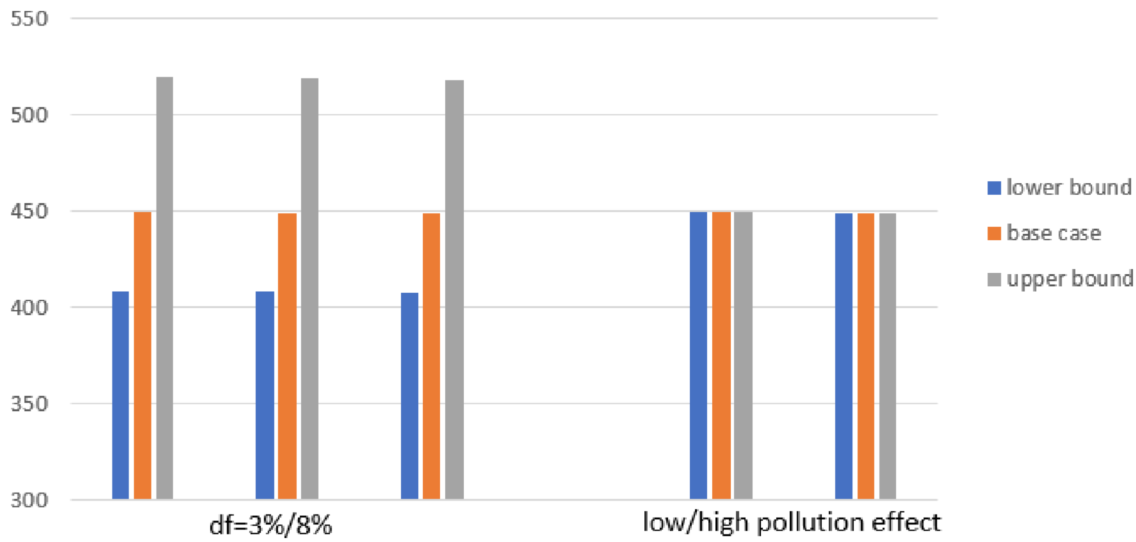

Figure 2 One-way sensitivity analyses for quality-adjusted life year.

has demonstrated that even lower concentrations of air pollution have large adverse health effects.[46] Existing studies have demonstrated the considerably greater health and economic benefits, particularly in preventing premature deaths, that can be achieved under the revised guideline.[47] Our analysis offers updated evidence of the potential cardiovascular benefits achievable under the revised WHO guidelines within the context of China. Additionally, our study further extends the existing knowledge by providing insights into the potential cardiovascular benefits under improved air quality scenarios from an economic perspective, demonstrating the sizeable economic benefits in terms of healthcare expenditure reductions and improved morbidity and longevity, measured through QALY.

Our models suggest that under the NAQAP's 35 μg/m^3 scenario, the estimated annual reductions of 0.2 million ischaemic stroke cases would be equivalent to 3% of the total stroke incidences reported nationally in 2020.[48] For CHD, this figure amounted to an annual average of 0.09 million cases, or 2% of the total national CHD events in 2019.[49] Moreover, the average annual reductions in medical costs related to CVD amounted to approximately 10% of the total CVD costs in 2015. This figure is comparable to that of a similar modelling study conducted in Beijing,[42] and represents approximately 2% of the total national direct medical expenses for stroke and CHD.[40 50] Additionally, estimates show that the total cost of implementing NAQAP between 2013 and 2017 amounted to RMB 1.65 trillion (US$229.17 billion).[51] This suggests that under our modelled scenario, the average annual potential reductions in PM2.5 induced CVD healthcare costs represent approximately 2% of annual average NAQAP mitigation costs. If we also incorporate monetised QALY gains using the WHO's recommended three times GDP per capita estimate (US$23 051),[52] this figure amounts to US$8.85 billion, or approximately 20% of the annual average NAQAP costs, highlighting the substantial contributions to economic benefits from QALY gains compared with savings in annual average medical costs.

Over the past decade, China has observed considerable air quality improvements, reducing national annual average PM2.5 concentrations from 72.2 μg/m^3 in 2013 to 32.7 μg/m^3 in 2020.[21 53] However, a recent study reported that the annual average PM2.5 concentrations in 49 cities was above 50 μg/m^3 in 2020,[54] surpassing national regulatory guidelines, and more than 10 times above the WHO suggested guidelines.[16] While reductions in annual PM2.5 concentration levels to NAQAP's target of 35 μg/m^3 is a sizeable, our findings suggest that a substantial increase in both cost savings and QALY gains could be achieved under more ambitious air quality standards. In 2023, China announced its latest national clean air standards as part of the 14th Five-Year Plan, mandating a 10% reduction in annual average PM2.5 concentrations by 2025 compared with 2020 levels across all 337 prefecture-level (or above) cities.[53] This initiative reflects the continued concerted efforts of the Chinese government to combat air pollution. While our analysis focuses on the period from 2015 to 2024, the findings have significant implications for current policy decision-making in several ways. Our analysis underscores the need for more stringent national standards, indicating that achieving the WHO-recommended target, as opposed to the NAQAP guidelines, could yield potential economic benefits nearly three times larger in terms of reduced medical costs and enhanced longevity. Additionally, our analysis demonstrates that the health and economic benefits of reducing PM2.5 exposure are more pronounced at lower concentrations compared with higher levels. This observation is supported by a range of recent epidemiological evidence indicating that reductions in PM2.5 at lower levels significantly impact various health outcomes, including stroke and CHD.[55] Given the anticipated stagnation of China's population and the challenges associated with an ageing demographic, further reductions in PM2.5 could yield enhanced benefits in both cardiovascular health and economic outcomes. Thus, this strengthens the argument to establishing further national pollution reduction regulations to meet WHO's recommended PM2.5 target. However, achieving the WHO's PM2.5 target necessitates long-term commitments to cleaner energy and lowering emissions involving transitioning to renewable energy sources, while phasing out energy reliance on fossil fuels. Moreover, comprehensive strategies addressing multifaceted pollution sources are needed.[56] These entail the continuation of existing policies, such as the 'ten measures' outlined in the 2013 NAQAP.[57]

According to estimates from the WHO, LMICs, particularly in South-East Asia, collectively account for over 89% of the disease burden associated with exposure to ambient air pollution worldwide.[1] China is one of the leading middle-income countries in this region to reduce its high pollution levels. Our findings, in addition to those of other health assessment studies, further contribute to the existing literature which demonstrates the substantial economic and health benefits associated with significant reductions in ambient air pollution in relation cardiovascular and other health outcomes in China.[42 58–65] This highlights the importance of encouraging governments within this region, such as India, Pakistan and Bangladesh, which have been identified as the top polluted countries in South-East Asia,[66] to establish effective national air quality regulatory standards. Further, economic evaluation studies have shown that the overall economic evidence of air pollution mitigation, when considering the comprehensive health-related benefits, significantly outweighs the corresponding mitigation costs.[51] Our model also demonstrated the sizeable additional benefits achievable at WHO's lower PM2.5 target of 5 μg/m^3 compared with existing national air quality targets, further incentivising governments in the region to adopt effective PM2.5 air quality standards for the long term.

This study has some limitations. Relevant to all economic health modelling studies, the accuracy of our model was constrained by its simplifying assumptions and the quality of the inputted data. First, we assumed that annual PM2.5 concentrations was indicative of long-term exposure, which may not fully capture actual population exposure due to factors like population movement and individual behaviours. Second, we assumed that the cardiovascular risk factors of the population would remain consistent throughout the modelled period. However, actual biomarkers and blood risk factors may vary over time due to biological factors, lifestyle changes and other individual health dynamics. Third, we modelled air quality improvement under the assumption that PM2.5 concentration levels would be consistent over the studied period. However, air quality improvement typically unfolds gradually over time. Finally, we focused on individuals aged 45 and above, limiting our ability to predict benefits for the entire national population. While existing evidence suggests that elders are most at risk of developing CVD due to exposure to air pollution and already contribute to the majority of the CVD disease burden,[37 67] future research could focus on estimating the health benefits attributable to reducing PM2.5 for the entire national population to gain a better understanding of its impact.

CONCLUSIONS

We used an economic health model to estimate cardiovascular health outcomes over a 10-year period, and compared the cumulative healthcare costs and QALY under 2015 ambient air quality conditions to the NAQAP and WHO PM2.5 standards of 35 μg/m^3 and 5 μg/m^3. Our analysis reveals that while significant reductions in costs and QALYs could be achievable at the 35 μg/m^3 level, further additional benefits of approximately US$20.81 billion in cost savings and 7.86 million QALYs could be realised if annual PM2.5 concentration levels meet the WHO's air quality guideline at 5 μg/m^3. This underscores the importance of setting more ambitious future air quality targets for China. Our findings highlight the importance of recognising PM2.5 exposure, alongside conventional risk factors, as a significant contributor to the overall burden of CVD. It also incentivises other LMICs within the Asia-Pacific region, which already bear a disproportionate disease burden associated with elevated levels of ambient air pollution, to establish long-term effective air quality standards.

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