Potential Cardiovascular and Total Mortality Benefits of Air Pollution Control in Urban China

Editorial, see p 1585

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BACKGROUND: Outdoor air pollution ranks fourth among preventable causes of China's burden of disease. We hypothesized that the magnitude of health gains from air quality improvement in urban China could compare with achieving recommended blood pressure or smoking control goals.

METHODS: The Cardiovascular Disease Policy Model–China projected coronary heart disease, stroke, and all-cause deaths in urban Chinese adults 35 to 84 years of age from 2017 to 2030 if recent air quality (particulate matter with aerodynamic diameter ≤2.5 µm, $PM_{2.5}$) and traditional cardiovascular risk factor trends continue. We projected life-years gained if urban China were to reach 1 of 3 air quality goals: Beijing Olympic Games level (mean $PM_{2.5}$, 55 µg/m^3), China Class II standard (35 µg/m^3), or World Health Organization standard (10 µg/m^3). We compared projected air pollution reduction control benefits with potential benefits of reaching World Health Organization hypertension and tobacco control goals.

RESULTS: Mean $PM_{2.5}$ reduction to Beijing Olympic levels by 2030 would gain ≈241,000 (95% uncertainty interval, 189 000–293 000) life-years annually. Achieving either the China Class II or World Health Organization $PM_{2.5}$ standard would yield greater health benefits (992 000 [95% uncertainty interval, 790 000–1 180 000] or 1 827 000 [95% uncertainty interval, 1 481 00–2 129 000] annual life-years gained, respectively) than World Health Organization–recommended goals of 25% improvement in systolic hypertension control and 30% reduction in smoking combined (928 000 [95% uncertainty interval, 830 000–1 033 000] life-years).

CONCLUSIONS: Air quality improvement in different scenarios could lead to graded health benefits ranging from 241 000 life-years gained to much greater benefits equal to or greater than the combined benefits of 25% improvement in systolic hypertension control and 30% smoking reduction.

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Sources of Funding, see page 1582

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Clinical Perspective

What Is New?

- This forecast is the first to indicate that cardiovascular disease deaths and life-years gained from reducing the national mean particulate matter with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) in 2017 to the 2008 Beijing Olympic Games level would be greater than benefits gained from 30% reduction in tobacco use among urban Chinese adults.
- Achieving the China Class II standard of 35 μg/m^3 or a more aggressive World Health Organization target of 10 μg/m^3 for $PM_{2.5}$ control would yield greater cardiovascular disease deaths reduction and life-year gains than the combined benefits of World Health Organization–recommended 25% systolic hypertension control and 30% smoking reduction in urban China.

What Are the Clinical Implications?

- The findings suggested that small risk reductions from air pollution control across the entire urban population yield health benefits similar to control for systolic hypertension and smoking in a high-risk segment of the urban Chinese population.
- Air quality improvement in China will call for joint efforts of the whole society, including development of green transportation, reduction of industrial emission, implementation of governmental control measures, and other collaborative actions in air pollution control.

In urban China, especially in northern cities, hazardous outdoor air pollution has become a major environmental problem. The annual population-weighted mean level of particulate matter with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) in all of China rose from 39 μg/m^3 in 1990 to 54 μg/m^3 by 2013.[1] Among 161 selected Chinese cities, mean $PM_{2.5}$ was 62 μg/m^3 in 2014,[2] 90% of cities were in excess of the China Class II air quality standard limit of 35 μg/m^3,[2] and all were above the World Health Organization (WHO) recommended level of 10 μg/m^3.[3] The highest annual average $PM_{2.5}$ level among these cities peaked at 130 μg/m^3, nearly 4-fold higher than the national limit.[2] During the period of the 2008 Beijing Olympic Games, a government program of aggressive air quality controls reduced the mean $PM_{2.5}$ by ≈30 μg/m^3.[4]

Outdoor air pollution is associated with increased population risk for cardiopulmonary diseases.[5] In 2010, ambient air pollution led to 3.3 million premature deaths per year globally, and most of these avoidable deaths occurred in Asia.[6] The global fractions of adult mortality attributable to the human-made component of $PM_{2.5}$ are 8.0% for cardiopulmonary disease and 9.4% for ischemic heart disease.[7] After dietary risks (51.7 million disability-adjusted life-years), high blood pressure (37.9 million disability-adjusted life-years), and tobacco smoking (30.0 million disability-adjusted life-years), ambient particulate matter pollution was the fourth leading preventable risk factor responsible for China's avoidable disease burden in 2010 (25.2 million disability-adjusted life-years).[8] Natural experiments associated a 10 μg/m^3 reduction in $PM_{2.5}$, with a 31% reduction in cardiovascular mortality over 8 years of follow-up.[9]

A long-term interventional trial with a large sample size will be optimal to illustrate the health benefits gained from air pollution control. However, it does not seem feasible to carry out such a trial with enough intervention time to observe cardiovascular health benefits currently. As an initial step, we conducted a computer simulation experiment to explore the potential cardiovascular and noncardiovascular health benefits of achieving 3 air quality targets and further compared the scale of predicted health benefits with active tobacco smoking and systolic hypertension controls in urban China.

METHODS

Cardiovascular Disease Policy Model–China Overview

The Cardiovascular Disease (CVD) Policy Model–China is a computer-simulation, state-transition (Markov cohort) mathematical model of coronary heart disease (CHD) and stroke incidence, prevalence, mortality, noncardiovascular deaths, and costs of health care in the Chinese population 35 to 84 years of age (Table 1 and Figure 1). This model has been used for CVD epidemiological projections and effectiveness analysis of specific policy interventions.[19] The urban-wide population from 2017 to 2030 was estimated using the projected total China population and urban-rural ratio from the *World Urbanization Prospects* (Table I in the online-only Data Supplement).[11,12] Means and proportions of CVD risk factors in urban Chinese adults 35 to 84 years of age were estimated from the China Cardiovascular Health Study and the China Multicenter Collaborative Study of Cardiovascular Epidemiology.[15,16] CHD, stroke incidence, and noncardiovascular mortality risk were predicted among individuals without CVD, stratified by age, sex, systolic blood pressure (SBP), body mass index (BMI), low-density lipoprotein cholesterol, high-density lipoprotein cholesterol, smoking status, and diabetes. Multivariable adjusted hazard ratios of SBP, low-density lipoprotein, high-density lipoprotein, BMI, smoking and diabetes mellitus for CHD, stroke, and noncardiovascular (non-CHD, nonstroke) deaths by age and sex were estimated from the China Multiprovincial Cohort Study[18] using a competing risk Cox proportional hazard model for each outcome (Table II in the online-only Data Supplement). Future traditional noncommunicable disease (NCD) risk factor trends were projected forward from 2017 to 2030 using the China Health Nutrition Surveys (CHNS) study (Table III in the online-only

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Table 1. Main Inputs for Cardiovascular Benefits Projections From Improved Air Pollution Among the Urban Chinese Population 35 to 84 Years of Age

Inputs	Definition	Source
Population	Population 35–84 years of age in urban China	The 6th population census of China in 2010[10]
	Impact of growth, aging, and urbanization on population	Projections from United Nations Population Division[11,12]
Air pollution	An annual population-weighted average level of $PM_{2.5}$ level during 2014–2015 in 190 cities	Zhang et al[13]
	Main estimates and SDs of risk coefficients of long-term exposure to $PM_{2.5}$ for CHD, stroke, and all-cause mortality with 1 μg/m³ increase in $PM_{2.5}$	Based on a meta-analysis by Hoek et al[14]
Traditional cardiovascular risk factors	Baseline levels of traditional cardiovascular risk factors were analyzed, including SBP, BMI, HDL, LDL, status of smoking, and diabetes mellitus	China Cardiovascular Health Study, ChinaMUCA[15,16]
	Trend estimations of risk factors were projected forward over years 2017 to 2030	CHNS study, China Cardiovascular Health Study, ChinaMUCA[15–17]
	Main estimates and SDs of risk coefficients of traditional cardiovascular risk factor on CHD, stroke, and all-cause mortality were estimated	CMCS study[18]

BMI indicates body mass index; CHD, coronary heart disease; ChinaMUCA, China Multicenter Collaborative Study of Cardiovascular Epidemiology; CHNS, China Health and Nutrition Survey; CMCS, Chinese Multi-Provincial Cohort; HDL, high-density lipoprotein cholesterol; LDL, low-density lipoprotein cholesterol; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm; SBP, systolic blood pressure; and SD, standard deviation.

Data Supplement).[17] An annual population-weighted average $PM_{2.5}$ level from 2014 to 2015 was extracted and assumed as the starting national $PM_{2.5}$ level in 2017.[13] Effects of long-term $PM_{2.5}$ exposure on CHD and stroke deaths based on a meta-analysis were incorporated into the model (Table IV and Figures I-III in the online-only Data Supplement).[14] Finally, starting with CHD and stroke case fatality obtained from the Sino-MONICA Beijing study (Monitoring Trends and Determinants in Cardiovascular Disease),[20] the CVD Policy Model–China mortality projections were calibrated to fit with age-specific and overall CHD and stroke mortality numbers from 2010 to 2011 based on mortality surveillance data from the China Center for Disease Control.[21] After CHD and stroke mortality were calibrated, age- and sex-specific noncardiovascular death rates were also calibrated so that the total of cardiovascular and noncardiovascular deaths fitted within the envelope of all-cause mortality reported by the China Center for Disease Control (Tables V–VIII in the online-only Data Supplement).[21]

The modeling study was approved by the Institutional Review Board at Fuwai Hospital in Beijing. All the preceding original studies included in the secondary analyses obtained written informed consent from each participant before data collection.

Projected Population of Urban China, 2017 to 2030

Population estimates for the urban China population were obtained from the 2010 6th China census.[10] The urban population from 2017 to 2030 was estimated by projecting population growth and aging trends from 2017 to 2030 and then multiplying the whole population estimate by the expected urbanization rate (Table I in the online-only Data Supplement).[11,12]

$PM_{2.5}$ Exposure and Effect on Mortality

The Chinese Ministry of Environmental Protection started to measure $PM_{2.5}$ concentrations in 2012. An annual population-weighted average $PM_{2.5}$ level from 2014 to 2015 was extracted in 190 cities with more than 950 monitoring sites and assumed as the starting national $PM_{2.5}$ level in 2017.[13] We started with the population-weighted mean 2014 to 2015

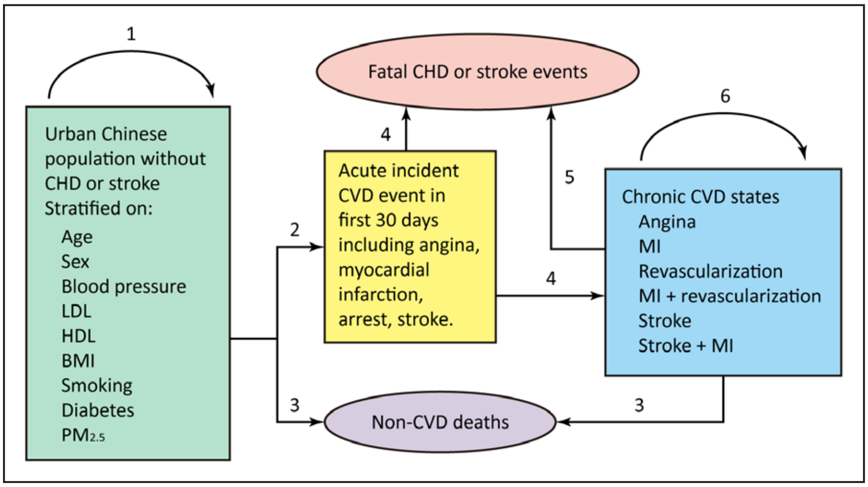

Figure 1. The CVD Policy Model–China structure.
Transition 1 = remain in CVD-free state. Transition 2 = incident CVD. Transition 3 = non-CVD death. Transitions 4 and 5 = survival or case fatality. Transition 6 = survival with or without repeat CVD event in patients with chronic CVD. BMI indicates body mass index; CHD, coronary heart disease; CVD, cardiovascular disease; HDL, high-density lipoprotein cholesterol; LDL, low-density lipoprotein cholesterol; MI, myocardial infarction; and $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm.

$PM_{2.5}$ of 61 μg/m^3 in urban China and projected it forward to 2030 as the status quo case.[13] To quantify the relative impacts of air pollution control, the $PM_{2.5}$ levels for the selected cities (Beijing, 79.8 μg/m^3, and Baoding, 118.8 μg/m^3) were also obtained.[13] For the 2008 Beijing Olympic Games air quality goal, because of the lack of a reliable $PM_{2.5}$ level measurement at the city-wide level in Beijing at that time, we based the level on mean $PM_{2.5}$ levels recorded by the US embassy in Beijing, located northeast of central Beijing.[22] Relative risks of CHD, stroke, and all-cause mortality associated with long-term $PM_{2.5}$ exposure were estimated in a meta-analysis of cohort studies using random effects model via the DerSimonian-Laird method (Table IV and Figures I-III in the online-only Data Supplement)[14] Because these studies included in the meta-analysis did not report effects of long-term $PM_{2.5}$ exposure on health stratified by age or sex, we assumed a uniform relative risk effect of $PM_{2.5}$ on all urban adults. Because our CVD Policy Model–China was not originally designed for pulmonary disease, we could not directly predict pulmonary deaths. Thus, prevented pulmonary deaths were estimated by taking a fixed proportion of prevented noncardiovascular deaths based on cause-specific mortality surveillance data from the China Center for Disease Control.[21]

Traditional NCD Risk Factor Trend Projections (2017–2030)

Future traditional NCD risk factor trends were projected forward from 2017 to 2030 based on recent temporal trends from 1990 to 2009 (Table III in the online-only Data Supplement). Temporal trend estimations were based on repeated CHNS from 1991 to 2009.[17] Temporal SBP, BMI, and active smoking trends were estimated using CHNS data and an age-adjusted mixed linear random effects model with 10-year age groups. Age-time interactions observed in trends for SBP, BMI, or active smoking were incorporated into age-specific risk factor trend projections. Because serum lipid data were available only for 2009, high- and low-density lipoprotein trends were assumed to be mediated by the BMI trend.[23] In this model analysis, diabetes mellitus was defined as having a past diagnosis of diabetes mellitus, taking anti–diabetes mellitus medications, or having a fasting glucose level ≥126 mg/dL. Diabetes mellitus prevalence recorded in the CHNS before 2009 might be underestimated without fasting glucose data. Therefore, we assumed that the diabetes mellitus awareness rate (the proportion of self-reported diabetes among participants defined as diabetes mellitus) gradually increased over time. The number of diabetes mellitus cases before 2009 was estimated using the following formula: the number of diabetes mellitus cases = self-reported diabetes mellitus/diabetes mellitus awareness rate. Self-reported diabetes mellitus information was obtained from the CHNS, whereas diabetes mellitus awareness data were from the China Cardiovascular Health Study and the China Multicenter Collaborative Study of Cardiovascular Epidemiology. Then the prevalence of diabetes mellitus could be obtained as the proportion of the estimated number of diabetes mellitus cases over the total number of subjects in CHNS. Based on the calculated diabetes mellitus prevalence, we projected a diabetes mellitus trend accordingly (Table III in the online-only Data Supplement).

Air Pollution, Smoking, and Systolic Hypertension Control Scenarios

In 2013, the Chinese government released the first National Action Plan on Air Pollution Prevention and Control (2013–2017), setting air pollution improvement goals for different areas, with 15% to 25% reductions in $PM_{2.5}$ by 2017.[24] The Beijing municipal government also announced a plan to improve air quality to the China Class II standard of 35 μg/m^3 by 2030. Additional health benefits could be gained by lowering $PM_{2.5}$ level to the WHO recommendation of 10 μg/m^3. We assumed that the health effects of controlled $PM_{2.5}$ levels on CHD and stroke mortality were roughly linear over the range 10 to 65 μg/m^3.[25] A status quo simulation projected cumulative CHD, stroke, and all-cause mortality events for Chinese adults from 2017 to 2030, projecting forward background traditional risk factor secular trends but no change from status quo level of $PM_{2.5}$. Life-years were tabulated without discounting. Annual CHD, stroke, and all-cause mortality and life-years were averaged over the simulation period. We simulated 3 air quality improvement scenarios, with a linear decrease in $PM_{2.5}$ to the following targets by 2030: (1) the Beijing Olympic Games $PM_{2.5}$ level of 55 μg/m^3, (2) the China Class II air quality standard level of 35 μg/m^3, or (3) the WHO-recommended level of 10 μg/m^3.

In 2013, the WHO developed a global monitoring framework aimed at reducing global mortality from 4 major NCDs, of which CVD is the main contributor.[26] The framework comprises 9 voluntary global NCD targets for 2025, including a 25% reduction in hypertension and a 30% reduction in tobacco use. Although reducing the air pollution level was not listed as 1 of the priorities in this framework, to better understand the magnitude of health gains possible of air pollution improvement with control of traditional NCD risk factors, we further projected the effects of a gradual control of systolic hypertension (from ≥140 mm Hg to <140 mm Hg) in 25% of patients with uncontrolled systolic hypertension and a gradual 30% reduction in tobacco use from 2017 to 2030, both individually and in combination. Furthermore, we titrated the effect size of simulated blood pressure and tobacco smoking prevalence reductions until the numbers of life-years gained matched the projected number of life-years gained with the 2008 Beijing Olympic $PM_{2.5}$ improvement.

Statistical Analysis

Projected deaths and life-years under different hypothetical scenarios were estimated using the CVD Policy Model–China, which incorporated urban China population projections, $PM_{2.5}$ effect on CVD incidence and CVD and non-CVD mortality, and traditional noncommunicable disease risk factor trend projections. Annual numbers of CVD events were deterministically predicted from hazard ratios estimated by Cox proportional hazard models for each simulated outcome (Table II in the online-only Data Supplement). Life-years were tabulated for the population alive in each model cycle. Further, deaths averted and life-years gained were compared between status quo and projected scenarios. We also performed multivariable probabilistic sensitivity (Markov Monte Carlo) analyses to estimate a range of uncertainty surrounding the results of projected air quality improvement and traditional risk factor intervention scenarios.

We assumed that the beta-coefficient distributions measuring the effect sizes for associations of SBP, smoking, and $PM_{2.5}$ with CVD mortality were normally distributed. We performed 1000 Markov simulations in which the 3 beta-coefficient distributions were randomly and simultaneously sampled in each simulation. The 95% uncertainty intervals (95% UIs) reported in Table 2 and the figures reflected the lower 2.5th and upper 97.5th percentiles of the 1000 results for each outcome.

In addition, several sensitivity analyses were conducted to make the results more interpretable. First, considering the potential reduced trend of $PM_{2.5}$ in China, health benefits were estimated with a graded reduction of $PM_{2.5}$ from 2017 to 2030 as an alternative status quo scenario. Second, a linear $PM_{2.5}$-CVD morality relationship assumption might overestimate the health benefits; thus, 10% and 20% attenuated $PM_{2.5}$-CVD health effects were used to quantify the impact of attenuated relative risk on health benefits. Details can be found in the Methods in the online-only Data Supplement.

RESULTS

Because of population growth, aging, and rural-to-urban migration, the urban Chinese population 35 to 84 years of age was projected to grow from 421 million in 2017 to 602 million in 2030 (Table I in the online-only Data Supplement). In the status quo simulation holding the $PM_{2.5}$ constant at 61 μg/m^3 and extending traditional risk factor trends forward, ≈7 900 000 (95% UI, 7 741 000–8 076 000) CHD deaths (annual average, 564 000 [95% UI, 553 000–577 000]) and 11 061 000 (95% UI, 10 408 000–11 617 000) stroke deaths (annual average, 790 000 [95% UI, 743 000–830 000]) were projected in urban China from 2017 to 2030 (Table 2).

Reduction in mean $PM_{2.5}$ level to the 2008 Beijing Olympics level would prevent ≈439 000 (95% UI, 233 000–643 000) CHD deaths (5.6% [95% UI, 3.0–8.1] reduction; annual average, −31 000 [95% UI, −46 000 to −17 000]), ≈237 000 (95% UI, 109 000–357 000) stroke deaths (2.1% [95% UI, 1.0–3.2] reduction; annual average, −17 000 [95% UI, −25 000 to −8000]), and ≈397 000 (95% UI, 386 000–409 000) noncardiovascular deaths (1.3% [95% UI, 1.2–1.4] reduction; annual average, −28 000 [95% UI, −29 000 to −27 000]), including ≈79 000 (95% UI, 77 000–82 000) pulmonary disease deaths (annual average, −5700 [95% UI, −5800 to −5500]) and would gain ≈3 379 000 (95% UI, 2 645 000–4 109 000) (annual average, +241 000 [95% UI, 189,000–293,000]) life-years in urban China. We projected that with air quality reaching the 2008 Beijing Olympic Games goal (55 μg/m^3), ≈43.4% (95% UI, 25.8–53.9) of CHD deaths, 20.7% (95% UI, 9.6–29.7) of stroke deaths, and 12.8% (95% UI, 12.1–13.6) of pulmonary deaths would be avoided in the highest $PM_{2.5}$ level city (Baoding, $PM_{2.5}$ 118.8 μg/m^3), and 20.8% (95% UI, 10.6–30.0) of CHD deaths, 8.7% (95% UI, 2.1–15.2) of stroke deaths, and 5.3% (95% UI, 4.7–6.0) of pulmonary deaths would be avoided in a contrast city (Beijing, $PM_{2.5}$ 79.8 μg/m^3).

The life-years gained from reducing national mean $PM_{2.5}$ to the 2008 Beijing Olympic Games level were fewer than controlling 25% of systolic hypertension but >30% reduction in tobacco use (Figure 2). Reaching the Beijing Games air quality goal was projected to yield health gains comparable in magnitude to the life-years gained by controlling 1.8% of systolic hyper-

Table 2. Projected CHD and Stroke Deaths Averted With Hypothetical Air Pollution Controls in the Urban Chinese Population 35 to 84 Years of Age From 2017 to 2030: The Cardiovascular Disease Policy Model–China

	Annual $PM_{2.5}$ Level (μg/m^3)	CHD Deaths (Thousands, 95% UI)	Averted CHD Deaths (Thousands, 95% UI)	Stroke Deaths (Thousands, 95% UI)	Averted Stroke Deaths (Thousands, 95% UI)
Status quo case (remain current $PM_{2.5}$ level)	61	7900 (7741–8076)	NA	11 061 (10 408–11 617)	NA
$PM_{2.5}$ improvement scenarios*					
Target 1: Beijing Olympic Games	55	7461 (7184–7778)	439 (233–643)	10 824 (10 181–11 391)	237 (109–357)
Target 2: China Class II standard limit	35	6216 (5524–7040)	1684 (947–2339)	10 080 (9335–10 797)	981 (466–1438)
Target 3: WHO-recommended level	10	5031 (4109–6255)	2870 (1717–3760)	9240 (8292–10 212)	1821 (896–2592)
Comparison scenarios*					
25% reduction in uncontrolled systolic hypertension (to <140 mm Hg)	61	7177 (7097–7242)	724 (577–889)	9793 (9299–10 204)	1268 (905–1663)
30% reduction in tobacco use	61	7489 (7229–7720)	412 (268–553)	10 944 (10 183–11 591)	116 (9–241)
25% reduction in uncontrolled systolic hypertension (to <140 mm Hg) plus 30% reduction in tobacco use	61	6806 (6607–6967)	1094 (890–1282)	9693 (9083–10 200)	1368 (1003–1764)

CHD indicates coronary heart disease; NA, not applicable; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm; UI, uncertainty interval; and WHO, World Health Organization.

*Each scenario is compared with the status quo case. Ninety-five percent UIs were calculated from the results of 1000 probabilistic simulations.

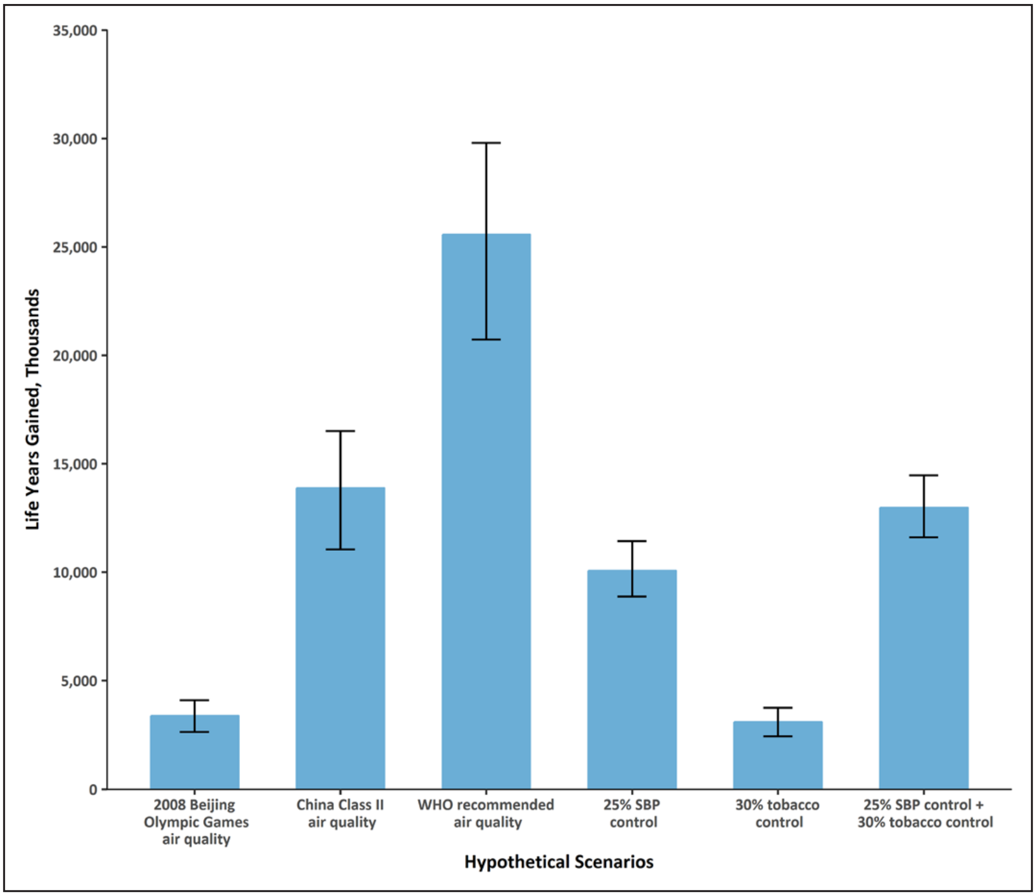

Figure 2. Projected life-years gained in hypothetical scenarios in the urban Chinese population 35 to 84 years of age from 2017 to 2030.
SBP indicates systolic blood pressure; and WHO, World Health Organization.

tension or a 40% reduction in tobacco use over the same time period. For instance, gradually lowering tobacco use by 30% of the 2017 prevalence proportion would prevent 412 000 (95% UI, 268 000–553 000) CHD deaths and 116 000 (95% UI, 9000–241 000) stroke deaths and gain ≈3 094 000 (95% UI, 2 439 000–3 763 000) life-years from 2017 to 2030 (annual averages of −29 000 [95% UI, −40 000 to −19 000], −8000 [95% UI, −17 000 to −1000], and +221 000 [95% UI, 174 000–269 000], respectively). Controlling 25% of SBP to <140 mm Hg among patients with systolic hypertension was projected to avert 724 000 (95% UI, 577 000–889 000) CHD deaths and 1 268 000 (95% UI, 905 000–1 663 000) stroke deaths and gain 10 066 000 (95% UI, 8 889 000–11 439 000) life-years (annual averages of −52 000 [95% UI, −63 000 to −41 000], −91 000 [95% UI, −119 000 to −65 000], and +719 000 [95% UI, 635 000–817 000], respectively), much larger health benefits than projected for the 2008 Beijing Olympics air quality goal (Table 2 and Figure 2).

Achieving the China Class II standard of 35 μg/m³ or the more aggressive WHO target in urban China would achieve much larger CVD mortality reductions and life-year gains (Table 2 and Figure 2). For example, from 2017 to 2030, 13 883 000 (95% UI, 11 061 000–16 514 000; annual average, +992 000 [95% UI, 790 000–1 180 000]) life-years and 25 576 000 (95% UI, 20 731 000–29 802 000; annual average, +1 827 000 [95% UI, 1 481 000–2 129 000]) life-years will be gained when achieving the goal of the China Class II standard and the WHO target, respectively. Reaching either goal would yield health gains greater than both 30% smoking and 25% systolic hypertension control combined (12 986 000 [95% UI, 11 614 000–14 468 000] life-years gained from 2017 to 2030; annual average, +928 000 [95% UI, 830 000–1 033 000] life-years).

In the sensitivity analysis, averted CVD deaths and life-years gained tended to be lesser when using a graded reduction of $PM_{2.5}$ from 2017 to 2030 as an alternative status quo. About 1 115 000 (95% UI, 1 281 000–1 950 000), 11 620 000 (95% UI, 9 738 000–14 355 000), and 23 313 000 (95% UI, 19 526 000–27 682 000) life-years could gain from reaching Beijing Olympic Game, China Class II, and WHO air quality level goals, respectively (Table IX in the online-only Data Supplement). As shown in Tables X and XI in the online-only Data Supplement, reaching the Beijing Olympic Game level would gain 3 177 000 (95% UI, 2 629 000–3 822 000) and 2 967 000 (95% UI, 2 128 000–3 803 000) life-years from 2017 to 2030 in 10% attenuated and 20% attenuated health effect scenarios, respectively.

DISCUSSION

Despite abundant evidence linking short- and long-term exposure to high $PM_{2.5}$ levels to increased cardiopulmonary disease risk, the air pollution level in most Chinese cities remains high. Our urban China population simulations projected that considerable health benefits could be gained from the modest $PM_{2.5}$ improvement achieved for the duration of the 2008 Beijing Olympic Games. The potential health benefits of $PM_{2.5}$ reductions to China Class II or WHO goals would be greater in magnitude than the benefits from both 30% reductions in smoking and 25% reduction in uncontrolled systolic hypertension combined.

With its dramatic economic growth during the past 3 decades, China has become the second largest economy in the world. However, China's accelerating economic engine increased energy consumption and resulted in harmful air pollution levels in most of urban China. Agricultural activities, motor vehicle exhaust, coal-powered winter heating, and biogenic emissions have all contributed to the problem. Special occasions such as the 2008 Beijing Olympic Games or the 2014 Asia-Pacific Economic Cooperation conference demonstrated that systematic air pollution emission control measures can result in substantial declines in air pollution, although these improvements were temporary. Indeed, air pollution rebounded to its prior level soon after the Olympics and Asia-Pacific Economic Cooperation emission control measures ended.[27,28] Practical and integrated air quality improvement policies are crucial for achieving sustained air quality improvement. Regulations established in the United States and other countries resulted in substantial reductions in particulate matter and other pollutant levels over the past several decades.[29] Los Angeles, London, and Mexico City, once well-known for poor air quality, all improved air quality through policy actions. In England, black smoke levels dropped from 42.7 μg/m^3 in 1971 to 11.8 μg/m^3 in 2001.[30] London's annual mean $PM_{2.5}$ has held at ≈20 μg/m^3. Recent average $PM_{2.5}$ levels in Los Angeles are near the WHO goal at 10 μg/m^3.[31] Mean $PM_{2.5}$ levels in Mexico City decreased from 35 μg/m^3 from 2000 to 2002 to 25 μg/m^3 in 2011,[32,33] indicating that air pollution control is also achievable in middle-income country cities. The Chinese government has already set ambitious air quality goals for the year 2030. A cost-benefit analysis of the Air Pollution Prevention and Control Action Plan promulgated by the Chinese government found that a combination of policy measures would be cost-effective from 2013 to 2017,[34] especially when taking into account joint regional air pollution measures.[35] In response to the framework proposed by WHO aiming to lower global NCDs mortality by 2025, our comparison of health gains from air pollution improvement with traditional NCD risk factors control has important implications. Traditional NCD risk factors convey a higher magnitude of individual risk than air pollution, but these risk factors affect only segments of the population. Although air pollution risk is small at the individual level, the entire population is exposed to poor air quality, so that our projected health benefits from more aggressive air pollution control policies were comparable in magnitude with control of 30% active smoking or 25% of systolic hypertension. Therefore, our findings suggested that China has a specific opportunity to prioritize air pollution control over some other measures to achieve the NCD control goal set by the WHO.

Several past modeling studies projected health benefits from planned air quality control policies in China.[4,9,36–39] However, most of these studies were conducted in a single city, with a projected health impact of reduction in particulate matter with aerodynamic diameter ≤10μm (PM_{10}),[9,38,39] or converted to $PM_{2.5}$ from a fixed proportion of PM_{10}.[36] The Benefits Mapping and Analysis Program projected an annual reduction of between 39 and 1400 all-cause deaths annually with air pollution control in Shanghai.[36] Another study showed that ≈4% (1% to 7%) of all-cause deaths in China can be avoided by implementing emission control policies.[37] Madaniyazi et al[40] projected that a 20.4 μg/m^3 decrease in mean $PM_{2.5}$ in East China between 2005 and 2030 under the "maximum technically feasible reduction" scenario would prevent 230 000 deaths. However, the aforementioned studies did not model the air pollution effects on health in the context of simultaneous trends in traditional disease risk factors, population aging and growth, and rural-to-urban migration. The GBD study (Global Burden of Disease) estimated air pollution effects on disease burden from 1990 to 2015 at global, regional, and country levels. Deaths attributed to ambient $PM_{2.5}$ pollution increased from 3.5 million to 4.2 million worldwide, and China experienced the world's largest air pollution–related disease burden in absolute numbers in 2015.[41] About 1.1 million total deaths among adults 25 to 80 years of age in urban and rural China were attributed to harmful levels of ambient $PM_{2.5}$ pollution ($PM_{2.5}$ >7.5 μg/m^3).[41] Furthermore, given forecasted demographic and epidemiological trends, China's average $PM_{2.5}$ level would need to decline by 29% from 2015 to 2030 merely to hold per-capita mortality attributable to $PM_{2.5}$ constant at the year 2010 level.[42] In this study, we projected an average reduction of ≈0.6 million annual total deaths from 2017 to 2030 if air quality could be gradually improved to the WHO-recommended concentration level (10 μg/m^3) among adults 35 to 84 years of age in urban China alone. Thus, substantial reduction in disease burden can be achieved for entire populations by controlling air pollution mainly via legislation, government policy, and joint initiatives at the national level.

Our study has several limitations. We based our status quo exposure scenario on mean $PM_{2.5}$ levels in all urban areas combined. Therefore, we did not assess the variable impact of $PM_{2.5}$ exposure by season or city. Although we calculated a mean $PM_{2.5}$ for urban China weighted according to city population size, we did not account for differences in population density among Chinese cities or specify our analysis to the city level. Because of the CVD Policy Model–China's characteristics, the relative risk of $PM_{2.5}$ CVD was not stratified by age. Considering the nonlinear exposure-risk relationship, we may have overestimated the health effects changes for cities in urban China. Our results from sensitivity analysis using attenuated health effects estimation provided further information to understand the health benefits from air pollution control. We modeled $PM_{2.5}$ as pollutant representative of multiple component pollutants. Integrated air pollution control of component sources of pollution might yield even greater benefits. Our study did not account for the cumulative effects of past air pollution exposures, which may be refractory to current air quality improvements. Our model is also limited in capturing the total health impact of air pollution control because it was specifically designed for CVD. Therefore, we likely underestimated the pulmonary disease burden averted by improved air quality and did not capture noncardiovascular health benefits of near-term smoking control that extend beyond 2030. Finally, the health gains from tobacco use reduction were likely underestimated because associated reductions in secondhand smoking were not included.

Air pollution is a leading cardiovascular cause of preventable disease burden in urban China. Our simulation modeling study results suggest that modestly controlling air pollution to the Beijing Olympics Games level, which still would be twice as high as current Mexico City, could prevent ≈439 000 CHD deaths and 237 000 stroke deaths and gain 3 379 000 life-years in urban China by 2030. Our findings indicated that more health benefits could be gained with more aggressive reductions in $PM_{2.5}$ levels. Aggressive air pollution control policies would result in health benefits on the same order of magnitude as the combined benefits of 25% improvement in hypertension control and 30% smoking reduction. Our results suggest that air quality improvement should be among the highest priority goals for preventing noncommunicable disease deaths and disability in China.

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DISCLOSURES

None.

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FOOTNOTES

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