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Reducing Fine Particulate to Improve Health: A Health Impact Assessment for Taiwan

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ABSTRACT. Recently various countries have adopted the new standards for $PM_{2.5}$ (particulate matter <2.5 μm in aerodynamic diameter), but Taiwan still maintains an old set of air quality guidelines for particulate matter; therefore, the authors quantified the public health impact of long-term exposure to $PM_{2.5}$ in terms of attributable number of deaths and the potential gain in life expectancy by reducing $PM_{2.5}$ annual levels to 25, 20, 15, and 10 μg/m^3. When the guideline for $PM_{2.5}$ long-term exposure was set at 25 μg/m^3, 3.3% of all-cause mortality or 4,500 deaths in 2009 could be prevented. The potential gain in life expectancy at age 30 of this reduction would increase by a range between 1 and 7 months in Taiwan. This study shows that guidelines for $PM_{2.5}$, especially for long-term exposure, should be adopted in Taiwan as soon as possible to protect public health.

KEYWORDS: air pollution, health impact assessment, particulate matter

Based on several severe air pollution events,[1–3] a correlation between extremely high concentrations of particulate air pollution and adverse health effects was well established by the epidemiological studies until 1970s. Since then, a series of legislative and regulatory efforts to control air pollution have been initiated. As a result, concentrations of particulate air pollutants have been reduced to moderate or low levels in western countries, for example, in the United States and the European Union.[4,5]

Epidemiological studies have consistently found that low levels of particulate matter air pollution can have both short-term and long-term effects.[6–8] Recently, particles with special health concern are those known as fine particulate matter (less than 2.5 μm in aerodynamic diameter; $PM_{2.5}$). These fine particulate matter include soot and acid condensates derived from vehicle emissions, manufacturing, power generation, and agricultural burning.[9] Pope and Dockery[10] emphasized the adverse health effects of $PM_{2.5}$ are more significant than those of PM_{10} (particulate matter <10 μm in aerodynamic diameter). These smaller particles are more likely to deposit in the smaller airways, for example, the bronchioles and the alveoli.[10,11] Both short-term and long-term effects of $PM_{2.5}$ have been described in recent studies, including substantial effects on life expectancy as a result of long-term exposure.[12–16] These studies have led to a reconsideration of air quality guidelines and standards.

The air quality standards in Taiwan were initiated in 1992 and revised in 1999 and 2004. For particulate matter, total suspended particulate (TSP) and PM_{10} have been regulated. But the threshold level established by Taiwan Environmental Protection Administration (TEPA) is still high compared with that of the other agencies, and $PM_{2.5}$, which is considered more harmful than PM_{10}, has not to be regulated. Table 1 summarizes several air quality guidelines and standards, including those of the World Health Organization (WHO),[17] the US Environmental Protection Agency (USEPA),[18] the European Union (EU),[19] and the TEPA.[20]

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Table 1.—World Health Organization (WHO), US Environmental Protection Agency (USEPA), European Union Directive (EU), and Taiwan Air Quality Standards for Particulate Matter (Taiwan)

PM	Average time	Agency			
		WHO*	USEPA**	EU[†]	Taiwan[§]
TSP	24 hours	—	—	—	250 μg/m^3
	Annual	—	—	—	130 μg/m^3
PM$_{10}$	24 hours	50 μg/m^3	150 μg/m^3	50 μg/m^{3‡}	125 μg/m^3
	Annual	20 μg/m^3	—	20 μg/m^3	65 μg/m^3
PM$_{2.5}$	24 hours	25 μg/m^3	35 μg/m^3	—	—
	Annual	10 μg/m^3	15 μg/m^3	25 μg/m^3(2015); 20 μg/m^3(2020)	—

Note. PM = particulate matter; TSP = total suspended particulates; PM$_{10}$ = PM less than 10 μm; PM$_{2.5}$ = PM less than 2.5 μm.
*Source: WHO (2005).
**Source: USEPA (2006).
[†]Source: European Union Directive (2008).
[‡]Maximum: 7 days.
[§]Source: Taiwan Environmental Protection Administration (2004).

Health impact assessment studies have been shown to be informative and effective tools of communication with the general public and policy makers.[21] In the domain of air pollution, health impact assessment would provide estimates of both burden of disease attributable to air pollution[22–24] and the potential benefits from policies driven to improve air quality.[25]

Regarding health impact, fine particulate matter air pollution is a major environmental factor affecting human health and there is no safe level of exposure, that is, a threshold has not been identified.[16,26] We investigated all-cause mortality as well as including cause-specific mortality (cardiopulmonary deaths and lung-cancer deaths) that could be prevented by reducing PM$_{2.5}$ annual levels to 25, 20, 15, and 10 μg/m^3 in 22 administrative areas of Taiwan. In addition to estimating attributable number of deaths at a given point of time, we also calculated the potential gain in life expectancy in order to provide a dynamic picture of the effects of air pollution on health over subjects' lifetimes.

METHODS

Subjects and design

We estimated the reduction in premature deaths and potential gain in life expectancy that could be achieved by lowering long-term PM$_{2.5}$ exposure levels in Taiwan area in 2009. The subjects covered by this study were 14,182,660 men and women aged older than 30 years.

This study followed WHO guidelines for environmental-health impact assessment,[27,28] and adopted the same health impact assessment model used in the United States[29] and European countries.[22,30,31] In these studies, 5 data components were required: definition of health outcome, slope of concentration-response function or relative risk, reference exposure level, population exposure distribution, and outcome frequency. Table 2 summarizes the first 3 components.

Primary health outcomes were all-cause mortality. To retain comparability with other health impact assessments, we added cardiopulmonary and lung cancer deaths in the assessment. Definition of health outcomes follows 10th revision of International Classification of Disease (ICD-10).

Associations between outdoor air pollution and health outcomes are described by the concentration-response function, which is the relative risk per 10 μg/m^3 unit. We extrapolated information by using data from one US large cohort study.[15]

As a comparison, we used 4 reference levels for PM$_{2.5}$ long-term exposure. The various concentrations were chosen as different reductions based on the limit values of the European Union Directive, the USEPA, and the World Health Organization, respectively. In the European Union, a new air quality directive came into force in 2008.[19] It sets new standards and target dates for reducing concentrations of PM$_{10}$ and PM$_{2.5}$. The limit values of annual PM$_{2.5}$ concentration in 2015 and 2020 are 25 and 20 μg/m^3, respectively. The USEPA strengthens the National Ambient Air Quality Standards for particulate matter in 2006. The 2006 standards tighten the short-term concentration to 35 μg/m^3 and retain the annual level at 15 μg/m^3 for PM$_{2.5}$.[18] The WHO revised Air Quality Guidelines for selected air pollutants in 2005. Annual PM$_{2.5}$ concentration has been set at 10 μg/m^3 with the aim to protect human health and the environment.[17]

We constructed the population exposure distribution of PM$_{2.5}$ annual mean exposure from 1-hour average concentrations in 2009, which the TEPA published.[20] The exposure data were from 76 air monitoring stations throughout the country. The monitoring station instrumentation were β-ray attenuation method and tapered element oscillating microbalance method for both PM$_{10}$ and PM$_{2.5}$. All instruments from TEPA have stringent quality assurance protocol to maintain the accuracy and reliability of the data.[32] We made our construction on the basis of the percentage of the whole population fell in each 5 μg/m^3 category of annual exposure.

Table 2.—Summary of Data Components Used for Health Impact Assessment of Long-term Exposure to PM$_{2.5}$ in Taiwan

Health indicator	ICD-10 Health outcome definitions	Tool	Relative risk	95% CI	Reference (μg/m^3)
Attributable cases					Annual mean
All-causes mortality	A00-Y98		1.04	1.01–1.08	25/20/15/10
			1.06	1.02–1.11	25/20/15/10
Cardiopulmonary mortality	I10-I70 and J00-J99	Excel spreadsheet	1.06	1.02–1.10	25/20/15/10
			1.09	1.03–1.16	25/20/15/10
Lung cancer	C33–C34		1.08	1.01–1.16	25/20/15/10
			1.14	1.04–1.23	25/20/15/10
Gain in life expectancy					
All-causes mortality	A00-Y98		1.04	1.01–1.08	25/20/15/10
			1.06	1.02–1.11	25/20/15/10
Cardiopulmonary mortality	I10-I70 and J00-J99	AirQ	1.06	1.02–1.10	25/20/15/10
			1.09	1.03–1.16	25/20/15/10
Lung cancer	C33–C34		1.08	1.01–1.16	25/20/15/10
			1.14	1.04–1.23	25/20/15/10

Note. ICD-10 = International Classification of Diseases, 10th revision; CI = confidence interval.

Therefore, we separated Taiwan into 22 districts according to administrative area. We then classified the percentage of the population in each district in each 5 μg/m^3 category according to its annual exposure (Table 3).

We estimated the attributable number of cases caused by long-term exposure to PM$_{2.5}$ above the defined reference levels and calculated the outcome frequency according to the health outcome in Table 2 from vital statistics, which were published by the Taiwan Department of Health (TDOH).[33]

Provided adequate data on population, health outcome, and exposure are available, uncertainties involved in estimating the health effects of air pollution are the first concern.[17,27,34] Assuming that the relation between particles and mortality

Table 3.—Percentage of Population Exposed to PM$_{2.5}$ in 2009

PM$_{2.5}$ concentration exposure class (μg/m^3)	Population exposure distribution to PM$_{2.5}$
0–5	0.0%
>5–10	0.0%
>10–15	0.0%
>15–20	3.0%
>20–25	3.6%
>25–30	41.3%
>30–35	5.6%
>35–40	30.1%
>40–45	3.3%
>45–50	13.2%
>50–55	0.0%
>55–60	0.0%
>60–65	0.0%
Mean	32.9

Note. Own calculations using data from TEPA (2009).

is causal, the major uncertainty in this work could arise from the selection of the risk estimate. Taking into account these uncertainties on the estimates of the attributable impact of PM$_{2.5}$, we decide to adopt an "at least" approach, which is choosing the alternative providing the lowest impact.[22]

The health impact assessment concentration-response functions for all-cause mortality, cardiopulmonary mortality, and lung cancer mortality in people aged 30 years or older were derived from the American Cancer Society (ACS) study performed by Pope and colleagues.[15] This is the largest cohort study assessing long-term effects of fine particulate air pollution on health. Data on risk factors for approximately 500,000 adults followed from 1982 to 1998 were linked to air pollution data for metropolitan areas in the United States and combined with vital status and cause of death. Concentrations of PM$_{2.5}$ were measured in 1979–1983 and 1999–2000. Models were estimated separately for each of the 2 PM$_{2.5}$ measurement periods and also for the average of them. The relative risk of dying from all causes per 10 μg/m^3 of chronic exposure to PM$_{2.5}$ was 1.06 (95% confidence interval [CI] = 1.02–1.11) for both the PM$_{2.5}$ average and the 1999–2000 period, and 1.04 (95% CI = 1.01–1.08) for the 1979–1983 period. We used the last one as the "at least" option and the former for the sensitivity analysis. The published estimates of Pope et al[15] used linear functions for mortality of the population aged 30 years and over in the exposure range between 10 and 30 μg/m^3. This corresponds to the range covered in our study (Figure 1), for which we also used a linear relationship for the population aged 30 years and over.

Model

Our method consisted of 3 steps. The method was similar to the health impact assessment method used in the United States,[28] European countries,[22,30,31] and Japan.[24]
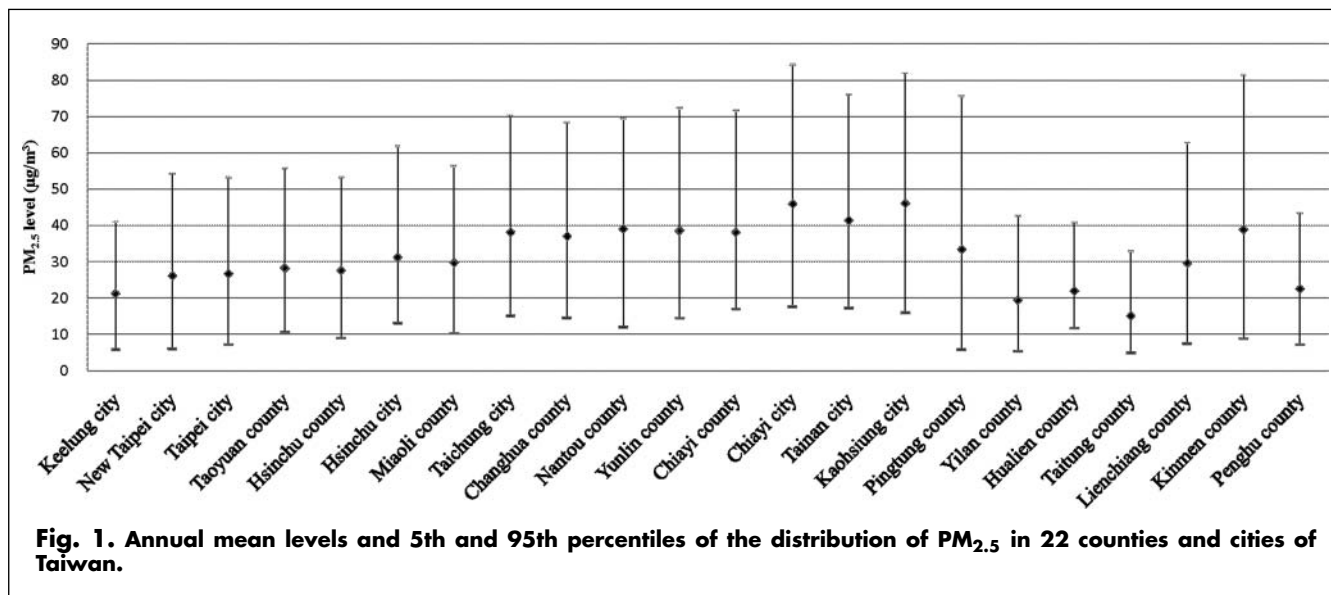
Fig. 1. Annual mean levels and 5th and 95th percentiles of the distribution of PM$_{2.5}$ in 22 counties and cities of Taiwan.

Step 1

First, we defined the reference exposure level, B, and current exposure, E. Next, we applied equation (1) to estimate the health outcome frequency, P$_0$, expected at B from current health outcome frequency, P$_E$.

$$P_0 = P_E / \{1 + [(RR − 1)(E − B)/10]\} \qquad (1)$$

where

P$_E$ is the observed or current health outcome frequency,
P$_0$ is the expected health outcome frequency at reference exposure level,
E is the observed or current exposure level,
B is the reference exposure level, and
RR is the relative risk per 10 μg/m^3 unit.

Step 2

With P$_0$, we calculated the attributable number of cases, D$_{10}$, per 1 million persons for a 10 μg/m^3 exposure increment:

$$D_{10} = 1,000,000 \times P_0 \times (RR − 1) \qquad (2)$$

To estimate a range of impact, we used the 95% confidence interval values of RR to estimate the 95% confidence interval values of D$_{10}$. With D$_{10}$ and the observed exposure distribution, then we estimated the attributable number of cases in each 5 μg/m^3 category.

Step 3

We summed the total number of cases that were attributable to fine particulate air pollution. Finally, we esti-

mated 95% confidence interval values of attributable cases according to the 95% confidence interval values of D$_{10}$.

On the basis of these data, we estimated the attributable number of cases with an EXCEL 12.0 spreadsheet. We also calculated the expected gain in life expectancy for the population aged 30 years and over using Air Quality (AirQ) software version 2.2.3, which is released by the WHO regional office for Europe to assess the health impact of air pollution.[35] This program uses a life-table approach and is based on the same risk estimates from cohort studies as are used in estimating attributable cases (Table 2).

AirQ compares the actual life expectancy with the hypothetical life expectancy obtained for the various baseline scenarios. The gains in life expectancy are estimated by linking the following different sets of information: first, change in annual mean concentrations of PM$_{2.5}$; second, a concentration-response function linking annual average PM$_{2.5}$ with a change (percentage per μg/m^3) in mortality hazard rates (ie age-specific death rates); third, demographic data (eg, age distribution, and age-specific death rates) of the target population. We assumed the same proportional hazard reduction for every age group (age > 30) to be consistent with the findings of Pope et al.[15]

RESULTS

Administrative districts with PM$_{2.5}$ annual mean concentrations ranged between 15.1 μg/m^3 in Taitung county and 46.0 μg/m^3 in Kaohsiung city (Figure 1). In northern Taiwan, the PM$_{2.5}$ annual mean concentrations ranged between 20 and 30 μg/m^3 (eg, New Taipei city and Taipei city, the 2 largest northern cities). In central Taiwan, the PM$_{2.5}$ annual mean concentrations are mildly higher, from 35 to 40 μg/m^3 (eg, Taichung city, the largest city in central Taiwan). The PM$_{2.5}$ annual mean concentrations increased above 40 μg/m^3 in

Table 4.—Summary Findings in Terms of Potential Reductions in The Number of Premature Deaths and Rates per 100,000 People in Taiwan

| | | | Potential long-term reduction in the number of deaths | | | | | |
| | | | Number of deaths | | Number of deaths/100,000/year | | Percentage reduction | |
Air pollution indicator	Health indicator	Reference	n	95% CI	n	95% CI	n	95% CI
PM$_{2.5}$	All-cause mortality	25	4,553	1,186–8,649	32	8–61	3.3	0.9–6.3
		20	6,900	1,813–12,969	49	13–91	5.0	1.3–9.4
		15	9,293	2,468–17,249	66	17–122	6.7	1.8–12.5
		10	11,649	3,130–21,339	82	22–150	8.4	2.3–15.5
	Cardiopulmonary mortality	25	2,128	748–3,378	15	5–24	4.7	1.6–7.4
		20	3,239	1,150–5,089	23	8–36	7.1	2.5–11.2
		15	4,357	1,569–6,766	31	11–48	9.6	3.5–14.9
		10	5,443	1,988–8,350	38	14–59	12.0	4.4–18.4
	Lung cancer mortality	25	482	66–878	3	0–6	6.1	0.8–11.1
		20	733	102–1,313	5	1–9	9.2	1.3–16.5
		15	982	140–1,723	7	1–12	12.4	1.8–21.7
		10	1,218	178–2,093	9	1–15	15.3	2.2–26.3

Note. CI = confidence interval; PM$_{2.5}$ = particles measuring less than 2.5 μm in diameter.

the southern Taiwan (eg, Kaohsiung city, the industrial and largest southern city). In eastern Taiwan including Hualien county and Taitung county, the least populated and industrial area of Taiwan, the PM$_{2.5}$ annual mean concentrations ranged between 15 and 22 μg/m^3. Table 4 shows the estimates of reductions in annual mortality rates among people aged 30 years and over for different scenarios of reduction in PM$_{2.5}$ levels for each the 22 administrative areas using the "at least" approach. The relative risks for all-cause, cardiopulmonary, and lung cancer mortality are 1.04 (95% CI = 1.01–1.08), 1.06 (95% CI = 1.02–1.10), and 1.08 (95% CI = 1.01–1.16) for a 10 μg/m^3 increase in chronic exposure to PM$_{2.5}$. If long-term exposure to the annual mean of PM$_{2.5}$ level were reduced to 25 μg/m^3 in Taiwan, the average reductions in the total burden of mortality among people aged 30 and over would be 3.3% (95% CI = 0.9%–6.3%). It would be 5.0% (95% CI = 1.3%–9.4%), for PM$_{2.5}$ reductions to 20 μg/m^3. The benefits clearly increase when the reduction scenarios are more ambitious, and rise to 6.7% (95% CI = 1.8%–12.5%) and 8.4% (95% CI = 2.3%–15.5%) for PM$_{2.5}$ reductions to 15 and 10 μg/m^3, respectively.

The attributable number of cases is, in other words, the number of preventable cases had exposure been lowered to the reference level. Regarding PM$_{2.5}$ long-term exposure using the "at least" approach, when the guideline was set at 25 μg/m^3, we could prevent 4,500 deaths from all-cause mortality, including 2,100 cardiopulmonary deaths, and 480 lung cancer deaths. In Taiwan, there were 3,464 deaths attributed to traffic accidents and 4,063 deaths attributed to suicide in 2009. The estimated number of deaths caused by PM$_{2.5}$ exposure was similar to the number of deaths from these causes.

In terms of life expectancy, we shows the results of the sensitivity analysis of the estimates for potential gain in life expectancy in people aged over than 30 years for Taiwan, using alternative options for the concentration-response function (RR = 1.06, 95 CI = 1.02–1.11) in Figure 2. If annual PM$_{2.5}$ level did not exceed 25 μg/m^3, for the "at least" scenario, the potential gain in life expectancy of a 30-year-old person would average between 1 month and more than a half year, due to the reduction in all-cause mortality. If higher relative risks were applied, it would average between 1 and 10 months.
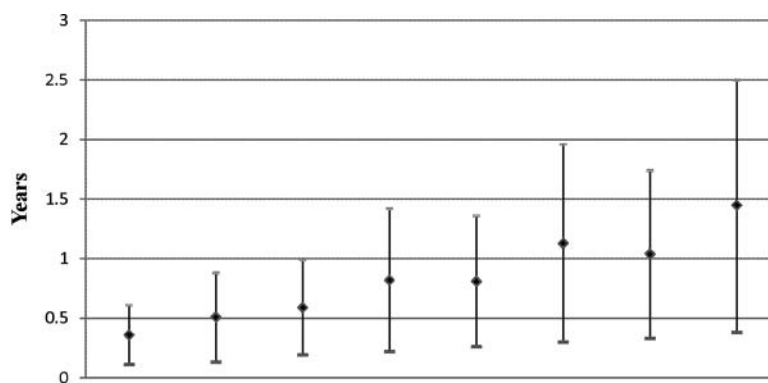
Figure 3 illustrates for the "at least" scenario the expected gain in life expectancy in year if PM$_{2.5}$ annual mean level were reduced to 20 μg/m^3. It shows by how much this gain would affect each age. Note that the expected gain is unchanged until age 30 because mortality risk at age <30 are assumed to be unaffected. The gain would remain greater than 3 months until 70 years of age.

Figure 4 shows the results of the sensitivity analysis of the estimates for potential reductions in premature mortality in people aged over than 30 years for Taiwan. When the higher relative risks are applied, a reduction in PM$_{2.5}$ annual levels to 25 μg/m^3 would prevent 4.8% (95% CI = 1.7%–8.3%) of the total burden of mortality. Reducing PM$_{2.5}$ concentrations to 20, 15, and 10 μg/m^3 would reduce the burden of mortality by 7.3% (95% CI = 2.6%–12.4%), 9.7% (95% CI = 3.5%–16.3%), and 12.1% (95% CI = 4.4%–20.0%), respectively.

COMMENT

Methodological considerations

Several limitations could affect health impact assessment estimates as sources of uncertainty and variability. Some of

Fig. 2. Sensitivity analysis of expected gain in life expectancy (central estimate and 95% CI) at 30 years of age in Taiwan for different decreases in annual PM$_{2.5}$ levels.

these uncertainties are intrinsic, for example, uncertainties in the estimation of the concentration-response function. The choice of the concentration-response functions is very influential in the health impact assessment process. To date, the Asian literature on chronic effects of long-term exposure to air pollution is more limited than the literature from Europe and North America, especially with regard to chronic cardiovascular disease. Nonetheless, the report from Health Effects

Institute (HEI) suggested that long-term exposure to air pollution from a variety of combustion sources is contributing to chronic respiratory disease in both children and adults, to lung cancer, and to adverse reproductive outcomes in Asian populations,[36] including 2 studies conducted in Taiwan that provide estimates of the relative risks of lung cancer incidence or mortality associated with exposure to industrial or petrochemical air pollution.[37,38] The majority of short-term
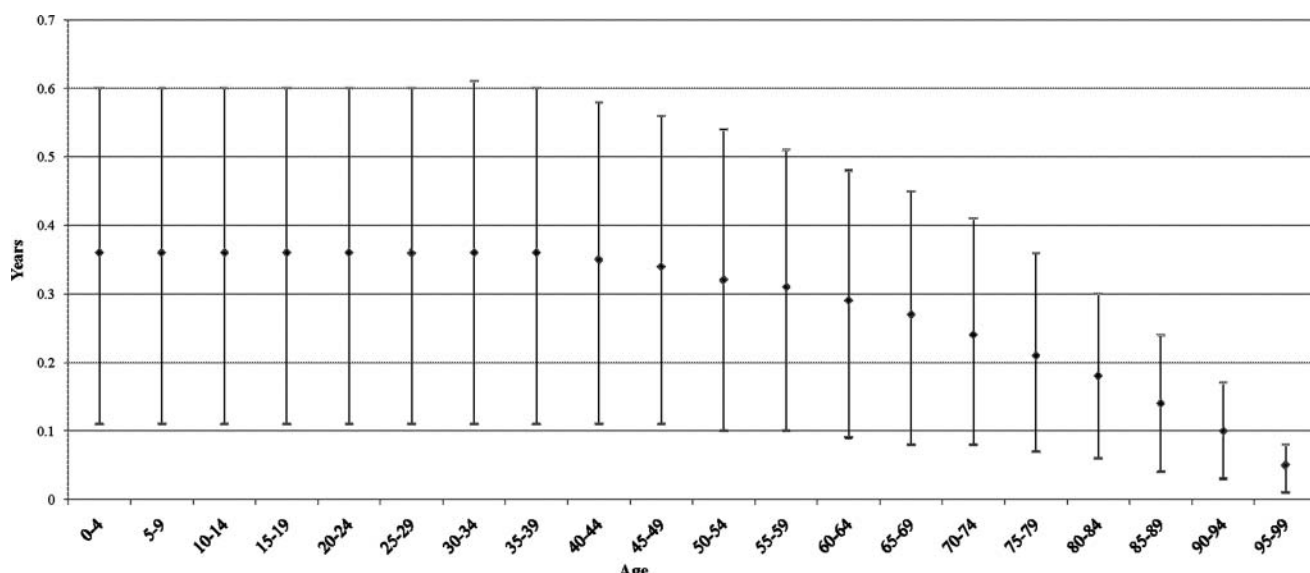

Fig. 3. Expected gain in life expectancy in year if PM$_{2.5}$ annual mean levels did not exceed 25 μg/m^3 in Taiwan.
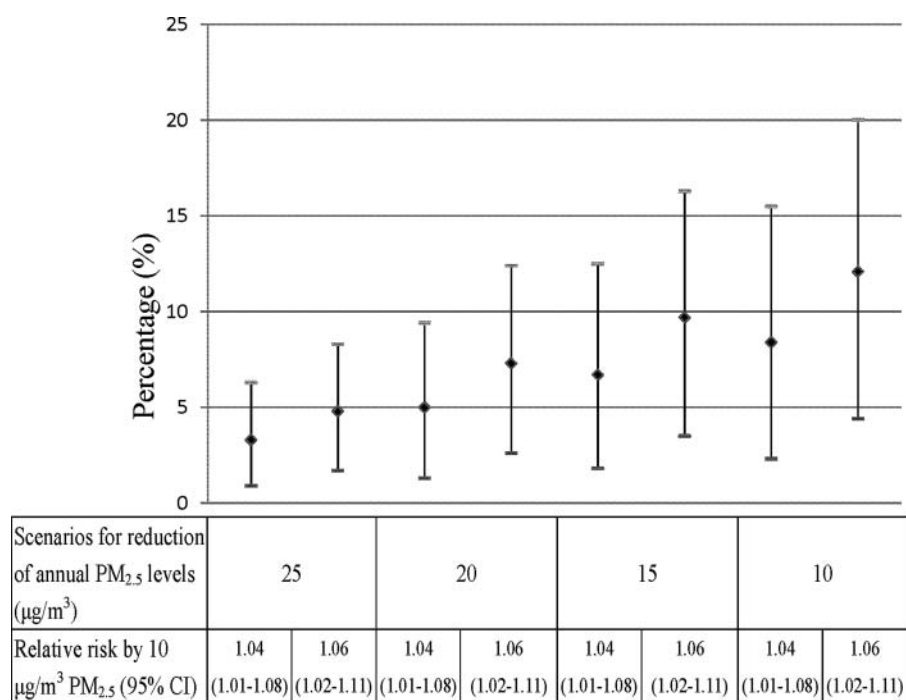
Fig. 4. Sensetivity analysis of potentials reductions in total annual deaths (central estimate and 95% CI) among people age 30 years and over in Taiwan for different decreases in annual PM$_{2.5}$ levels.

Scenarios for reduction of annual PM$_{2.5}$ levels (μg/m^3)		25		20		15		10
Relative risk by 10 μg/m^3 PM$_{2.5}$ (95% CI)	1.04 (1.01-1.08)	1.06 (1.02-1.11)	1.04 (1.01-1.08)	1.06 (1.02-1.11)	1.04 (1.01-1.08)	1.06 (1.02-1.11)	1.04 (1.01-1.08)	1.06 (1.02-1.11)

PM$_{2.5}$ exposure studies in Asia showed positive associations between all-natural-cause and cause-specific mortality.[39–41] However, negative associations between hospital admissions and PM$_{2.5}$ were observed by Chan and associates[42] and Bell and colleagues.[43] The broad consistency of the results of Asian time-series studies of mortality with those in western countries, including the evidence of greater rates of cardiovascular morbidity and mortality among older people than among younger people, supports the continued use of data from western cohort studies to estimate the health impact of air pollution in Asia.[35]

In the absence of robust concentration-response functions in Taiwan or Asian region for long-term exposure to PM$_{2.5}$, we extrapolated from foreign studies prudently. In line with previous health impact assessment, we used estimates from cohort studies to capture the long-term effects.[21–23,25,44] Although we used the estimates from the US ACS study,[15] it is of note that longitudinal studies from various countries in Europe have shown results consistent with a causal link between long-term air pollution exposure and mortality.[45–48] Moreover, the reanalysis of the ACS data among participants from southern California, using more detailed assignment of exposure,[49] and an update of the Harvard Six Cities Study in the United States,[50] provided larger estimates than the original ACS study. The percentage increase in total mortality estimated in the ACS study for a 10 μg/m^3 increment in PM$_{2.5}$ was about 6%, whereas in the more recent and powerful studies, this percentage is between 15% and 18%. The newer evidence is also reflected in an expert elicitation conducted by the USEPA.[51] A causal association between the air pollution and mortality was considered the most likely interpretation of the literature for the concentration-response functions ranged higher than those used in this study. Thus, we conclude that health benefits of improved air quality would be most likely larger than those expressed in our study.

The validity of the extrapolation of relative risks to our target population is a concern. There are little and insignificant differences in sociodemographic characterisitics among the target population in Taiwan, and the 2 cohort study groups, the Harvard Six Cities Study[7] and the ACS study.[12,15] First, the mean age of subjects in Taiwan was 50.4 years,[33] whereas the subjects were between the 48.3 and 51.8 years of age in the Harvard Six Cities Study and 56.6 years of age in the ACS study. As for sex ratio, the proportion of women in Taiwan was 50.5%, which is near the 52% to 56% in the Harvard Six Cities Study[7] and the 55.9% in the ACS study.[12,15]

We should be cautious when applying linear concentration-response functions to cities/counties whose PM$_{2.5}$ concentrations exceed the range of the original study. However, for most of the administrative areas studied, annual mean PM$_{2.5}$ was within the exposure range of between 10 and 30 μg/m^3 of the ACS study, the only marked exceptions being Tainan city, Chiayi city, and Kaohsiung city. Furthermore, the general linearity of the concentration-response

functions within the ranges studied gives some reassurance that extrapolation above these ranges should not be seriously misleading.[52] In respect of exposure assessment, Asian populations whose culture practices and living styles are distinct from those in developed countries. Lung and associates found personal PM_{10} exposures in Taiwan were higher than those observed in the United States and outdoor levels rather than indoor levels contributed significantly to personal exposure.[53] Thus, results of this study would not be overestimated.

The health impact and benefit assessment in this study has led to considering $PM_{2.5}$ as an indicator of the complex air pollution mixture. Although there have been suggestions that specific particulate matter fractions, for example, the primary combustion-derived particles combined with nitrogen dioxide from motor vehicles, are more important for toxicity and adverse health effects,[54] it was not possible to precisely quantify the contribution of different sources and different particulate matter components. Recent research is to better understand the specific toxicity of certain particulate matter fractions and the evidence on the effects of particulate matter on health is more robust today.[55] To the extent that $PM_{2.5}$ values will be subject to clean air regulations, and given that numerous epidemiological studies are based on this measure, it is of policy relevance to express the health impact using $PM_{2.5}$ as well.

Sarnat and colleagues pointed out that other ambient co-pollutants work only as surrogates of $PM_{2.5}$ and not as confounders.[56] Thus, other co-pollutants may not influence the health effects caused by $PM_{2.5}$ and our estimated values. Although we examined influential characteristics between target population and study groups, those characteristics would not overestimate the results. Our health impact assessment actually might have a limitation of extrapolating relative risks like the previous European assessment and the APHEIS (Air Pollution and Health: A European Information System).[22,31,57] Future studies should be conducted to identify the relative risks of $PM_{2.5}$ in Asian region.

For the first time in Taiwan, we also estimated the increase in life expectancy resulting from reductions in exposures to $PM_{2.5}$ pollution levels in different scenarios. The findings of this study suggest that long-term exposure in recent $PM_{2.5}$ concentration levels do reduce life expectancy in Taiwan. Other studies in the literatures obtained similar conclusions when they analyzed the effects of air pollution on life expectancy.[25,58–61]

Regarding health outcomes, it is likely that our assessment underestimates the full actual impact of fine particulate matter in Taiwan. First, we only assessed the $PM_{2.5}$ impact on mortality, but morbidity was not analyzed. Second, we did not consider the $PM_{2.5}$ impact on mortality under the age of 30 years, because valid concentration-response functions were not available when we carried out this assessment. There is now sufficient evidence to infer a causal relationship between particulate air pollution and respiratory deaths in the post-neonatal period.[62,63] Obviously, deaths at an early age affect substantially life expectancy in a population. Third,

most of the acute effects on mortality are included in effects of long-term exposure and represent around 15% of these chronic effects, when judged in terms of the number of attributable cases.[44] But not all short-term health impacts are included in the long-term impacts.[32,44,64] Consequently, in our study, omitting concentration-response functions from time series also led to underestimating the short-term impact on mortality.

Our study did not focus on sensitive subgroup of the population. The ACS study[15] reported higher risks among people with lower educational status, and the ACS study itself included an underrepresentation of people with lower educational attainment, and there was an underestimation of risks overall. In addition, the benefit may be achieved much later than predicted. In our case, lower air pollution levels would take years to be fully achieved and the lag time between exposure reduction and the consequent reduction in mortality risks is not well-established yet, though intervention studies[65,66] show substantial reductions in mortality risks in the years immediately following major reductions in ambient pollution, and evidence from the Harvard Six Cities Study shows a decrease in $PM_{2.5}$ levels in the more recent years of the study associated with reduced mortality risk.[50]

Policy implications

Although several limitations in this assessment methodology have been described, its use has proved helpful in estimating the potential health impact of different environmental scenarios and consequently in helping the decision-making process in public health and environmental policies.[67] Lowering $PM_{2.5}$ levels in Taiwan could result in a substantial decrease in the number of premature deaths and in a considerable gain in life expectancy. Therefore, establishing guidelines for long-term exposure to $PM_{2.5}$ is needed in Taiwan. We emphasize that the full benefit as expressed in our calculations, including acute and chronic effects, are unlikely to happen in the very first year. A model based on air pollution studies concluded that more than 80% of the total annual benefit in reduced death might be reached within 5 years.[68]

Our study is limited to the quantification of the health benefits of $PM_{2.5}$ reduction; we do not consider the specific regulatory strategies to reach lower levels, their technical feasibility, or associated costs. Other studies have analyzed the economic implications, as a key consideration in most environmental policies. Based on benefit estimates by the USEPA, it has been estimated that meeting the annual standard of 15 $\mu g/m^3$ for $PM_{2.5}$ will result in benefits ranging from \$20 billion to \$160 billion a year.[18] In Europe, the cost-benefit analysis of Clear Air for Europe program (CAFE) has shown that large benefits are predicted. The reduction in air pollution could reduce annual costs by €89 billion to €183 billion per year from current policies by 2020.[69] Analyses of relevant economic cost of health impacts due to particulate air pollution have been carried out in Asian cities and countries, indicating that cost is substantial both in absolute and relative

terms. In Singapore, the economic cost to health accounted for 4.31% of gross domestic product in 1999. In urban area of Shanghai, it accounted for 1.3% of gross domestic product in 2001; and it accounted for about 6.55% of Beijing's gross domestic product each year between 2000 and 2004.[70–72] It is clear that lowering air pollution concentrations is not an easy task but the economic and health benefits have been proved.

Conclusion

This study estimates the reduction in premature deaths that could be achieved by lowering annual $PM_{2.5}$ levels in Taiwan. Specifically, using the "at least" approach in 22 administrative areas of Taiwan, annual mean levels of $PM_{2.5}$ to 15 $\mu g/m^3$ could lead to a reduction in the total burden of mortality among people aged 30 years and over which is 2 times greater than the reduction in mortality that could be achieved by reducing to 25 $\mu g/m^3$ (6.7% vs 3.3% reduction). In terms of life expectancy, if the annual mean of $PM_{2.5}$ did not exceed 15 $\mu g/m^3$, the potential gain in life expectancy of a 30-year-old person is also 2 times longer than the life expectancy when the annual mean of $PM_{2.5}$ did not exceed 25 $\mu g/m^3$ (4.3 vs 9.2 months). These results are according to the reported $PM_{2.5}$ values reported by TEPA.[20,32]

In conclusion, in the context of the debate on the proposal for $PM_{2.5}$, we add further support to WHO's view that "it is reasonable to assume that a reduction of air pollution will lead to considerable health benefits"[73] and these benefits are expected to occur at levels well below those currently experienced in Taiwan. Meeting USEPA standards on air quality, or at least those in the Europe in general, would produce considerable health benefits in Taiwan; as such, these standards should be adopted as soon as possible.

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