Mortality Burden Due to Short-term Exposure to Fine Particulate Matter in Korea

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Objectives: Excess mortality associated with long-term exposure to fine particulate matter (PM2.5) has been documented. However, research on the disease burden following short-term exposure is scarce. We investigated the cause-specific mortality burden of short-term exposure to PM2.5 by considering the potential non-linear concentration–response relationship in Korea.

Methods: Daily cause-specific mortality rates and PM2.5 exposure levels from 2010 to 2019 were collected for 8 Korean cities and 9 provinces. A generalized additive mixed model was employed to estimate the non-linear relationship between PM2.5 exposure and cause-specific mortality levels. We assumed no detrimental health effects of PM2.5 concentrations below 15 μg/m3. Overall deaths attributable to short-term PM2.5 exposure were estimated by summing the daily numbers of excess deaths associated with ambient PM2.5 exposure.

Results: Of the 2,749,704 recorded deaths, 2,453,686 (89.2%) were non-accidental, 591,267 (21.5%) were cardiovascular, and 141,066 (5.1%) were respiratory in nature. A non-linear relationship was observed between all-cause mortality and exposure to PM2.5 at lag0, whereas linear associations were evident for cause-specific mortalities. Overall, 10,814 all-cause, 7,855 non-accidental, 1,642 cardiovascular, and 708 respiratory deaths were attributed to short-term exposure to PM2.5. The estimated number of all-cause excess deaths due to short-term PM2.5 exposure in 2019 was 1,039 (95% confidence interval, 604 to 1,472).

Conclusions: Our findings indicate an association between short-term PM2.5 exposure and various mortality rates (all-cause, non-accidental, cardiovascular, and respiratory) in Korea over the period from 2010 to 2019. Consequently, action plans should be developed to reduce deaths attributable to short-term exposure to PM2.5.

Key words: Burden of disease, Particulate matter, Health impact assessment, Premature death, Republic of Korea

INTRODUCTION

Many epidemiological studies have investigated the health burden of long-term exposure to fine particulate matter (PM2.5) [1-4]. A global study estimated that in 2019, air pollution was responsible for 6.7 million deaths, with 4.5 million of these attributed to ambient PM2.5 and ground-level ozone [1]. Previously, our research group assessed the mortality impact...
of chronic PM$_{2.5}$ exposure in Korea, identifying 11 924 premature deaths associated with PM$_{2.5}$ in 2015 [5].

Many studies have reported an association between short-term exposure to PM$_{2.5}$ and mortality [6-10]. Most of these investigations have been conducted in Asia, Europe, and North America. However, research on attributable deaths (ADs) due to short-term exposure to PM$_{2.5}$ remains scarce relative to studies on chronic effects.

Additionally, although the exposure–response relationship between PM$_{2.5}$ and cause-specific mortality may vary across regions, most studies have applied uniform concentration–response (C-R) functions. In studies of long-term exposure, results from several cohorts have been combined to present C-R functions for cause-specific mortality [2,3,11]. However, evidence for C-R functions in the context of short-term exposure is insufficient.

North America and Europe exhibit lower concentrations of PM$_{2.5}$ than Asian countries, including Korea. Research from the former indicates a linear relationship between short-term exposure to PM$_{2.5}$ and mortality [6]. In contrast, studies from Asia have identified a supralinear (non-linear) association between short-term PM$_{2.5}$ exposure and death [9,10,12]. However, little research has been published in the form of health impact assessments that consider the non-linearity of short-term PM$_{2.5}$ exposure effects.

To address this issue, we previously estimated the mortality burden associated with ambient PM$_{2.5}$ exposure in Korea by generating country-specific C-R functions [10]. We assumed a non-linear relationship between PM$_{2.5}$ levels and mortality between 2006 and 2016 and estimated the excess deaths attributable to short-term exposure to PM$_{2.5}$ [10].

However, we did not address cause-specific mortality or temporal trends (namely, the annual rate of change (ARC)) in deaths related to PM$_{2.5}$ exposure. Additionally, we referenced the World Health Organization (WHO) air quality guidelines that were in place prior to their 2021 update [13].

According to studies by Ramachandran and Rajesh [14], and by Cheng et al. [15] Asian countries often experience days with sharp increases in PM$_{2.5}$ concentrations. Although Korea’s annual trends in PM$_{2.5}$ concentrations exhibit a decreasing pattern, spikes still occur frequently. These short-term elevations in PM$_{2.5}$ levels can impact the mortality burden. Moreover, ongoing population aging may alter the annual temporal trends in mortality associated with short-term exposure to PM$_{2.5}$.

Therefore, in this study, we aimed to establish a country-specific C-R function for the relationship between short-term exposure to PM$_{2.5}$ and cause-specific mortality (including all-cause, non-accidental, cardiovascular, and respiratory mortality) in Korea. Additionally, we sought to estimate the cause-specific mortality burden attributable to short-term exposure to PM$_{2.5}$.

**METHODS**

**Daily Death Count Data**

We obtained cause-of-death statistics for the years 2010-2019 from the Microdata Integrated Service system of the Korea National Statistical Office (https://mdis.kostat.go.kr). The dataset included the date of death, cause of death, age at death, and region, the last of which encompassed cities and provinces. The regions included 8 metropolitan cities (Seoul, Busan, Daegu, Incheon, Gwangju, Daejeon, Ulsan, and Sejong) and 9 provinces (Gyeonggi, Gangwon, Chungcheongbuk, Chungcheongnam, Jeollabuk, Jeollanam, Gyeongsangbuk, Gyeongsangnam, and Jeju). We categorized cause-specific mortalities into 4 groups: all-cause (A00-Z99), non-accidental (A00-R99), cardiovascular disease (CVD; I00-I99), and respiratory disease (J00-J99), following the International Classification of Diseases, 10th edition. In our subgroup analyses, which considered gender and age group, we excluded 453 deaths from the total of 2 750 157 due to missing age information. We then calculated daily cause-specific mortality counts across the 17 regions from 2010 to 2019.

**Fine Particulate Matter Data**

We utilized data from fixed monitoring stations and modeled them to estimate PM$_{2.5}$ concentrations. Korea has been recording PM$_{2.5}$ levels since 2015; as a result, direct measurement data from before this year are not available across the various regions. In 2015, Korea had 260 active air pollution monitoring stations, which increased to 333 by 2018 [16]. The regional distribution of monitoring stations varied, with as few as 4 stations in Jeju and as many as 81 in Gyeonggi.

For the years 2010 to 2015, we therefore utilized modeled PM$_{2.5}$ data, generated with the Community Multiscale Air Quality (CMAQ) model, version 4.7.1 [17]. The CMAQ model, developed and distributed by the US Environmental Protection Agency (https://www.epa.gov/cmaq), is an atmospheric chemistry transport model that addresses a broad spectrum of air quality issues, including PM$_{2.5}$, ozone, and various toxic pollutants. It
was applied with a horizontal resolution of 27 km for Northeast Asia and 9 km for the Korean region. The model calculates the 3-dimensional distributions of both gaseous and particulate air pollutants in each grid cell on an hourly basis. Meteorological input data for air quality modeling were generated using the Weather Research and Forecasting model, version 3.4.1. The initial fields for this model were derived from the 1 × 1 Final Operational Global Analysis data provided by the National Centers for Environmental Prediction, which were obtained through the National Oceanic and Atmospheric Administration reanalysis. Previous studies have provided more detailed information on the exposure model data [5, 10, 18]. As such, we calculated the daily mean PM$_{2.5}$ concentration for each region.

From 2016 to 2019, we collected hourly PM$_{2.5}$ data from the Korea Environment Corporation (https://www.airkorea.or.kr/web). We calculated the daily PM$_{2.5}$ averages for each region by averaging these hourly levels. A day’s data were deemed invalid if 25% or more of the hourly measurements were missing.

The correlation coefficient ($r = 0.99$) was calculated between the nationwide daily CMAQ modeled data and the monitored PM$_{2.5}$ data for 2015, when the exposure data overlapped.

**Meteorological Data**

Meteorological data for each region, which included daily mean temperature, humidity, and dew point, were sourced from the Korea Meteorological Administration for the years 2010 to 2019. Utilizing this daily meteorological data, we calculated the daily apparent temperature (AT) using the following formula:

\[
AT = -2.653 + 0.994 \times \text{mean temperature} + (0.0153 \times \text{daily dew point temperature})^2
\]

[19, 20].

**Statistical Analysis**

We conducted a 2-stage statistical analysis to estimate the number of deaths attributable to short-term exposure to ambient PM$_{2.5}$. First, we employed a generalized additive mixed model (GAMM) with an assumed Poisson distribution to estimate the country-specific relative risk (RR) associated with daily air pollution and cause-specific mortality. Within the GAMM, adjustments were made for time trends, day of the week, and AT, incorporating a random intercept for the regions, per the following formula.

\[
\log(E_i) = \beta_0 + s(AP) + s(\text{Time}, df = 6 \times 10) + s(AT) + \gamma \times \text{dow} + \text{random intercept(region)}
\]

Here, $E$ represents the expected number of daily deaths, while $i$ and $j$ indicate the day and region, respectively. The term $s$ denotes the penalized spline term, and $\text{dow}$ signifies the day of the week, from Sunday to Saturday. Consistent with prior research, we employed a penalized spline to account for non-linear relationships with PM$_{2.5}$, time, and AT. The degrees of freedom (df) for the time trend, PM$_{2.5}$, and AT were established based on findings from earlier studies [7, 10, 21] and a model evaluation index, which included generalized cross-validation and the Akaike information criterion. Specifically, we chose to use 6 df per year for the time trend, resulting in a total of 60 df over the 10-year study period, and we selected appropriate df values for PM$_{2.5}$ and AT.

The C-R function depicting the association between daily exposure to PM$_{2.5}$ and cause-specific mortality is illustrated in Supplemental Material 1.

By incorporating a lag structure, we accounted for the delayed association between daily exposure to PM$_{2.5}$ and mortality. To identify the optimal lag day for the main analysis, we evaluated lag days up to day 6, then selected lag0 according to the best-fit model (Supplemental Material 2).

Estimates of the association between daily exposure to PM$_{2.5}$ and mortality are expressed as RR and 95% confidence intervals (CIs) for each concentration level—ranging from 0 μg/m$^3$ to 230 μg/m$^3$ at 1 μg/m$^3$ intervals—compared with the reference concentration. Since the maximum observed PM$_{2.5}$ concentration was 230 μg/m$^3$, we presented an RR and 95% CI for each increment from 1 μg/m$^3$ to 230 μg/m$^3$ (Supplemental Material 3).

We assumed that concentrations below 15 μg/m$^3$ posed no risk. These values are based on the updated WHO Air Quality Guidelines for a 24-hour period [13]. For comparison with the results of the non-linear association, we estimated the number of excess deaths attributable to PM$_{2.5}$ under the assumption of a linear association.

**Estimated Excess Deaths**

The population attributable fraction (PAF) and AD were calculated as follows:

\[
P_{\text{AF}} = 1 - \frac{1}{R_{\text{RR}(\text{PM}_{2.5}, cf)}}
\]

for PM$_{2.5}$ concentration $< cf$, $RR=1$

\[
\Delta AD = \text{Deaths} \times P_{\text{AF}}(\text{PM}_{2.5}, cf)
\]

Here, $cf$ indicates the counterfactual concentration. If the PM$_{2.5}$ concentration fell below the reference concentration, we
presumed that no associated risk was present. Furthermore, we estimated the excess deaths under various scenarios with differing reference concentrations. Specifically, we posited that no risk was conferred when the daily PM$_{2.5}$ concentration was less than 10 μg/m$^3$ or less than 5 μg/m$^3$. The resulting reference concentrations of 15 μg/m$^3$, 10 μg/m$^3$, and 5 μg/m$^3$ were applied as concentration scenarios 1, 2, and 3, respectively.

Similarly, the 95% CIs for excess deaths attributable to short-term exposure to PM$_{2.5}$ were calculated using the lower and upper bounds of the RR.

**Annual Rate of Change**

We considered the ARC for ADs resulting from short-term exposure to PM$_{2.5}$ over the years 2010 to 2019 across Korea. The formula used to determine the ARC is as follows [22]:

$$ARC = \frac{B - A}{A} \times \frac{1}{t} \times 100\%$$

Here, $A$ and $B$ denote the number of excess deaths in 2010 and 2019, respectively, while $t$ represents the number of years in the interval (the study period).

**Subgroup Analysis**

We performed subgroup analyses stratified by gender and age group (under 65 vs. 65 years and older). These analyses followed the 2-stage statistical approach previously described. In the first stage, we conducted a time-series analysis using GAMM for each gender and age category. In the second stage, we utilized the RR associated with each PM$_{2.5}$ concentration interval, as determined by each model, to estimate excess deaths. Notably, because the results vary across models, the sum of the estimated excess deaths for each subgroup may not equate to the total estimated excess deaths.

All analyses were conducted using R version 4.2.1 (packages: dplyr, ggplot2, gamm4, and gridExtra; R Foundation for Statistical Computing, Vienna, Austria).

**Ethics Statement**

This study was exempted from review by the Institutional Review Board of Seoul National University Hospital in Korea (IRB No. E-2105-043-1218).

**RESULTS**

We analyzed a total of 2,749,704 deaths that occurred in Korea from 2010 to 2019. Of these, 2,453,686 (89.2%) were non-accidental, 591,267 (21.5%) were due to cardiovascular causes, and 141,066 (5.1%) were respiratory-related deaths. In 2019, the death rates per 100,000 people were 574.7 for all causes, 521.6 for non-accidental causes, 117.3 for cardiovascular causes, and 71.4 for respiratory causes, respectively. The daily mean PM$_{2.5}$ levels varied, with the lowest at 14.7 μg/m$^3$ (recorded in Jeju) and the highest at 28.4 μg/m$^3$ (observed in Chungbuk) (Table 1, Supplemental Material 4).

Supplemental Material 5 presents the daily counts of cause-specific deaths, PM$_{2.5}$ concentrations, and AT throughout the study period. An upward trend was observed in the number of cause-specific deaths over time.

The distribution of deaths in relation to PM$_{2.5}$ exposure concentration exhibited a right-skewed pattern (Figure 1). Between 2010 and 2019, approximately 76.5% of the days recorded PM$_{2.5}$ concentrations exceeding the WHO’s recommended air quality limit for a 24-hour period, which is 15 μg/m$^3$ (Supplemental Material 6).

The relationship between exposure to PM$_{2.5}$ at lag0 and all-cause mortality exhibited a linear association from 0 μg/m$^3$ to 104 μg/m$^3$. In contrast, the RR decreased at high concentrations (>104 μg/m$^3$) (Figure 1). However, short-term exposure to PM$_{2.5}$ was positively associated with non-accidental, CVD, and respiratory deaths, demonstrating a linear relationship (Supplemental Material 7).

During the study period (2010-2019), there were 10,814 (95% CI, 6,428 to 15,183) all-cause deaths, 7,855 (95% CI, 6,142 to 9,563) non-accidental deaths, 1,642 (95% CI, 801 to 2,480) cardiovascular deaths, and 708 (95% CI, 135 to 1,278) respiratory deaths attributable to short-term exposure to PM$_{2.5}$, according to the WHO guidelines (Table 2). In 2019, excess deaths due to short-term exposure to PM$_{2.5}$ were estimated at 1,029 (95% CI, 604 to 1,472). The years with the highest and lowest numbers of excess deaths due to short-term PM$_{2.5}$ exposure were 2013 (n=1,172; 95% CI, 709 to 1,634) and 2012 (n=953; 95% CI, 568 to 1,337), respectively. The estimated excess all-cause deaths due to short-term exposure based on non-linear (n=10,814; 95% CI, 6,428 to 15,183) and linear (n=10,407; 95% CI, 7,550 to 13,256) assumptions were similar (Supplemental Materials 8 and 9).

By applying various concentration scenarios, we found that a lower reference concentration of PM$_{2.5}$ was associated with a higher number of excess deaths attributed to daily exposure to PM$_{2.5}$ in 2019 (Table 3). Specifically, when comparing scenario 1 (reference concentration: 15 μg/m$^3$) to scenario 3 (5 μg/m$^3$),...
Table 1. Region- and cause-specific mortality and air pollution levels in Korea, 2010-2019

<table>
<thead>
<tr>
<th>City/Province</th>
<th>Population (2019)</th>
<th>All-cause</th>
<th>Non-accidental</th>
<th>CVD</th>
<th>Respiratory</th>
<th>Deaths (all-cause)</th>
<th>PM$_{2.5}$ (μg/m$^3$)</th>
<th>AT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seoul</td>
<td>9,578,975</td>
<td>424,690</td>
<td>457.4</td>
<td>380,394</td>
<td>416.9</td>
<td>82,511</td>
<td>90.6</td>
<td>35,437</td>
</tr>
<tr>
<td>Busan</td>
<td>3,390,160</td>
<td>208,296</td>
<td>656.2</td>
<td>188,489</td>
<td>597.8</td>
<td>51,864</td>
<td>151.1</td>
<td>19,357</td>
</tr>
<tr>
<td>Daegu</td>
<td>2,431,140</td>
<td>129,953</td>
<td>565.6</td>
<td>116,776</td>
<td>512.0</td>
<td>31,000</td>
<td>117.4</td>
<td>12,693</td>
</tr>
<tr>
<td>Incheon</td>
<td>2,927,320</td>
<td>136,196</td>
<td>516.8</td>
<td>121,219</td>
<td>467.7</td>
<td>29,555</td>
<td>100.8</td>
<td>12,789</td>
</tr>
<tr>
<td>Gwangju</td>
<td>1,448,843</td>
<td>71,482</td>
<td>527.0</td>
<td>63,858</td>
<td>478.8</td>
<td>14,307</td>
<td>98.1</td>
<td>7,829</td>
</tr>
<tr>
<td>Daejeon</td>
<td>1,471,770</td>
<td>68,274</td>
<td>509.7</td>
<td>60,310</td>
<td>460.7</td>
<td>13,349</td>
<td>84.7</td>
<td>6,218</td>
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<td>Ulsan</td>
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<td>48,285</td>
<td>459.8</td>
<td>42,518</td>
<td>410.7</td>
<td>11,278</td>
<td>106.6</td>
<td>4,280</td>
</tr>
<tr>
<td>Sejong</td>
<td>326,245</td>
<td>9485</td>
<td>374.3</td>
<td>8422</td>
<td>335.0</td>
<td>2013</td>
<td>72.3</td>
<td>1,271</td>
</tr>
<tr>
<td>Gyeonggi</td>
<td>13,043,732</td>
<td>534,922</td>
<td>464.3</td>
<td>473,711</td>
<td>419.6</td>
<td>111,328</td>
<td>95.2</td>
<td>47,131</td>
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<tr>
<td>Gangwon</td>
<td>1,528,656</td>
<td>112,181</td>
<td>778.6</td>
<td>99,622</td>
<td>703.7</td>
<td>24,108</td>
<td>157.4</td>
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<td>Chungcheongbuk</td>
<td>1,589,355</td>
<td>106,228</td>
<td>714.8</td>
<td>94,630</td>
<td>650.3</td>
<td>21,624</td>
<td>140.3</td>
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<tr>
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<td>34,854</td>
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<td>746.6</td>
<td>48,059</td>
<td>172.9</td>
<td>24,531</td>
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<td>Gyeongsangnam</td>
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<td>208,686</td>
<td>660.0</td>
<td>186,865</td>
<td>599.2</td>
<td>50,819</td>
<td>144.4</td>
<td>21,419</td>
</tr>
<tr>
<td>Jeju</td>
<td>663,489</td>
<td>34,369</td>
<td>598.2</td>
<td>30,235</td>
<td>533.8</td>
<td>6132</td>
<td>97.5</td>
<td>3,572</td>
</tr>
<tr>
<td>Total</td>
<td>51,337,424</td>
<td>2,749,704</td>
<td>574.7</td>
<td>2,453,686</td>
<td>521.6</td>
<td>591,267</td>
<td>117.3</td>
<td>272,107</td>
</tr>
</tbody>
</table>

CVD, cardiovascular disease; SD, standard deviation; PM$_{2.5}$, fine particulate matter; AT, apparent temperature.

1 Deaths per 100,000 people.
the estimated number of all-cause attributable deaths approximately tripled under the latter conditions (scenario 1: 1039 deaths vs. scenario 3: 3743 deaths).

In the subgroup analyses, we demonstrated a non-linear association between PM$_{2.5}$ exposure and all-cause as well as non-accidental mortality in the elderly group (age at death $\geq$ 65 years) (Supplemental Material 10). The other results indicated linear associations. In 2019, the estimated attributable all-cause mortality in scenario 3 was approximately twice as high for men, women, and younger participants, and 5 times...
Compared to men, women experienced higher rates of non-accidental, cardiovascular, and respiratory deaths associated with short-term exposure to PM$_{2.5}$ (Figure 2). The elderly participants recorded more deaths than the younger group (age of death < 65 years), with further pronounced disparities across exposure scenarios. For instance, for the elderly group, scenario 1 was associated with 389 deaths (95% CI, 19 to 757), while scenario 3 corresponded to 1888 deaths (95% CI, 1355 to 2419).

From 2010 to 2019, regarding deaths due to short-term exposure to PM$_{2.5}$, the ARC was -1.1% for all-cause mortality, -1.2% for non-accidental mortality, and -2.0% for CVD deaths. In contrast, the ARC for respiratory deaths was positive, at 5.3% (Supplemental Material 11).

**DISCUSSION**

We established country-specific C-R functions relating daily exposure to PM$_{2.5}$ with cause-specific mortality, then used these functions to calculate the excess burden attributable to PM$_{2.5}$ in Korea. The country-specific C-R function demonstrated a non-linear relationship, plateaing at concentrations greater than 104 μg/m$^3$, while exhibiting a linear relationship at lower concentrations. Over the 10-year study period, the estimated
excess deaths totaled 10,814 for all causes, 7,855 for non-accidental causes, 1,642 for cardiovascular causes, and 708 for respiratory causes. The burden was disproportionately higher among women and the elderly compared to men and younger participants.

A previous Korean study estimated that chronic exposure to PM$_{2.5}$ resulted in 11,924 premature deaths in 2015 [5]. That study utilized an integrated exposure-response function to assess the mortality burden from 4 major causes of death: ischemic heart disease, stroke, chronic obstructive pulmonary disease, and lung cancer. In our analysis, we estimated that short-term exposure to PM$_{2.5}$ was responsible for 1033 deaths in that same year. Another study of disease burden indicated that the health impact of short-term PM$_{2.5}$ exposure in Korea was smaller than that of long-term exposure [10]. When compared with the 2016 findings of Lim et al. [10], our study estimated a lower number of excess non-accidental deaths attributable to PM$_{2.5}$ (850 vs. 1,638). This difference may stem from variations in the study periods (2010-2019 vs. 2006-2016) and the range of lag days considered (lag0 vs. lag0-7).

Li et al. [9] identified non-linear associations between daily mean PM$_{2.5}$ exposure and all-cause mortality across 104 counties in China from 2013 to 2015. In the present study, we observed a lower number of excess deaths (2.04 vs. 13.78 per 100,000 people). This discrepancy largely stems from variations in population characteristics, such as the study period, population size, and mortality rate, as well as differences in exposure levels. Specifically, the daily mean concentration of PM$_{2.5}$ was 24.4 μg/m$^3$ in our study compared to 61.6 μg/m$^3$ in the study by Li et al. [9].

We observed a non-linear association between daily exposure to PM$_{2.5}$ and all-cause mortality, with the RR attenuated at high concentrations (>104 μg/m$^3$). This pattern aligns with previous studies that have reported non-linear associations in Asian populations [7,9]. In a 2019 study, Cho and Kim [23] surveyed 171 Koreans regarding their perceptions of ambient PM$_{2.5}$ levels and their corresponding adaptive behaviors. The participants indicated that they checked the daily PM$_{2.5}$ levels or avoided outdoor activities on days when the concentrations were high. The observed decrease in RR at elevated concentrations may be attributed to several factors, including the potential tendency to stay indoors or wear masks when PM$_{2.5}$ levels are high.

PM$_{2.5}$ exposure was more strongly associated with respiratory mortality than with mortality from the other examined causes. The ARC for respiratory deaths due to daily PM$_{2.5}$ exposure (5.3%) indicated an increase between 2010 and 2019. In contrast, the number of excess deaths for all causes, non-accidental causes, and CVDs declined over the same period, with decreases of 1.1%, 1.2%, and 2.0%, respectively. These trends may reflect the sharp rise in deaths from respiratory disease linked to the rapid aging of the population [24]. Consequently, the data suggest that the number of excess deaths from respiratory diseases attributable to short-term PM$_{2.5}$ exposure increased by an average of 5.3% annually from 2010 to 2019.

Excess deaths attributable to air pollution depend on data regarding population size, exposure levels, and the effect size (that is, RR). As the proportion of the elderly—a predominantly vulnerable demographic—grows annually, the concentration of PM$_{2.5}$ has been observed to decrease each year. Consequently, the count of excess deaths fluctuates in response to these 3 variables: population numbers, exposure concentrations, and RR. The ARC may also vary. This study underscores how shifts in excess deaths resulting from short-term exposure to PM$_{2.5}$ could be influenced by daily concentration variations and an increase in underlying deaths due to an aging population.

To account for demographic shifts due to population aging and regional population variations, we incorporated population density in our model as an offset term for sensitivity analysis. When population density was considered, the estimated number of excess deaths attributable to short-term exposure to PM$_{2.5}$ was marginally lower (all-cause: 8,628 [95% CI, 6,909 to 10,343]; non-accidental: 6,307 [95% CI, 4,770 to 7,840]; CVD: 1,336 [95% CI, 965 to 1,707]; respiratory: 569 [95% CI, 399 to 739]) than the primary findings (all-cause: 10,814 [95% CI, 6,428 to 15,183]; non-accidental: 7,855 [95% CI, 6,142 to 9,563]; CVD: 1,642 [95% CI, 801 to 2,480]; respiratory: 708 [95% CI, 135 to 1,278]), as detailed in Supplemental Material 12.

In this study, women and the elderly exhibited higher mortality due to short-term PM$_{2.5}$ exposure relative to men and younger groups. These disparities could be attributed to a range of factors, including biological mechanisms, socioeconomic status (such as income and occupation), lifestyle choices (including the frequency of alcohol consumption, smoking habits, and levels of physical activity), and population aging [25-28]. In particular, the population of Korea is aging at an unprecedented rate [27]. Consequently, if the current levels of PM$_{2.5}$ concentration persist, we may see an increase in excess deaths associated with short-term exposure to PM$_{2.5}$.
tal in crafting effective public health interventions, which include defining, evaluating, and reviewing air quality standards [29,30]. Qu et al. [30] conducted a study on the PM$_{2.5}$-related health and economic benefits of an Air Improvement Action Plan, reporting 21 384 premature deaths in Wuhan from 2013 to 2017. In Korea, the Special Act on the Reduction and Management of Fine Dust (Fine Dust Act) has been in effect since February 15, 2019. Assessing the health impacts and benefits associated with PM$_{2.5}$ reduction is essential. Moreover, air quality recommendations differ across countries, and few meet the WHO air quality guidelines for a 24-hour period (which stipulate a limit of 15 μg/m$^3$). The Korean Ministry of Environment has set a more lenient daily air quality guideline for PM$_{2.5}$ at 35 μg/m$^3$ [31].

From 2010 to 2019, we found that 23.5% of days had an average daily PM$_{2.5}$ concentration of 15 μg/m$^3$ or less; 7.0%, had concentrations of 10 μg/m$^3$ or less; and 0.2% had concentrations of 5 μg/m$^3$ or less. Hence, the population is still exposed to concentrations above the exposure limit recommended by the WHO. Based on our exposure scenario analysis, differences in the burden of death are pronounced (scenario 1 [15 μg/m$^3$]: 1039 deaths vs. scenario 3 [5 μg/m$^3$]: 3743 deaths). Therefore, reducing exposure levels through air pollution management and reduction strategies can decrease the mortality burden associated with short-term exposure to PM$_{2.5}$.

This study evaluated the disease burden of cause-specific mortality associated with daily PM$_{2.5}$ exposure. Three reference concentration scenarios were considered. Should the government or policymakers intensify their efforts to reduce PM$_{2.5}$ levels in Korea, premature deaths associated with short-term exposure to these pollutants may be prevented. Furthermore, the estimated ARC for excess mortality linked to PM$_{2.5}$ could inform policy improvements. Previous research has employed a non-linear (specifically, supralinear) approach to estimate the global exposure-response function (incorporating both the global exposure mortality model and the integrated exposure-response) for long-term exposure to PM$_{2.5}$, drawing on data from multiple cohort studies [2,3,11]. However, a global exposure-response function for short-term exposure to PM$_{2.5}$ has yet to be established.

Due to heterogeneity in exposure levels and population density across regions, the association between short-term exposure to PM$_{2.5}$ and mortality may not be statistically significant in certain areas. Furthermore, the nature of the exposure-response relationships can differ. In this study, we estimated a unified RR for the association between short-term exposure to PM$_{2.5}$ and mortality on a national scale. Our findings can assist in estimating the mortality burden and inform the global response to short-term exposure to PM$_{2.5}$.

The present study had several limitations. First, we cannot rule out the possibility of measurement errors and misclassification of exposure levels. Although such misclassifications can introduce bias towards null or event outcomes, this is unlikely to occur in the case of Berkson-type errors. Therefore, we remain confident that the significance of our findings is not due to measurement error [32]. Future research should aim to connect high-resolution exposure data with more precise exposure allocation. Second, any establishment of a causal relationship was limited by the nature of our study, which relied on ecological time-series data from the population. Third, our analysis was based on aggregated data from the general population, which precluded the examination of individual characteristics such as income level, disability, and underlying diseases. It is possible that socioeconomically vulnerable groups or patients with certain conditions may exhibit greater sensitivity to PM$_{2.5}$ [28,33,34]. Consequently, additional research is necessary to assess the disease burden while reflecting individual characteristics.

In conclusion, we estimated the health burden attributable to daily exposure to PM$_{2.5}$ in Korea from 2010 to 2019. Our findings can assist in air pollution management, regulation, and policy-making. Since lower reference levels markedly increased ADs, immediate action plans are needed to protect the population from daily PM$_{2.5}$ exposure. Furthermore, our findings may be applicable to other Asian countries with similar PM$_{2.5}$ concentrations.

**NOTES**

**Supplemental Materials**

Supplemental materials are available at https://doi.org/10.3961/jpmph.23.514.

**Conflict of Interest**

The authors have no conflicts of interest associated with the material presented in this paper.

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REFERENCES

13. World Health Organization. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide,
sulfur dioxide and carbon monoxide; 2021 [cited 2024 Jan 2]. Available from: https://www.who.int/publications/i/item/9789240034228


23. Cho ME, Kim MJ. Residents’ perceptions of and response behav-