Original Article

J Prev Med Public Health 2024;57:185-196 • https://doi.org/10.3961/jpmph.23.514

pISSN 1975-8375 eISSN 2233-4521

Journal of Preventive Medicine & Public Health

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 ($PM_{2.5}$) 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 $PM_{2.5}$ by considering the potential non-linear concentration–response relationship in Korea.

Methods: Daily cause-specific mortality rates and $PM_{2.5}$ 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 $PM_{2.5}$ exposure and cause-specific mortality levels. We assumed no detrimental health effects of $PM_{2.5}$ concentrations below 15 μg/m^3. Overall deaths attributable to short-term $PM_{2.5}$ exposure were estimated by summing the daily numbers of excess deaths associated with ambient $PM_{2.5}$ 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 $PM_{2.5}$ at lag0, whereas linear associations were evident for cause-specific mortalities. Overall, 10 814 all-cause, 7855 non-accidental, 1642 cardiovascular, and 708 respiratory deaths were attributed to short-term exposure to $PM_{2.5}$. The estimated number of all-cause excess deaths due to short-term $PM_{2.5}$ exposure in 2019 was 1039 (95% confidence interval, 604 to 1472).

Conclusions: Our findings indicate an association between short-term $PM_{2.5}$ 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 $PM_{2.5}$.

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

Received: Nov 13, 2023 Revised: Jan 15, 2024 Accepted: Feb 22, 2024

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INTRODUCTION

Many epidemiological studies have investigated the health burden of long-term exposure to fine particulate matter ($PM_{2.5}$) [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 $PM_{2.5}$ 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 ($\rho=0.99$) 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×daily mean temperature+(0.0153×[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.

$$\text{Log}(E_{ij})=\beta_0+s(AP_{ij})+s(Time_i, df=6\times 10)+s(AT_{ij})+\gamma\times dow+random\ intercept(region_j)$$

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 *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 RRs 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:

$$PAF_\beta=1-\frac{1}{RR_\beta(PM_{2.5},cf)}$$

$$for\ \mathrm{PM}_{2.5}\ \text{concentration} < cf\,;\ RR=1$$

$$\Delta AD = Deaths\ \times PAF_\beta(PM_{2.5}, cf)$$

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, 6428 to 15 183) all-cause deaths, 7855 (95% CI, 6142 to 9563) non-accidental deaths, 1642 (95% CI, 801 to 2480) cardiovascular deaths, and 708 (95% CI, 135 to 1278) 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 1039 (95% CI, 604 to 1472). The years with the highest and lowest numbers of excess deaths due to short-term $PM_{2.5}$ exposure were 2013 (n=1172; 95% CI, 709 to 1634) and 2012 (n=953; 95% CI, 568 to 1337), respectively. The estimated excess all-cause deaths due to short-term exposure based on non-linear (n=10 814; 95% CI, 6428 to 15 183) and linear (n=10 407; 95% CI, 7550 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

City/Province	Population (2019)	All-cause		Non-accidental		CVD		Respiratory		Daily mean±SD		
		Count (2010-2019)	Mortality (2019)[1]	Count (2010-2019)	Mortality (2019)[1]	Count (2010-2019)	Mortality (2019)[1]	Count (2010-2019)	Mortality (2019)[1]	Deaths (all-cause)	$PM_{2.5}$ (μg/m³)	AT (°C)
Seoul	9 578 975	424 690	457.4	380 394	416.9	82 511	90.6	35 437	48.5	116.3±13.8	27.7±16.6	12.8±12.1
Busan	3 390 160	208 296	656.2	188 489	597.8	51 864	151.1	19 357	60.0	57.0±9.0	24.6±12.6	15.4±10.4
Daegu	2 431 140	129 953	565.6	116 776	512.0	31 000	117.4	12 693	72.3	35.6±6.8	24.7±13.6	14.5±11.3
Incheon	2 927 320	136 196	516.8	121 219	467.7	29 555	100.8	12 789	58.4	37.3±7.0	26.7±15.2	12.8±12.4
Gwangju	1 448 843	71 482	527.0	63 858	478.8	14 307	98.1	7829	76.8	19.6±4.7	23.7±14.6	14.5±12.1
Daejeon	1 471 770	68 274	509.7	60 310	460.7	13 349	84.7	6218	68.8	18.7±(4.7	26.0±16.3	13.4±12.6
Ulsan	1 145 705	48 285	459.8	42 518	410.7	11 278	106.6	4280	39.5	13.2±3.9	24.5±13.7	14.7±10.9
Sejong	326 245	9485	374.3	8422	335.0	2013	72.3	1271	44.1	2.6±1.7	26.6±17.4	18.1±11.5
Gyeonggi	13 043 732	534 922	464.3	473 711	419.6	111 328	95.2	47 131	54.4	146.5±19.4	27.4±15.6	11.8±12.4
Gangwon	1 528 656	112 181	778.6	99 622	703.7	24 108	157.4	13 470	114.5	30.7±6.1	22.2±12.4	11.2±11.3
Chungcheongbuk	1 589 355	106 228	714.8	94 630	650.3	21 624	140.3	12 846	107.7	29.1±5.9	28.4±16.9	11.6±12.0
Chungcheongnam	2 110 584	144 490	738.8	127 260	663.0	29 512	145.9	15 553	101.0	39.6±7.3	25.4±14.7	12.3±12.7
Jeollabuk	1 816 001	138 201	799.6	123 494	730.1	28 954	158.0	15 570	120.3	37.8±7.0	27.1±15.5	12.7±12.2
Jeollanam	1 863 279	165 208	900.6	147 782	827.7	34 854	184.4	18 141	119.7	45.2±7.7	20.2±11.3	13.8±11.5
Gyeongsangbuk	2 653 916	208 758	817.5	187 561	746.6	48 059	172.9	24 531	124.6	57.2±9.0	22.1±12.5	12.5±11.3
Gyeongsangnam	3 348 258	208 686	660.0	186 865	599.2	50 819	144.4	21 419	83.4	57.1±9.2	22.8±11.9	14.0±11.2
Jeju	663 489	34 369	596.2	30 235	533.8	6132	97.5	3572	86.5	9.4±3.3	14.7±11.0	16.6±10.6
Total	51 337 424	2 749 704	574.7	2 453 686	521.6	591 267	117.3	272 107	71.4	752.9±69.3	24.4±12.7	13.4±11.6

CVD, cardiovascular disease; SD, standard deviation; $PM_{2.5}$, fine particulate matter; AT, apparent temperature.
[1]Deaths per 100 000 people.

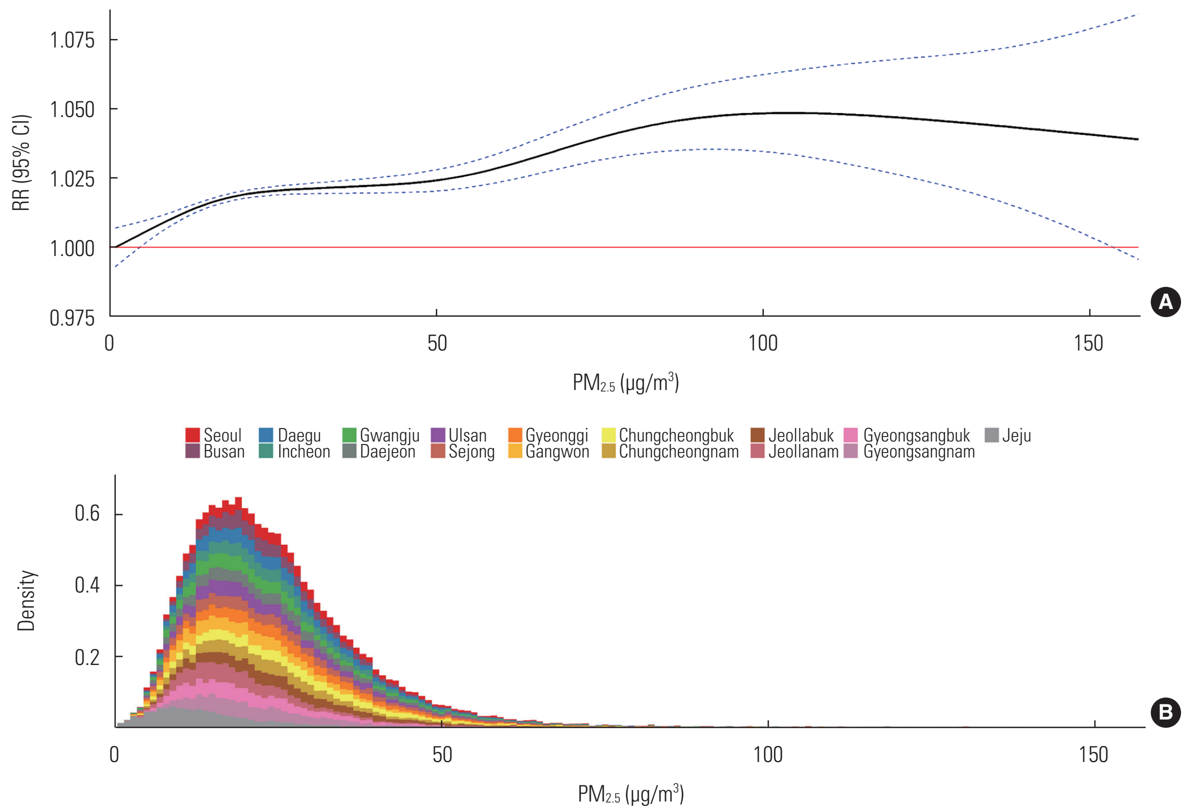

Figure 1. The exposure-response relationship between short-term exposure to (A) fine particulate matter ($PM_{2.5}$) and (B) all-cause deaths in Korea in 2010-2019. The black solid line and blue dotted lines indicate the relative risk (RR) and 95% confidence intervals (CI). The black dotted vertical line indicates the $PM_{2.5}$ concentration level at 15 μg/m^3 (reference concentration level).

Table 2. Deaths attributable to daily exposure to $PM_{2.5}$ in Korea, 2010-2019

Year	All-cause	Non-accidental	CVD	Respiratory
2010	1153 (675, 1627)	838 (650, 1025)	183 (87, 279)	56 (9, 102)
2011	1095 (631, 1555)	792 (620, 963)	172 (84, 259)	57 (11, 103)
2012	953 (568, 1337)	657 (520, 793)	142 (73, 211)	53 (13, 93)
2013	1172 (709, 1634)	858 (668, 1047)	179 (86, 272)	67 (12, 121)
2014	1108 (660, 1554)	814 (624, 1004)	170 (77, 262)	69 (9, 128)
2015	1033 (618, 1447)	753 (593, 913)	157 (79, 235)	71 (15, 127)
2016	1151 (695, 1606)	850 (677, 1023)	177 (92, 261)	81 (20, 142)
2017	1088 (655, 1519)	793 (625, 961)	164 (82, 246)	82 (17, 146)
2018	1023 (613, 1432)	761 (594, 927)	153 (74, 232)	90 (16, 163)
2019	1039 (604, 1472)	739 (570, 908)	145 (67, 223)	83 (13, 153)
Total	10 814 (6428, 15 183)	7855 (6142, 9563)	1642 (801, 2480)	708 (135, 1278)

Values are presented as excess death (95% confidence interval).
$PM_{2.5}$, fine particulate matter; CVD, cardiovascular disease.

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 ≥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

Table 3. Deaths attributable to daily exposure to $PM_{2.5}$ in Korea in 2019 by exposure scenario

Scenario (S)	All-cause	Non-accidental	CVD	Respiratory
S1: 15 μg/m³	1039 (604, 1472)	739 (570, 908)	145 (67, 223)	83 (13, 153)
S2: 10 μg/m³	2142 (1620, 2662)	1030 (807, 1252)	202 (100, 304)	116 (23, 207)
S3: 5 μg/m³	3743 (3123, 4360)	1379 (1107, 1651)	270 (145, 394)	155 (42, 266)

Values are presented as excess death (95% confidence interval).
$PM_{2.5}$, fine particulate matter; CVD, cardiovascular disease.

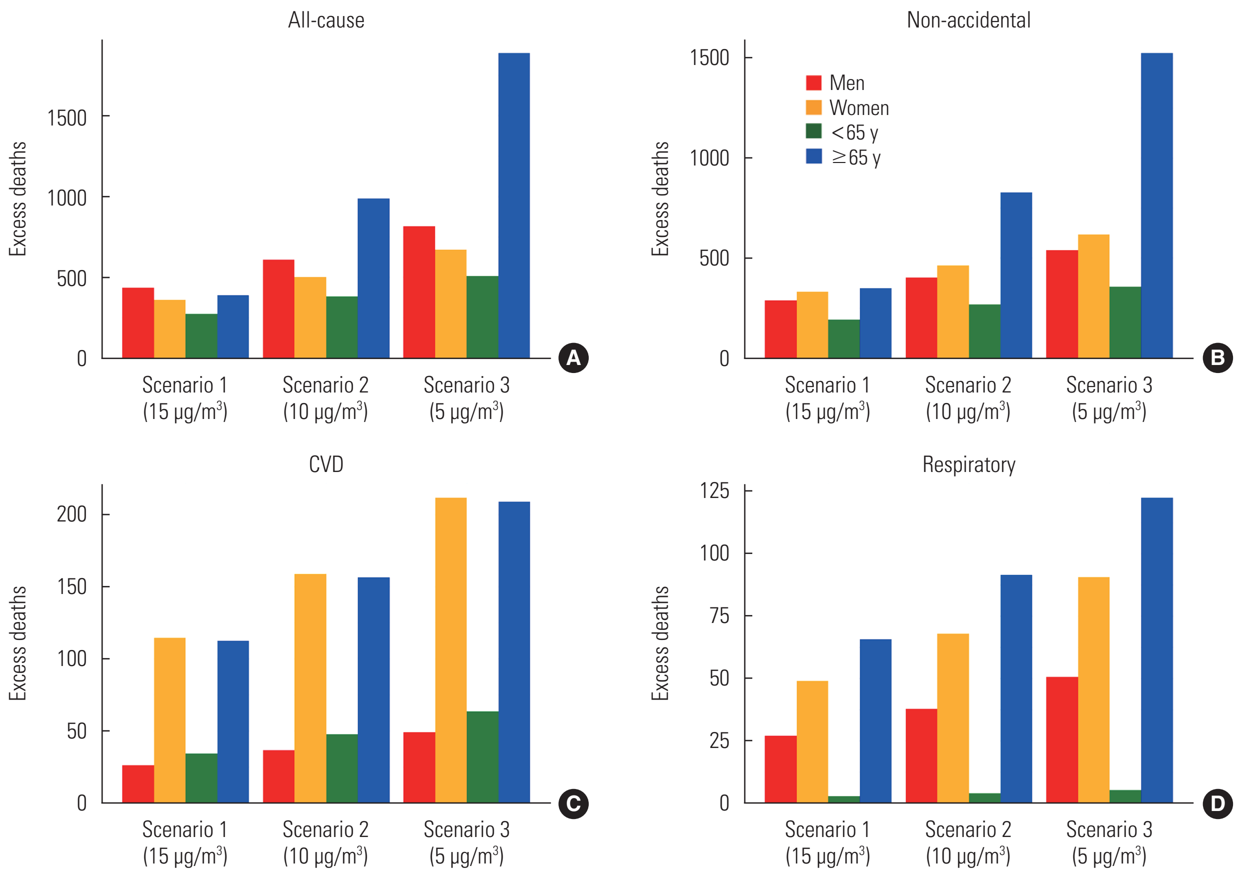

Figure 2. Attributable deaths (A) all-cause, (B) non-accidental, (C) cardiovascular disease (CVD), and (D) respiratory by gender and age group due to daily exposure to fine particulate matter in Korea according to the exposure scenario in 2019.

higher for older individuals, compared to scenario 1 (Figure 2).

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, plateauing at concentrations greater than 104 μg/m³, while exhibiting a linear relationship at lower concentrations. Over the 10-year study period, the estimated excess deaths totaled 10 814 for all causes, 7855 for non-accidental causes, 1642 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. 1638). 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: 8628 [95% CI, 6909 to 10 343]; non-accidental: 6307 [95% CI, 4770 to 7840]; CVD: 1336 [95% CI, 965 to 1707]; respiratory: 569 [95% CI, 399 to 739]) than the primary findings (all-cause: 10 814 [95% CI, 6428 to 15 183]; non-accidental: 7855 [95% CI, 6142 to 9563]; CVD: 1642 [95% CI, 801 to 2480]; respiratory: 708 [95% CI, 135 to 1278]), 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 $PM_{2.5}$.

Quantifying the health burden of air pollution is instrumental 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.

Funding

This work was supported by the Korea Environment Industry & Technology Institute (KEITI) through the Digital Infrastructure Building Project for Monitoring, Surveying, and Evaluating Environmental Health, funded by the Korea Ministry of Environment (MOE) [grant No. RS-2021-KE001615].

Acknowledgements

JO was supported as a trainee of the environmental health training program provided by the Environmental Health Centre of the Catholic University of Korea, funded by the Ministry of Environment, Republic of Korea (2023).

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Conceptualization: Oh J, Lim YH, Bae HJ. Data curation: Oh J, Kim S. Formal analysis: Oh J, Lim YH. Funding acquisition: Bae HJ. Methodology: Oh J, Lim YH, Han C, Lee DW, Myung J, Hong YC, Bae HJ. Project administration: Bae HJ. Visualization: Oh J. Writing – original draft: Oh J, Lim YH, Han C, Lee DW, Myung J, Hong YC, Bae HJ. Writing – review & editing: Oh J, Lim YH, Han C, Lee DW, Myung J, Hong YC, Kim S, Bae HJ.

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