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Ambient fine particulate matter and mortality risk among people with disability in Korea based on the National Health Insurance database: a retrospective cohort study

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Abstract

Background People with disabilities (PWD) may be more vulnerable to the adverse health effects of air pollution than the general population. This study examined the association between long-term exposure to ambient fine particulate matter ($PM_{2.5}$) and mortality risk in PWD considering disability type and severity.

Methods Data from the Korean National Health Insurance Service and Statistics Korea were analyzed in this retrospective cohort study, including 2,880,265 individuals (41,501,709 person-years), of which 176,410 were PWD (2,011,231 person-years). $PM_{2.5}$ exposure was estimated using simulated data from 2006 to 2019. Causes of death included all causes, non-accidental causes, respiratory disease, lung cancer, and cardiovascular disease. Cox proportional hazard models were used to estimate hazard ratios (HRs) for mortality associated with $PM_{2.5}$ stratified by disability type and severity.

Results PWD, particularly those with severe disabilities or specific impairments such as kidney problems or brain lesions, showed significantly high mortality risks from all causes, non-accidental causes, and cardiovascular diseases due to $PM_{2.5}$ exposure. For individuals with kidney impairment, the HR (95% confidence interval) for mortality on increasing $PM_{2.5}$ by 10 $\mu g/m^3$ was 1.79 (1.27–2.52) from all causes, while for those with brain lesions, it was 1.10 (1.00–1.22) from cardiovascular disease. PWD were not susceptible to mortality from respiratory causes.

Conclusions This study highlights the increased vulnerability of PWD, especially those with severe disabilities or specific impairments, to the adverse effects of $PM_{2.5}$ exposure. Targeted interventions tailored to disability type and severity, along with stricter air quality standards and specialized healthcare approaches, are needed.

Keywords $PM_{2.5}$, Mortality, People with disabilities, Disability type, Disability severity

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Background

In 2019, ambient air pollution was estimated to cause approximately 4.2 million premature deaths worldwide [1]. Fine particulate matter ($PM_{2.5}$) originates from primary sources, such as fuel combustion in power generation facilities, industries, or vehicles, and secondary sources, such as chemical reactions between gases [2]. Adverse health effects of $PM_{2.5}$ exposure, such as cardiovascular, respiratory, neurological diseases, and cancer, have been widely reported. Furthermore, $PM_{2.5}$ is associated with a high risk of mortality from all causes, nonaccidental causes, and cardiovascular diseases [2].

Approximately 1.3 billion people, 16% of the world's population, experience significant disabilities [3]. In Korea, the registered disability system has been a crucial component of the social and health infrastructure, covering approximately 5% of the population since 2009 [4]. Although this percentage is lower than that in Western developed countries, it is expected to increase owing to the aging population and the growing recognition of disabilities.

People with disabilities (PWD) face various challenges due to their pre-existing conditions, limited mobility, restricted medical accessibility, and potential socioeconomic disadvantages, which heighten their susceptibility to environmental risks [5]. Previous studies have examined the association between exposure to particulate matter (PM) and health outcomes in PWD. A systematic review reported that PWD experience higher risks of cardiovascular disease, obesity, and post-stroke functional issues due to air pollution, including $PM_{2.5}$, compared to non-disabled (ND) individuals [6]. Among the included studies, three focused on short-term exposure [7–9], while the other three investigated long-term exposure [10–12], with one evaluating PM as a mediator rather than a direct factor [10]. However, existing studies on air pollution–disability epidemiology have not fully explored the intersection of $PM_{2.5}$ with factors such as disability type and severity.

Therefore, this study aimed to investigate the long-term association between ambient $PM_{2.5}$ and mortality risk among PWD using the National Health Insurance Database (DB). We also used the Statistics Korea Database to determine specific causes of mortality.

Methods

Database

The National Health Insurance (NHI) system in Korea provides mandatory health insurance to all eligible citizens, ensuring access to coverage across all age groups. The NHI offers benefits for various medical services, including inpatient and outpatient care and treatment for severe diseases, although certain exclusions may apply depending on the nature of the treatment or service required [13]. The Korean National Health Insurance System (KNHIS) DB includes data on both NHI-covered individuals and beneficiaries of medical aid programs.

This retrospective cohort study utilized a 5% sample ($n=$ 2,897,075) selected through simple random sampling from the entire population registered since 2002. The follow-up period spanned from 2006, when exposure modeling data became available, to 2019. The DB provided individual-level data [14], including monthly residential address information at the municipality level (250 municipalities; average size: 401 km^2). The KNHIS DB comprises four main parts: an annual or monthly qualification DB, a health insurance claims DB, a mortality DB, and health check-up DB. The qualification DB includes personal details such as personal identification number (PIN), geographical region, sex, age, and insurance fees (a proxy for economic status), and disability type and severity. The mortality DB records the date of death, while the health check-up DB includes clinical examinations and medical history.

The following were excluded from among 2,897,075 persons: death before December 31, 2006 ($n=$ 12,229), transition from PWD to ND ($n=$ 3,491), no information on air pollutant concentration ($n=$ 1,088), and those born before 1900 who were still alive (i.e., aged >120 years; $n=$ 2). Finally, 2,880,265 individuals (41,501,709 person-years [PY]), including 176,410 PWD (2,011,231 PY) and 2,703,855 ND (39,490,478 PY), were included in this study cohort (Fig. 1).

Type and severity of disability

Disability information was obtained from the KNHIS qualification DB. In Korea, the Enforcement Decree of the Act on Welfare of PWD has defined the following 15 disability types in four fields since 2003: impairment in external bodily functions including hearing, visual, physical, speech, and facial functions or brain lesions; impairment in internal organs including epilepsy or kidney, hepatic, or cardiac dysfunction, intestinal/urinary fistula, or respiratory dysfunction; developmental disability including intellectual or autistic disorder; and mental disorders. After the abolition of the grading system for PWD on July 1, 2019, disabilities are now classified as either "severely disabled" or "mild disabled" [15].

Ambient $PM_{2.5}$

Ambient $PM_{2.5}$ data were simulated using models incorporating weather conditions, human-made and natural emissions, and the transport of chemicals [16–19]. The analysis utilized the Community Multiscale Air Quality (CMAQ) system (ver. 5.3.2; https://www.epa.gov/cmaq) with the AERO6 Aerosol Module. Weather simulations

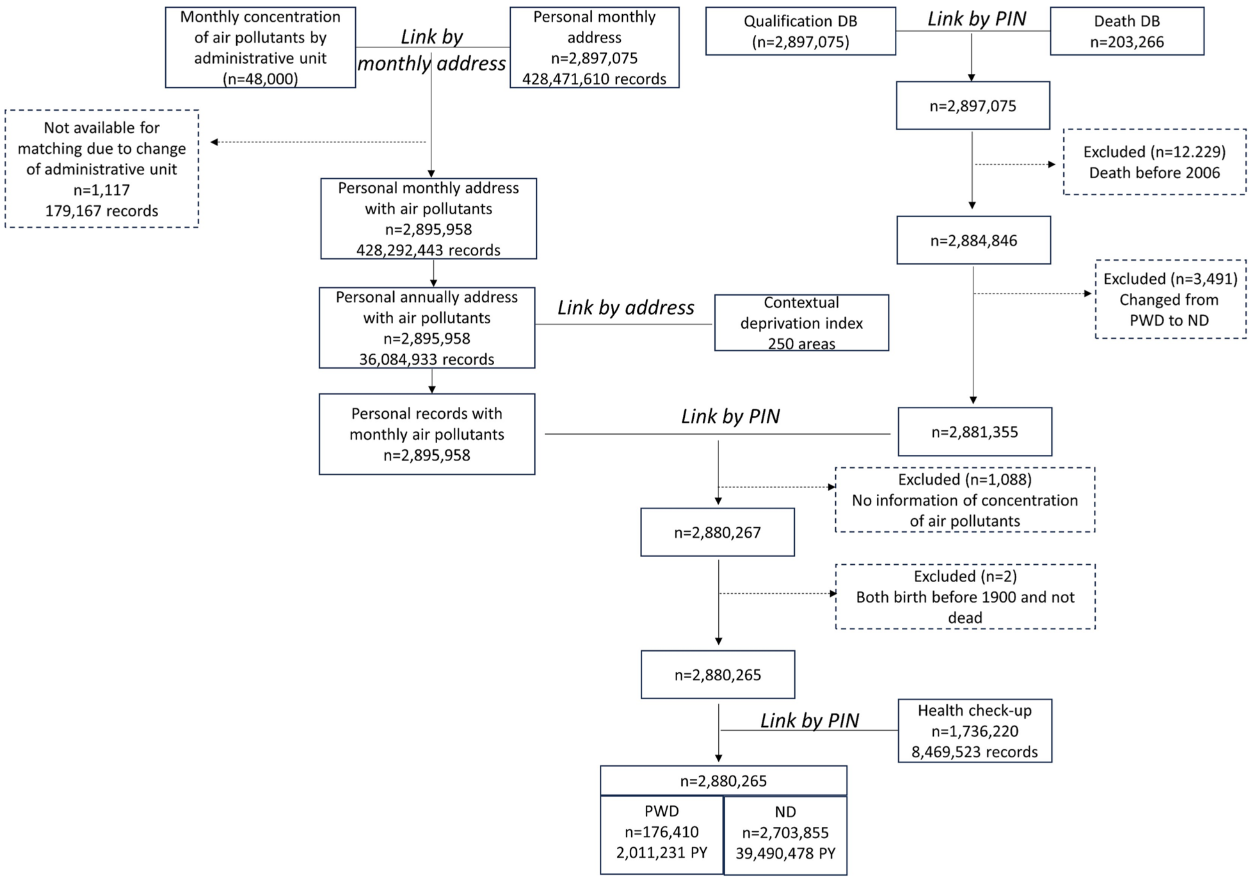

Fig. 1 Participant selection process for 5% sample cohort from the Korean National Health Insurance database

were conducted using the Weather Research and Forecasting model (ver. 4.4). Initial field data were sourced from the National Center for Environmental Protection. CMAQ-ready meteorological data were generated using the Meteorology Interface Processor. The Korean National Emissions Inventory was processed using the Sparse Matrix Operator Kernel Emissions system (ver. 4.8). Estimates of biogenic emissions were generated using the Model of Emissions of Gases and Aerosols from Nature. The CMAQ system provided hourly $PM_{2.5}$ concentration across Korean cities using a 3 ×3 km grid modeling domain, and representative values for each administrative district were calculated using the kriging interpolation method suggested by Son et al. [20]. Daily average $PM_{2.5}$ concentrations for each city were calculated from January 1, 2006, to December 31, 2019. As $PM_{2.5}$ monitoring data have only been available since 2015, we utilized data based on methodologies established in previous studies that extended $PM_{2.5}$ estimates back to 2006 when measurements in Korea were first initiated in Seoul metropolitan city [19]. The entry point for ND was defined as their first appearance in the cohort after 2006. For PWD, the entry point was 2006 for those who acquired their disability before 2006 or the time of acquisition for those who acquired their disability after 2006. We assigned a monthly concentration for each municipality based on their monthly address information and then averaged over the year for individual. For individuals, the average annual concentration was applied to their year of entry.

Mortality and follow-up time

Participants who died before December 31, 2006, were excluded from the analysis. The causes of death were obtained via the death cause DB of Statistics Korea, and then individually linked with KNHIS DB by PIN. The causes of death were coded according to the International Classification of Disease, 10 th version (ICD-10). We classified the causes of death into five types: all causes, non-accidental causes (excluding ICD-10: V01–Y98), respiratory disease (ICD-10: J00–J99), lung cancer (ICD-10: C33–C34), and cardiovascular disease (ICD-10: I00–I99).

Follow-up time was defined as an individual's age at death or censored. Censoring was applied to individuals who were alive during the follow-up period and included cases of health insurance disqualification or the conclusion of the study period (December 31, 2019).

Covariates

Information on age and sex was sourced from the qualification DB. Insurance fees as proxy of economic status were classified into two types: company and local fees. The monthly insurance fee was adjusted by dividing it by the square root of the family members'count. This adjusted fee was then organized into quartiles for each insurance type. Medical aid groups were classified separately. Information on smoking history and history of chronic diseases (hypertension, heart disease, stroke, or diabetes) was obtained from the health check-up DB. The Korean contextual deprivation index was used as a regional variable at the city district level to reflect the contextual effect of the residential area and regional socioeconomic levels in a multidimensional manner [21]. Using the 2015 National Statistical Office Population and Housing Census, six indicators at the individual level and four at the household level were aggregated and calculated for each city district. The six indicators were proportion of adults aged 35–64 years with an education level of below a high school diploma, percentage of female household heads, percentage of divorced and widowed people aged ≥ 15 years, low social class proportion based on the adult head of household aged 15–64 years, unemployment rate for men aged 15–64 years, and proportion of the older population aged ≥ 65 years. The four indicators were the proportion of single-person households, proportion of households without homes, proportion of households without cars, and proportion of households residing in housing options other than apartments. The 10 indicators were converted to z-scores using a standard normal distribution, and the values were added to calculate the total score. A higher score indicated a lower socioeconomic level in the region [21].

Statistical analysis

Differences in the general characteristics between PWD and ND or severe and mild groups were evaluated using the t-test or chi-square test. To assess the differences in general characteristics among ND individuals, those with mild disabilities, and those with severe disabilities, analysis of variance or the chi-square test was employed. Hazard ratios (HRs) and 95% confidence intervals (CIs) for mortality on increasing $PM_{2.5}$ by 10 μg/m^3 were calculated using the Cox proportional hazard model adjusted for age, sex, insurance fee, smoking history, chronic disease status, and contextual deprivation index, with strata for entry year and province. The data were stratified by the presence, type, and severity of the disability, and separate models were fitted. To compare the differences in the mortality effects of $PM_{2.5}$ across age groups (< 65 years, ≥ 65 years), the Z-test was performed using the beta coefficients and standard errors for each subgroup.

Results

Table 1 shows the distribution of the general characteristics according to the disability and its severity. PWD accounted for 6.1% of the study sample. The annual proportion of PWD was like that reported in formal Korean statistics (online Additional file 1). The PWD cohort included men, older patients, patients in medical aid group, participants of health check-ups, patients with smoking history, and patients with chronic diseases. The proportions of men and history of stroke were higher in the severely disabled subgroup than in the mildly disabled subgroup.

Figure 2 illustrates the distribution of $PM_{2.5}$, by disability, entry year, and type of disability. The concentration was higher in the ND group than in the PWD group until 2010.

Figure 3–1 illustrates the HR and 95% CI of $PM_{2.5}$ (per increment of 10 μg/m^3) for mortality by disability and severity. The effect of $PM_{2.5}$ on cardiovascular mortality was significantly increased in PWD, whereas it was not significant in ND (PWD: 1.08, 95% CI: 1.030–1.151, ND: 0.982, 95% CI: 0.948–1.017). In the severely disabled subgroup, the HRs for mortality of increasing $PM_{2.5}$ concentration were significantly increased for all causes (1.133, 95% CI: 1.028–1.248), non-accidental (1.148, 95% CI: 1.038–1.269), and cardiovascular diseases (1.109, 95% CI: 1.032–1.191), whereas those for respiratory mortality were significantly decreased. The detailed results are presented in online Additional files 2 and 3.

Figure 3–2 illustrates the HR and 95% CI of $PM_{2.5}$ (per increment of 10 μg/m^3) for mortality by disability type. The HRs were statistically increased for mortality from all causes (1.786, 95% CI: 1.265–2.520) and non-accidental cause (1.847, 95% CI: 1.301–2.624) in PWD with kidney impairment by increasing $PM_{2.5}$ concentration. The HR for cardiovascular disease was significantly increased among PWD with brain lesions by increasing $PM_{2.5}$ concentration (1.104, 95% CI: 1.003–1.216). However, the HR for non-accidental mortality in PWD with visual impairment and respiratory mortality in PWD with brain lesions indicated inverse associations by increasing $PM_{2.5}$ concentration. The detailed results are presented in online Additional files 2 and 4.

Among PWD with external impairments, the HR for mortality of $PM_{2.5}$ (per 10 μg/m^3 increment) was significantly increased for cardiovascular disease (HR: 1.089, 95% CI: 1.028–1.155). In contrast, for respiratory disease, the HR for mortality was significantly decreased

Table 1 General characteristics by disability and severity in 5% sample cohort using KNHIS database, 2006–2019

	All		ND		PWD								
					All		Mild		Severe				
	N	%	N	%	N	%	N	%	N	%	*p*-value[a]	*p*-value[b]	*p*-value[c]
All	2,880,265	100	2,703,855	93.9	176,410	6.1	108,028	3.8	68,382	2.4			
Follow-up time (years), Mean (SD)	14.4	(3.5)	14.6	(3.3)	11.4	(5.0)	11.6	(4.9)	11.1	(5.2)	< 0.0001	< 0.0001	< 0.0001
Follow-up time (years), Median (min–max)	16.0	(1–16)	16.0	(1–16)	13.0	(1–16)	13.0	(1–16)	13.0	(1–16)			
Person-years	41,501,709		39,490,478		2,011,231		1,251,398		759,833				
Gender											< 0.0001	< 0.0001	< 0.0001
Male	1,456,397	50.6	1,353,183	50.0	103,214	58.5	62,027	57.4	41,187	60.2			
Female	1,423,868	49.4	1,350,672	50.0	73,196	41.5	46,001	42.6	27,195	39.8			
Age at entry year (years), Mean (SD)	32.2	(21.8)	30.7	(21.1)	55.4	(18.9)	58.6	(16.4)	50.4	(21.5)	< 0.0001	< 0.0001	< 0.0001
Age at entry year (years)											< 0.0001	< 0.0001	< 0.0001
0–9	559,552	19.4	554,748	20.5	4804	2.7	907	0.8	3897	5.7			
10–19	342,219	11.9	336,873	12.5	5346	3.0	995	0.9	4351	6.4			
20–29	424,578	14.7	416,806	15.4	7772	4.4	3583	3.3	4189	6.1			
30–39	470,472	16.3	455,641	16.9	14,831	8.4	8204	7.6	6627	9.7			
40–49	442,340	15.4	415,076	15.4	27,264	15.5	16,407	15.2	10,857	15.9			
50–59	295,326	10.3	261,489	9.7	33,837	19.2	21,891	20.3	11,946	17.5			
60–69	192,089	6.7	153,798	5.7	38,291	21.7	25,939	24.0	12,352	18.1			
70–79	111,350	3.9	79,773	3.0	31,577	17.9	21,281	19.7	10,296	15.1			
80 +	42,339	1.5	29,651	1.1	12,688	7.2	8821	8.2	3867	5.7			
Entry year											< 0.0001	< 0.0001	< 0.0001
2006	2,395,503	83.2	2,297,823	85.0	97,680	55.4	54,999	50.9	42,681	62.4			
2007	44,811	1.6	34,330	1.3	10,481	5.9	7020	6.5	3461	5.1			
2008	43,988	1.5	33,525	1.2	10,463	5.9	7122	6.6	3341	4.9			
2009	42,015	1.5	31,023	1.1	10,992	6.2	7683	7.1	3309	4.8			
2010	39,334	1.4	32,684	1.2	6650	3.8	4841	4.5	1809	2.6			
2011	38,357	1.3	34,255	1.3	4102	2.3	2569	2.4	1533	2.2			
2012	37,660	1.3	34,093	1.3	3567	2.0	2092	1.9	1475	2.2			
2013	34,745	1.2	31,393	1.2	3352	1.9	1884	1.7	1468	2.1			
2014	35,225	1.2	31,838	1.2	3387	1.9	1878	1.7	1509	2.2			
2015	35,503	1.2	31,496	1.2	4007	2.3	2200	2.0	1807	2.6			
2016	34,646	1.2	29,842	1.1	4804	2.7	3053	2.8	1751	2.6			
2017	31,795	1.1	26,424	1.0	5371	3.0	3571	3.3	1800	2.6			
2018	31,748	1.1	25,791	1.0	5957	3.4	4205	3.9	1752	2.6			
2019	34,935	1.2	29,338	1.1	5597	3.2	4911	4.5	686	1.0			

Table 1 (continued)

	All		ND		PWD								
					All		Mild		Severe				
	N	%	N	%	N	%	N	%	N	%	*p*-value[a]	*p*-value[b]	*p*-value[c]
Type and grade of Insurance fee[d]											< 0.0001	< 0.0001	< 0.0001
Medical aid	90,144	3.1	63,743	2.4	26,401	15.0	9872	9.1	16,529	24.2			
Local Q1	282,913	9.8	264,588	9.8	18,325	10.4	11,773	10.9	6552	9.6			
Local Q2	284,576	9.9	271,987	10.1	12,589	7.1	7702	7.1	4887	7.1			
Local Q3	275,211	9.6	264,094	9.8	11,117	6.3	6871	6.4	4246	6.2			
Local Q4	280,327	9.7	261,336	9.7	18,991	10.8	12,615	11.7	6376	9.3			
Company Q1	456,358	15.8	433,530	16.0	22,828	12.9	14,684	13.6	8144	11.9			
Company Q2	402,069	14.0	382,419	14.1	19,650	11.1	12,756	11.8	6894	10.1			
Company Q3	403,007	14.0	382,892	14.2	20,115	11.4	13,335	12.3	6780	9.9			
Company Q4	405,660	14.1	379,266	14.0	26,394	15.0	18,420	17.1	7974	11.7			
Contextual deprivation index											< 0.0001	< 0.0001	< 0.0001
T1	966,298	33.5	894,063	33.1	72,235	40.9	44,400	41.1	27,835	40.7			
T2	971,775	33.7	914,698	33.8	57,077	32.4	34,923	32.3	22,154	32.4			
T3	942,192	32.7	895,094	33.1	47,098	26.7	28,705	26.6	18,393	26.9			
Contextual deprivation index, Mean (SD)	155.3	(61.2)	156.2	(60.9)	143.0	(64.4)	142.7	(64.6)	143.6	(64.2)	< 0.0001	< 0.0001	< 0.0001
Health check-up											< 0.0001	< 0.0001	< 0.0001
No	1,147,095	39.8	1,095,770	40.5	51,325	29.1	20,623	19.1	30,702	44.9			
Yes	1,733,170	60.2	1,608,085	59.5	125,085	70.9	87,405	80.9	37,680	55.1			
Health behaviors among health check-up													
Smoking history											< 0.0001	< 0.0001	< 0.0001
No	974,760	56.2	909,136	56.5	65,624	52.5	44,526	50.9	21,098	56.0			
Yes	754,912	43.6	696,051	43.3	58,861	47.1	42,575	48.7	16,286	43.2			
Unknown	3498	0.2	2898	0.2	600	0.5	304	0.3	296	0.8			
History of alcohol intake											< 0.0001	< 0.0001	< 0.0001
No	709,787	41.0	640,097	39.8	69,690	55.7	45,381	51.9	24,309	64.5			
Yes	1,020,010	58.9	965,200	60.0	54,810	43.8	41,726	47.7	13,084	34.7			
Unknown	3373	0.2	2788	0.2	585	0.5	298	0.3	287	0.8			
Physical activity											< 0.0001	< 0.0001	< 0.0001
No	338,794	19.5	302,971	18.8	35,823	28.6	21,672	24.8	14,151	37.6			
Yes	1,390,877	80.3	1,302,226	81.0	88,651	70.9	65,415	74.8	23,236	61.7			
Unknown	3499	0.2	2888	0.2	611	0.5	318	0.4	293	0.8			

Table 1 (continued)

	All		ND		PWD								
					All		Mild		Severe				
	N	%	N	%	N	%	N	%	N	%	*p*-value[a]	*p*-value[b]	*p*-value[c]
History of chronic disease											< 0.0001	< 0.0001	< 0.0001
No	998,511	57.6	957,825	59.6	40,686	32.5	28,399	32.5	12,287	32.6			
Yes	526,895	30.4	455,138	28.3	71,757	57.4	51,288	58.7	20,469	54.3			
Unknown	207,764	12.0	195,122	12.1	12,642	10.1	7718	8.8	4924	13.1			
History of hypertension (yes)	428,089	24.7	369,313	23.0	58,776	47.0	42,620	48.8	16,156	42.9	< 0.0001	< 0.0001	< 0.0001
History of heart disease (yes)	77,417	4.5	64,192	4.0	13,225	10.6	9642	11.0	3583	9.5	< 0.0001	< 0.0001	< 0.0001
History of stroke (yes)	40,301	2.3	28,342	1.8	11,959	9.6	6871	7.9	5088	13.5	< 0.0001	< 0.0001	< 0.0001
History of diabetes (yes)	181,913	10.5	153,974	9.6	27,939	22.3	19,595	22.4	8344	22.1	< 0.0001	< 0.0001	< 0.0001
Type of disability													< 0.0001
Physical	–	–	–	–	80,698	45.7	63,425	58.7	17,273	25.3			
Brain lesion	–	–	–	–	21,941	12.4	7058	6.5	14,883	21.8			
Visual	–	–	–	–	17,134	9.7	14,003	13.0	3131	4.6			
Hearing	–	–	–	–	24,103	13.7	18,565	17.2	5538	8.1			
Speech	–	–	–	–	1565	0.9	779	0.7	786	1.1			
Intellectual	–	–	–	–	11,277	6.4	194	0.2	11,083	16.2			
Autistic	–	–	–	–	1281	0.7	45	0.0	1236	1.8			
Mental	–	–	–	–	5584	3.2	82	0.1	5502	8.0			
Kidney	–	–	–	–	6907	3.9	925	0.9	5982	8.7			
Cardiac	–	–	–	–	732	0.4	47	0.0	685	1.0			
Respiratory	–	–	–	–	1490	0.8	43	0.0	1447	2.1			
Hepatic	–	–	–	–	1147	0.7	670	0.6	477	0.7			
Facial	–	–	–	–	185	0.1	116	0.1	69	0.1			
Intestinal/Urinary	–	–	–	–	1794	1.0	1702	1.6	92	0.1			
Epilepsy	–	–	–	–	572	0.3	374	0.3	198	0.3			

ND Non-Disabled, *PWD* Person with Disability, *SD* Standard deviation

p-value estimated using t-test, analysis of variance, or chi-square test

[a] difference between non-disabled and disabled

[b] difference among non-disabled, mild, and severe disabled

[c] difference between mild and severe disabled among disabled

[d] insurance fee per month/sqrt (number of family member)

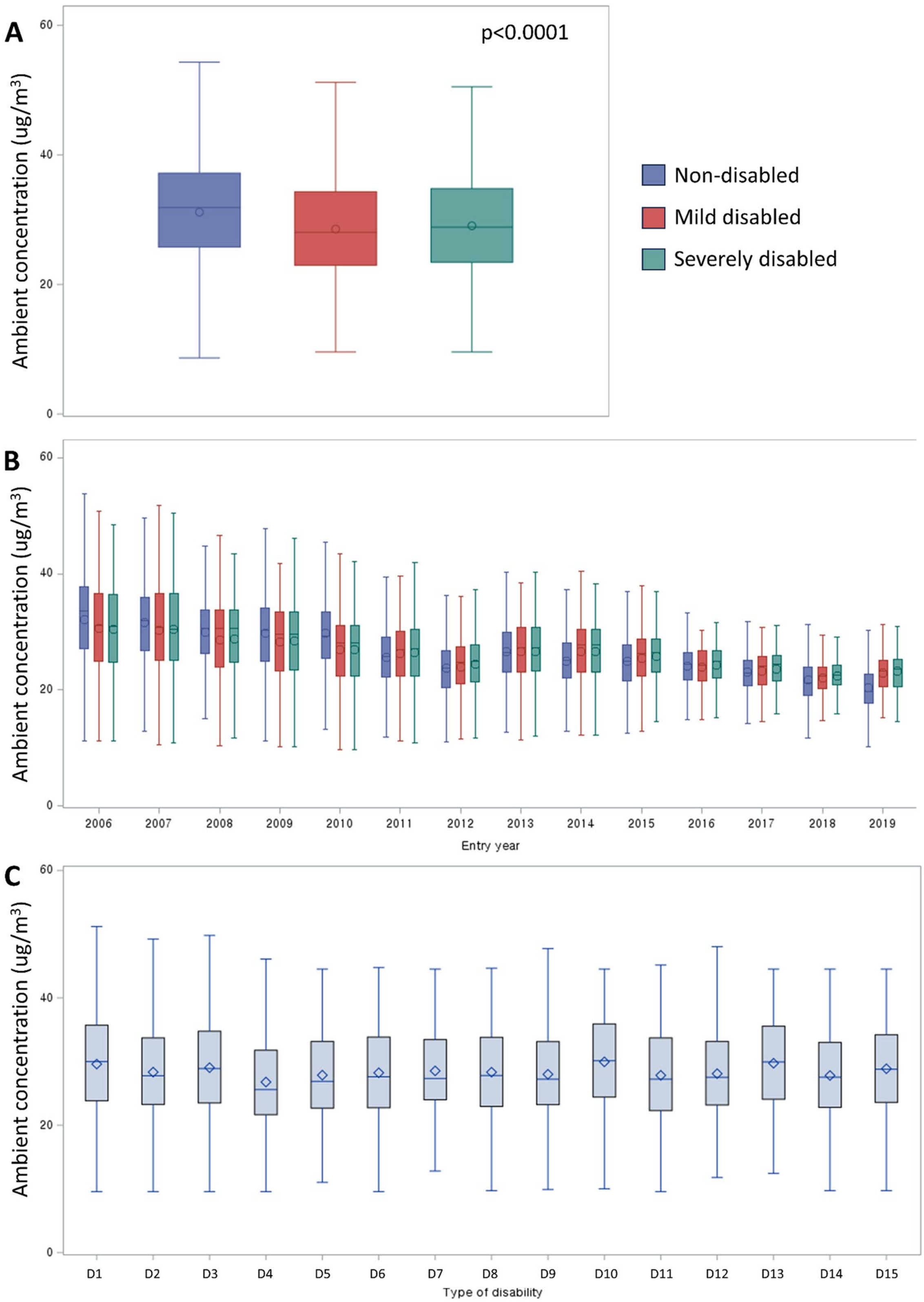

Fig. 2 Distribution of ambient fine particulate matter ($PM_{2.5}$) concentration by disability in the 5% sample cohort in Korea. **A**: severity; (**B**): entry year; (**C**): type of disability. D1: physical; D2: brain lesion; D3: visual; D4: hearing; D5: speech; D6: intellectual; D7: autistic; D8: mental; D9: kidney; D10: cardiac; D11: respiratory; D12: hepatic; D13: facial; D14: intestinal or urinary fistula; D15: epilepsy

by increasing $PM_{2.5}$ concentration (HR: 0.861, 95% CI: 0.785–0.945) (Fig. 3–3). The detailed results are presented in online Additional files 2 and 5.

Figure 4 illustrates the HR and 95% CI of $PM_{2.5}$ (per increment of 10 $\mu g/m^3$) for mortality by disability and severity stratified by age group. The HR for non-accidental mortality by increasing $PM_{2.5}$ concentration was statistically increased in severely disabled aged <65 years (1.070, 95% CI: 1.004–1.140) and that for cardiovascular disease mortality was statistically increased in severely disabled aged ≥65 years (1.128, 95% CI: 1.035–1.229). However, respiratory disease mortality by increasing $PM_{2.5}$ concentration was significantly decreased in PWD of both the age groups. The differences in the mortality effects of $PM_{2.5}$ across the age groups were not statistically significant in any subgroup. Detailed results are presented in online Additional files 2 and 6.

Discussion

This study showed that exposure to ambient $PM_{2.5}$ was linked to increased mortality from all causes, non-accidental causes, and cardiovascular diseases, especially among individuals with severe disabilities. Furthermore, individuals with kidney impairment and brain lesions with disabilities had a high mortality risk. However, exposure to ambient $PM_{2.5}$ had inverse associations with respiratory mortality in individuals with disabilities.

In this study, PWD were found to have a high risk of mortality associated with $PM_{2.5}$ than those without disabilities. While some previous studies focused on the association between PM and hospital admission, very few have delved into the specific association between $PM_{2.5}$ and mortality in PWD. Our results are similar to those of previous studies in this field. One study found that Medicaid enrollees with low socioeconomic status and disabilities had a higher risk of hospital admissions due to cardiovascular diseases from short-term exposure to $PM_{2.5}$ than non-Medicaid-eligible Medicare enrollees [8]. Another study found that PWD had a higher risk of hospital admission for cardiovascular issues due to short-term exposure to PM_{10} than those without disabilities [9].

Our research further indicates that individuals with severe disabilities have a higher mortality risk than those with mild disabilities. One study showed that an increase in residential greenness, which mediates the reduction in air pollution, significantly decreased the total mortality impact. This protective effect was high for people with mild disabilities than for those with severe disabilities, supporting our findings [10]. Furthermore, another study reported that people with severe disabilities had a higher risk of hospital admission for cardiovascular issues due to short-term exposure to PM_{10} than those with mild disabilities [9].

This study found that individuals with disabilities involving kidney impairment and brain lesions had a high risk of mortality associated with increasing $PM_{2.5}$. A previous Korean study showed that individuals with brain lesions had a high risk of hospital admission for cardiovascular issues due to PM exposure than those with other types of disabilities [9], although the risk for those with kidney impairment was not evaluated separately. They employed a cohort of one million samples from the KNHIS and utilized a case–crossover design to assess the short-term effect of PM_{10} exposure on the hospital admission rate, which is different from the method used in our study. The study did not evaluate the effects of disability type in detail; individuals with specific types of disabilities may be more vulnerable to $PM_{2.5}$ and further research is needed to determine the underlying reasons.

This study also observed an inverse association between $PM_{2.5}$ and respiratory disease mortality. Previous studies have reported controversial results; some studies reported a high risk of respiratory mortality associated with $PM_{2.5}$, whereas others did not. One study analyzing the Canadian Census Health and Environment Cohort reported a significantly negative association between $PM_{2.5}$ and respiratory mortality, with negative and null findings for chronic obstructive pulmonary disease (COPD) mortality [22]. Another study reported an unexpected inverse association between $PM_{2.5}$ and mortality from respiratory disease and COPD [23]. Other studies have reported a negative and null association between $PM_{2.5}$ and respiratory disease or COPD mortality [24–26]. Studies conducted in Korea have reported a significant negative association between PM_{10} and respiratory mortality [27, 28]. We suggest several possible

(See figure on next page.)

Fig. 3 HRs and 95% CI of fine particulate matter for mortality by disability, disability type, and disability severity. **A**: All causes; (**B**): non-accidental cause; (**C**): respiratory disease (J00-J99); (**D**): lung cancer (C33-C34); (**E**): cardiovascular disease (I00-I99). Cox proportional hazard model adjusted for sex, age, level of insurance fee, smoking history, having chronic disease, and contextual deprivation index. ND, non-disabled; PWD, people with disability. The disability type was classified by Korean law: D1, physical; D2, brain lesion; D3, visual; D4, hearing; D5, speech; D6, intellectual; D7, autistic; D8, mental; D9, kidney; D10, cardiac; D11, respiratory; D12, hepatic; D13, facial; D14, intestinal or urinary fistula; D15, epilepsy. External: impairment in external bodily functions includes hearing, visual, physical, speech, facial, or brain lesion. Internal: Disability in internal organs includes epilepsy, kidney, hepatic, or cardiac dysfunction, intestinal or urinary fistula, or respiratory dysfunction. Developmental: Developmental disability includes intellectual or autistic disorder. If HR is not available to estimate, it is not shown in the graph

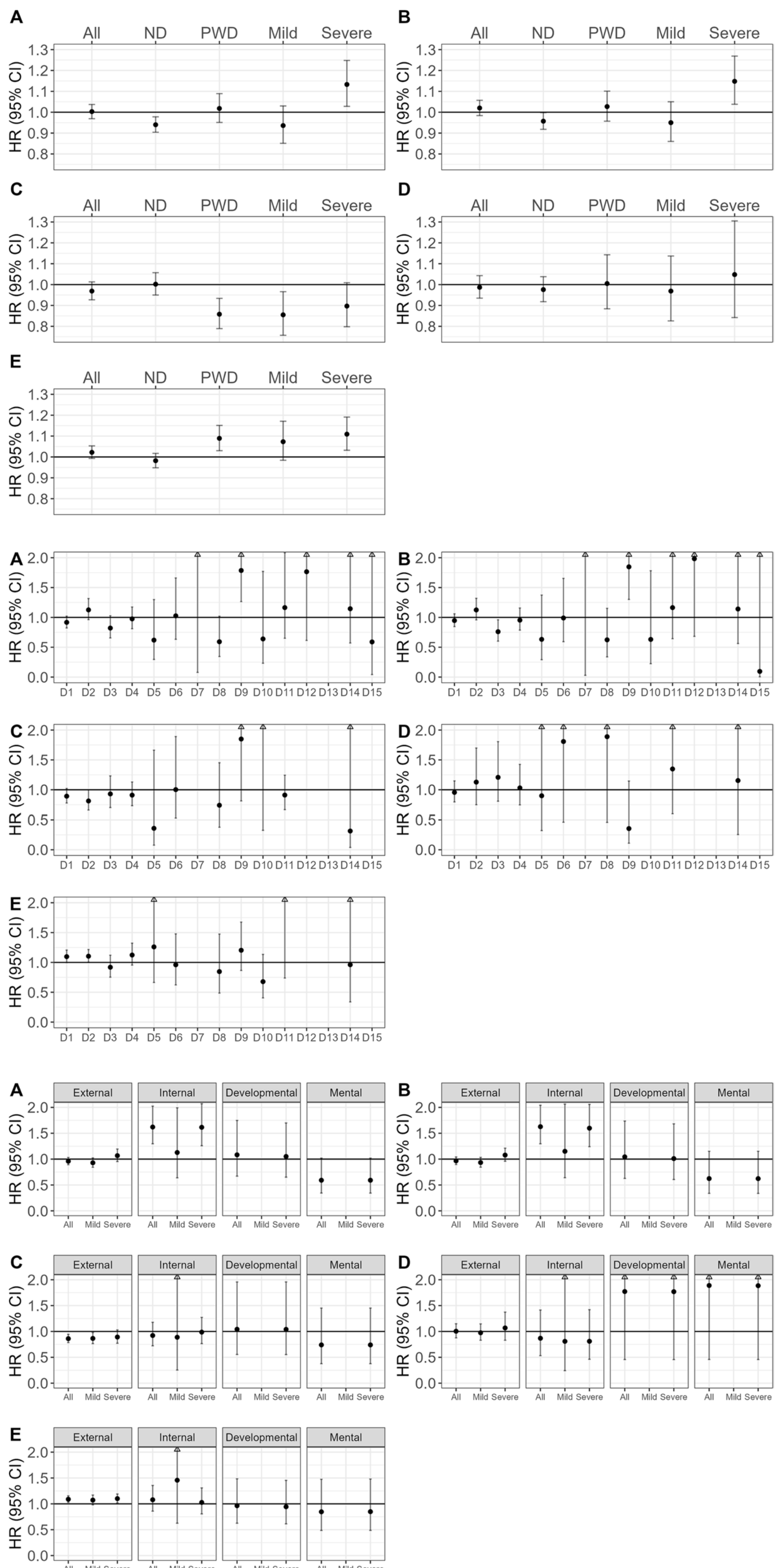

Fig. 3 (See legend on previous page.)

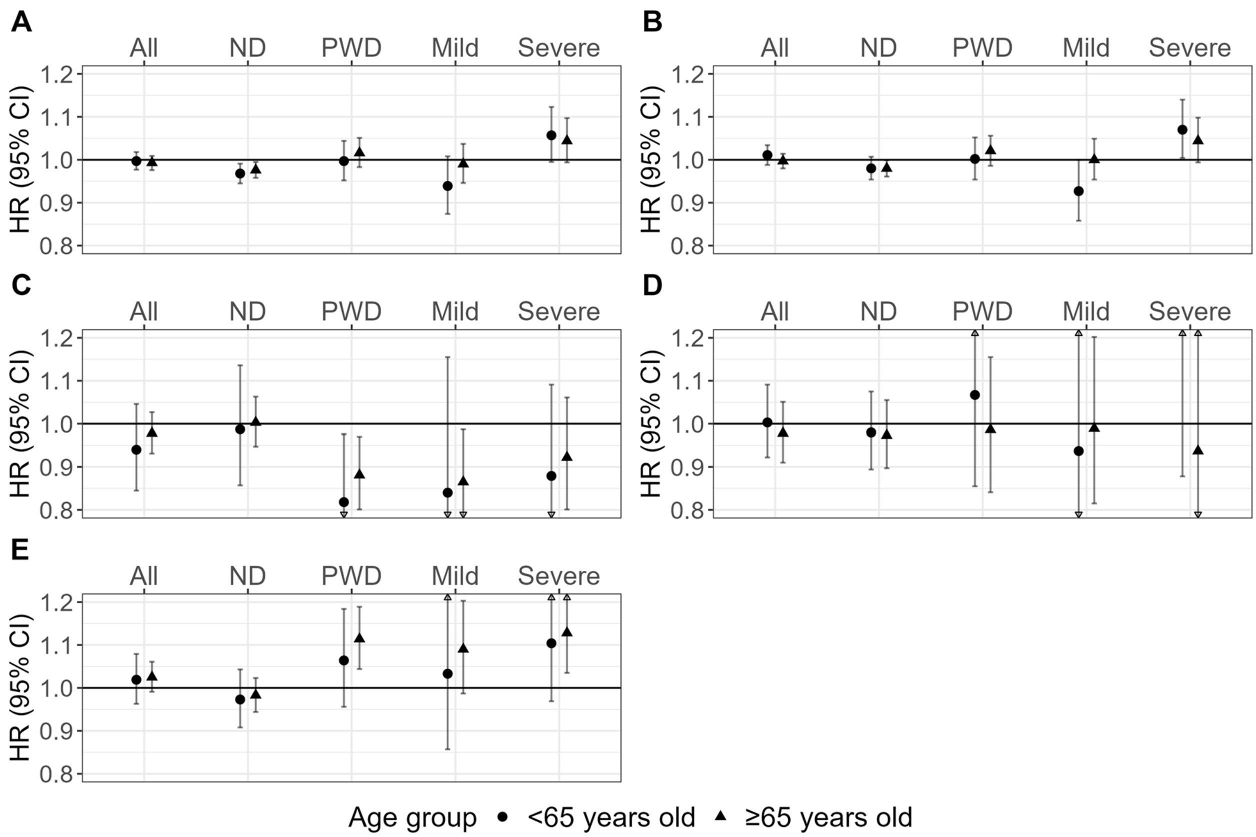

Fig. 4 HRs and 95% CI of fine particulate matter for mortality by disability type and severity in disabled persons, stratified by age. **A**: All causes; (**B**): non-accidental cause; (**C**): respiratory disease (J00-J99); (**D**): lung cancer (C33-C34); (**E**): cardiovascular disease (I00-I99). Cox proportional hazard model was adjusted for sex, age, level of insurance fee, smoking history, having chronic disease, and contextual deprivation index

reasons for the inconsistent data on the association between PM exposure and respiratory diseases. First, a complex interplay exists among socioeconomic status, PM, and health. High socioeconomic status is often correlated with living in urbanized areas with high PM exposure. This correlation can confound the association between PM exposure and health outcomes, particularly in countries like Korea, where urban concentrations are high. A study reported that the association between $PM_{2.5}$, respiratory disease, and COPD mortality was null in an unadjusted model but became significant after the model was adjusted for socioeconomic and behavioral covariates [29]. To solve this problem, we adjusted our model for individual socioeconomic status and the area deprivation index; however, residual confounding may still exist. Second, patients with worsened COPD progression due to PM are likely to die from cardiovascular diseases, presenting a competing risk that could mislead the association between PM and respiratory mortality [23]. Third, oxidant gases, such as ozone or nitrogen dioxide could alter the relationship between $PM_{2.5}$ and respiratory mortality, as increases in the levels of these gases enhance lung epithelium permeability, potentially intensifying the harmful effects of $PM_{2.5}$. Threshold levels of oxidant gas concentrations may weaken the association between $PM_{2.5}$ and respiratory mortality, necessitating further research in this regard [30]. Fourth, factors such as inaccuracies in exposure measurements, chemical composition differences in $PM_{2.5}$, the complex association between ambient and indoor air pollution and bioaerosol pollutants, individual health and underlying conditions, genetic predispositions, the effects of medications, protective behaviors, and adaptive responses of individuals continuously exposed to high levels of air pollution could blur the association, leading to inconsistent findings [31, 32]. Further research using in-depth information on these factors is needed to clarify the complex association between PM and respiratory health effects.

Our findings highlight that the effect of $PM_{2.5}$ on mortality among people with severe disabilities was statistically significant for non-accidental causes in individuals aged < 65 years and for cardiovascular disease mortality in those aged > 65 years. Owing to the scarcity of research on PWD, the observed age-based differences are challenging to explain; however, several reasons could contribute to this. Younger individuals generally have a lower baseline mortality risk but may be exposed to PM to a greater extent because of their tendency to breathe through their mouths and engage in outdoor activities [33]; their immature immune systems [34], combined with various predisposing factors, lower socioeconomic status, and reduced access to healthcare in PWD, may worsen their susceptibility. Further research is required to understand the susceptibility factors and identify specific diseases to which young individuals with disabilities are susceptible. Exposure to $PM_{2.5}$ is linked to several cardiovascular risk factors including hypertension, type 2 diabetes, obesity, dyslipidemia, intimal–medial thickness, atherosclerosis, and coronary artery calcification. Older individuals who are likely to have chronic conditions may be vulnerable to mortality triggered by these cardiovascular disease risk factors [35–38].

$PM_{2.5}$ exposure can increase the health risks in PWD via several potential mechanisms. Some disabilities may limit a person's mobility or confine them to environments with poor air quality, such as poorly ventilated homes or facilities. Reduced mobility can lead to prolonged exposure to $PM_{2.5}$, increasing the risk of adverse health effects. Individuals with disabilities are more likely to experience poverty and social exclusion, which leads to poor health outcomes. Additionally, chronic stress and psychological conditions, which may be more prevalent among populations with disabilities, can worsen the health impacts of $PM_{2.5}$. The evidence presented in previous studies have suggested that psychological stress activates inflammatory responses [39, 40]. Additionally, $PM_{2.5}$ can lead to systemic inflammation and trigger sympathetic activation within the cardiovascular system [41]. Stress can increase an individual's susceptibility to the harmful effects of $PM_{2.5}$ due to its potential to worsen stress-induced inflammatory processes.

This study's strength lies in its adjustment for socioeconomic levels in the statistical model at both individual and regional levels, using insurance fees and the regional deprivation index, respectively. As Korea has higher $PM_{2.5}$ concentrations in areas with better socioeconomic levels, it can act as a serious confounding variable. Therefore, the model was designed to account for this. Furthermore, this study benefits from the ability to adjust for various individual health behaviors and medical histories by utilizing health checkup data from KNHIS. To the best of our knowledge, this study is the first in Korea to analyze the mortality effects of long-term exposure to $PM_{2.5}$ while considering disability types in detail. The results provide valuable data for the development of healthcare policies for individuals with disabilities.

This study had some limitations. First, as we used regional $PM_{2.5}$, there may be errors in the actual $PM_{2.5}$ exposure of individuals. However, we attempted to minimize this error by assigning $PM_{2.5}$, considering personal addresses monthly. Additionally, we utilized a 3 ×3 km grid exposure model, which may introduce uncertainties due to resolution limitations. To enhance the accuracy of exposure, we used the kriging interpolation method. It is necessary to assess changes in health effect estimates when exposure accuracy is potentially improved through methods such as land-use regression [42]. Previous studies have reported that the performance of exposure models can either remain consistent or vary depending on resolution [43], and resolution may also influence the direction and magnitude of exposure bias, particularly in highly populated areas [43]. Meanwhile, such errors may include Berkson errors, which are less likely to significantly affect risk estimates [44]. Therefore, future research is needed to examine how health impact estimates vary with different resolutions. Second, the results are not fully generalizable because we used 2006 as the year of initial entry and analyzed $PM_{2.5}$ exposure in that year. Further research is required to determine the health effects of long-term $PM_{2.5}$ exposure in individuals with disabilities that occur over multiple periods. Specifically, it should address these limitations by studying the changes in the definition of long-term exposure in PWD and by advancing the Cox proportional hazard model with time-varying exposure. Third, disabilities can develop in individuals with pre-existing chronic diseases [45]. In this study, we did not account for a washout period for chronic diseases but adjusted for chronic diseases in the model. The immortal time, which refers to the period between the onset of a chronic disease and the occurrence of a disability, may influence the vulnerability of PWD. However, the relationship between pre-existing conditions and disabilities does not weaken the implication that we should strengthen efforts to manage the vulnerabilities of PWD. We also stratified disability type and severity to overcome these limitations. Future research should focus on differentiating the contribution of pre-existing conditions and the subsequent development of disabilities to the vulnerability of PWD. Fourth, other air pollutants such as ozone or nitrogen dioxide may confound the effects of $PM_{2.5}$ [46]. Although this study did not account for these factors, future research should consider analyses using multi-pollutant models.

Conclusion

This study implies that PWD, especially those with severe disabilities or specific impairments such as kidney problems or brain lesions, exhibit high mortality risks except for respiratory diseases due to $PM_{2.5}$ exposure. Therefore, system interventions are suggested, such as improving air quality standards and developing targeted healthcare approaches based on disability type and severity of the increased vulnerability of PWD to air pollution.

Abbreviations

CI	Confidence intervals
CMAQ	Community Multiscale Air Quality
COPD	Chronic obstructive pulmonary disease
DB	Database
HR	Hazard ratios
ICD-10	International Classification of Disease, 10th version
KNHIS	Korean National Health Insurance System
ND	Non-disabled
PIN	Personal identification number
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter
PWD	People with disabilities
PY	Person-years

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-22923-w.

Additional file 1. Comparison between participants and total Korean population by disability.

Additional file 2. Number of deaths by cause of death and disability type.

Additional file 3. Hazard ratio (HR) and 95% confidence intervals (CI) of fine particulate matter (per 10 μg/m^3) for mortality by disability and severity among 5% sample cohort in Korea using National Health Insurance Database, 2006-2019 – Figure 3-1.

Additional file 4. Hazard ratio (HR) and 95% confidence intervals (CI) of fine particulate matter (per 10 μg/m^3) for mortality by disability type among disabled from the 5% sample cohort in Korea using National Health Insurance Database, 2006-2019 – Figure 3-2.

Additional file 5. Hazard ratio (HR) and 95% confidence intervals (CI) of fine particulate matter (per 10 μg/m^3) for mortality by disability type and severity among disabled from the 5% sample cohort in Korea using National Health Insurance Database, 2006-2019 – Figure 3-3.

Additional file 6. Hazard ratio (HR) and 95% confidence intervals (CI) of fine particulate matter (per 10 μg/m^3) for mortality by disability type and severity among disabled stratified with age group from the 5% sample cohort in Korea using National Health Insurance Database, 2006-2019 – Figure 4.

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Authors' contributions

JC—data curation, software, visualization, writing (original draft), writing (review and editing). HL—data curation, data interpretation, writing (review and editing). HJK—data collection, data interpretation, writing (review and editing). MH—data interpretation, writing (review and editing). SK—data collection, writing (review and editing). KHC—conceptualization, study design, funding acquisition, methodology, formal analysis, software, supervision, project administration, literature review, data interpretation, writing (original draft), writing (review and editing). All authors had final responsibility for the decision to submit for publication. KHC had final responsibility for submission and is the guarantor. All authors reviewed the manuscript.

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Data availability

The mortality data for NDs and PWD can be obtained from the KNHIS DB at [https://nhiss.nhis.or.kr/bd/ab/bdaba021eng.do] and MicroData Integrated Service (MDIS) of Statistics Korea at [https://mdis.kostat.go.kr/eng/index.do;jsessionid=xE2MQqswZ8GURLn21zZjuCvWiiepxG2 tEHA4BF6 JyulkCzBQzqz5Dn-vgFcuOQ2pq.mdexwas2_servlet_engine2]. For using the KNHIS DB, there is a need for reasonable requests, IRB admission, and permission from KNHIS and it is protected by strict confidentiality. For using the MDIS data, there is a need for reasonable requests, IRB admission, and permission from Statistics Korea and it is protected by strict confidentiality. The PM2.5 modeling data is not available to the public due to the results of an ongoing project.

Declarations

Ethical approval and consent to participate

The study protocol was approved by the Institutional Review Board (IRB) of Dankook University (IRB NO. DKU 2023–04-004–004). We confirmed that all methods were carried out according to relevant guidelines and regulations. This study was conducted using secondary data; the need for informed consent was waived by the IRB of Dankook University (IRB NO. DKU 2023–04-004–004).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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