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The effects of fine and coarse particulate matter on lung function among the elderly

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Impaired lung function is associated with morbidity and mortality in the elderly. However, there is a paucity of data regarding the long-term effects of particulate matter (PM) on lung function among the elderly. This study evaluated the exposure-response relationship between ambient PM and different lung function indices among the elderly in Taiwan. A cross-sectional survey of individuals aged $\geq$65 years was conducted in Taiwan from October 2015 to September 2016. Those who attended the annual health examination for the elderly in five hospitals of varying background PM concentrations were enrolled. The long-term (2015 annual mean concentration) exposure to air pollution was estimated by the Kriging method at the residence of each subject. The association between ambient PM exposure and lung function was evaluated by linear regression modeling, with adjustments for age, sex, height, weight, educational attainment, presence of asthma or chronic obstructive pulmonary disease, smoking status, season, and co-pollutants. There were 1241 subjects (mean age, 70.5 years). The mean residential PM$_{2.5}$ and PM$_{2.5-10}$ in 2015 was 26.02 and 18.01 µg/m^3, respectively. After adjustments for confounders and co-pollutants, the FVC decrease was best associated with fine particles (PM$_{2.5}$), whereas the FEV$_1$, FEF$_{25-75\%}$, FEF$_{25\%}$ and FEF$_{50\%}$ decreases were best associated with coarse particles (PM$_{2.5-10}$). An IQR (10 µg/m^3) increase in PM$_{2.5}$ decreased FVC by 106.38 ml (4.47%), while an IQR (7.29 µg/m^3) increase in PM$_{2.5-10}$ decreased FEV$_1$ and FEF$_{25-75\%}$ by 91.23 ml (4.85%) and 104.44 ml/s (5.58%), respectively. Among the Taiwanese elderly, long-term PM$_{2.5}$ exposure mainly decreases the vital capacity of lung function. Moreover, PM$_{2.5-10}$ has a stronger negative effect on the function of conductive airways than PM$_{2.5}$.

Lung function is a known predictor of mortality risk. Large follow-up studies in adults have provided evidences that lower baseline force vital capacity (FVC) and forced expiratory volume in one second (FEV$_1$) are associated with higher all-cause mortality risk[1,2]. While there is substantial evidence on the short- and long-term effects of ambient air pollution on lung function in children and adults[3,4], few studies have focused on the long-term effects of air pollution on lung function among the elderly, a vulnerable population. Previous research conducted in low

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polluted areas (10.8 μg/m^3 of annual average $PM_{2.5}$) reveals a exposure-response relationship between long-term $PM_{2.5}$ exposure and lung function decrement in the middle- to older-aged pollution, with 18.7 ml (0.45%) and 13.5 ml (0.42%) decreases in FVC and FEV_1, respectively, for every 2 μg/m^3 increase in $PM_{2.5}$[5]. However, there is paucity of information in highly polluted areas.

In 2015, the median of the annual average $PM_{2.5}$ in Taiwan was approximately 22.5 μg/m^3, which was more than twice that of the regulated levels proposed by the World Health Organization (10 μg/m^3). A previous study in Taiwan showed stronger effects of sub-chronic (two-month period) exposure to ambient fine particles and ozone on lung function in schoolchildren compared to that of acute exposure (lag 1 day). A 10 μg/m^3 increase in sub-chronic $PM_{2.5}$ exposure (Q1–Q3 at 32–44 μg/m^3) was also associated with a 3.3% and 3.1% reduction in FVC and FEV1, respectively, which in turn was 40% and 48% larger, respectively, than the effects found in a relatively less polluted area (Q1–Q3 at 10–17 μg/m^3)[6]. Whether or not the elderly in Taiwan have a similar response to ambient air pollution as children do is not known. The observed exposure-response relationship of long-term air pollution on lung function in the elderly may be used to predict mortality burden and may be informative for policy makers in areas with relatively high ambient air pollution.

Inhalable particulate matter includes fine and coarse particles with aerodynamic diameter $\leq$2.5 μm ($PM_{2.5}$) and 2.5–10 μm ($PM_{2.5-10}$), respectively. The main source of $PM_{2.5}$ is the combustion of fossil fuel and the high-temperature industrial process, whereas that of $PM_{2.5-10}$ includes mechanical disruption of various materials and microbial fragments[7]. According to previous deposition models[8–10], particles with aerodynamic diameter $>$10 μm deposit approximately 100% in the human nose or extra-thoracic airway during rest and light exercise, while inhaled coarse particles of 3–6 μm can reach and deposit in the lower respiratory tract. Moreover, $PM_{2.5}$ can penetrate deep into the alveolar region, but $PM_{2.5-10}$ deposits mainly in the tracheo-bronchial airways.

Given the variations in source, composition, and airway deposition between fine and coarse PM, there may be different patterns of health effects. An integrated science assessment by the United States Environmental Protection Agency considers the respiratory effects of long-term $PM_{2.5}$ exposure as "likely to be causal", but only "suggestive" for $PM_{2.5-10}$ due to the lack of epidemiologic information[7]. Identifying the different health effects of fine and coarse PM may provide the foundation for source controlling policy and disease prevention.

Materials and Methods

Study design and subjects.

We conducted a cross-sectional survey from October 2015 to September 2016 on the elderly (age $\geq$65 years) who lived in five areas in Taiwan (including Taipei city, New Taipei city, Hualien county, Chiayi county, and Kaohsiung city) with varying background PM concentration. The elders were consented to participate in this study during their annual geriatric health examination. To resemble general elderly population, we excluded those with malignancy and difficulties in mobility and general communication. The study was approved by the institution review board of the National Health Research Institutes (EC 1040508-E-R2) and was conducted in accordance with relevant guidelines and regulation. Each participant has signed the informed consent.

Questionnaire.

We designed a standard questionnaire to collect information including personal habits (such as cigarette smoking, alcohol consumption, etc.), medical conditions (underlying diseases and treatment received), and educational attainment. In order to overcome some difficulties with questionnaire completion (such as visual impairment, reading ability, etc.), five well-trained interviewers conducted the interviews.

Measurement of pulmonary function.

Lung function was measured by five well-trained technicians using spirometer (Otthon Mobile Handheld Spirometer, THOR Asian Pacific), and according to the standard of the American Thoracic Society. Each spirometer was calibrated monthly using 3 L flow-volume syringes. The elders underwent spirometry in the sitting position, in doors, and in the morning. The forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1), FEV_1/FVC ratio, and forced expiratory flow rates at different lung volumes (including $FEF_{25\%}$, $FEF_{50\%}$, $FEF_{75\%}$, and $FEF_{25-75\%}$) were measured. We collected at least three acceptable spirograms per subject. An acceptable spirogram was defined as good start of blowing without hesitation, smooth blowing curve without artifacts, and at least 6 seconds of expiratory duration, or with a plateau $>$1 second in the end expiration in the volume-time curve. A maximum of 8 blows were allowed for each lung function test.

We only included the tests where the differences between the two largest FVC and FEV_1 were both within 150 ml. We also measured the body height and weight at the time of spirometry for adjustment.

Assessment of air pollution exposure.

Each subject's exposure to ambient air pollution was estimated based on his or her residential site. We also retrieved the data of hourly levels of pollutants including $PM_{2.5}$, PM_{10}, nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and sulphur dioxide (SO_2), from 73 Taiwan Environmental Protection Administrion (EPA) monitoring stations, to calculate the one-year average concentration of air pollution in 2015. The kriging method developed by Liao *et al.*[11] were used to estimate the long- term residential exposure of air pollution.

Spatial estimation of pollution concentration was done by using the ArcView GIS(version 9.3) program. 10-Fold cross-validation was applied to verify the reliability of Kriging estimation. In brief, 90% of the air quality monitoring stations (training dataset) were randomly selected for Kriging interpolation and the remaining 10% used as validation dataset[12]. Particulate matter with aerodynamic diameter of 2.5–10 μm ($PM_{2.5-10}$) was derived by subtracting $PM_{2.5}$ from PM_{10}.

Statistical analysis.

We calculated the Pearson's correlation coefficient between each air pollutant and examined the relationship between the air pollutants and lung function by multiple linear regression, using the JMP software version 5.0 (SAS Institute, Gary, NC, USA). To evaluate the long-term effect of air pollution on lung

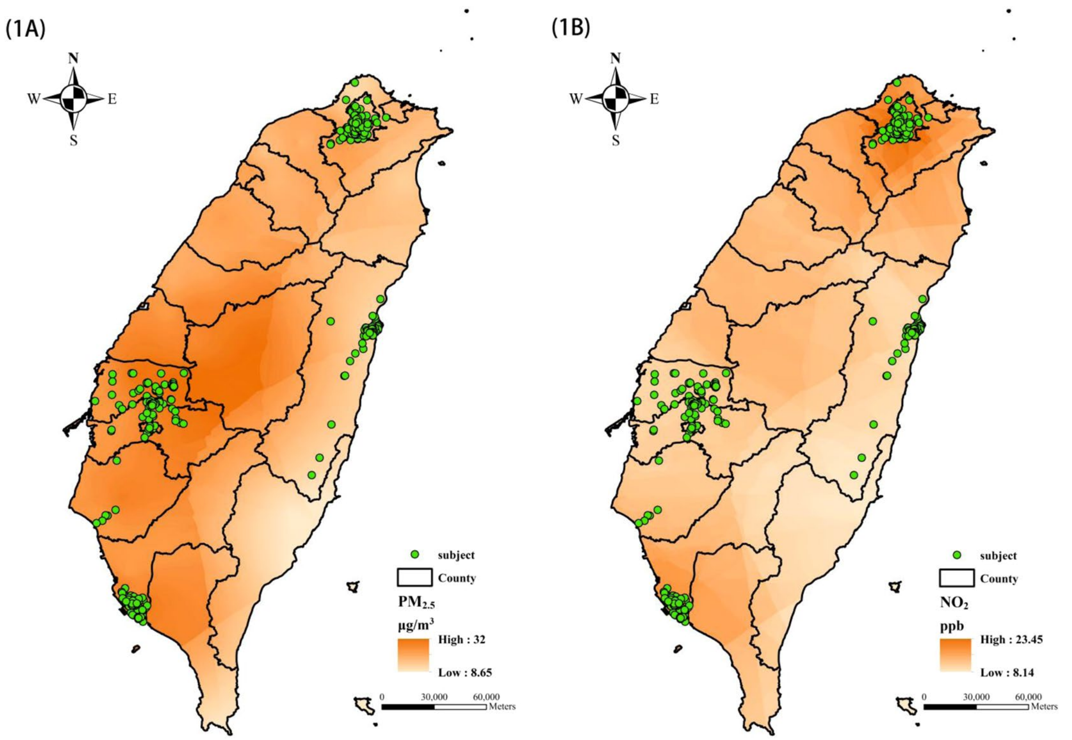

Figure 1. The residential locations of the study subjects (n = 1241) and the Kriging estimation of ambient $PM_{2.5}$ and NO_2 for the year 2015. **(A)** $PM_{2.5}$. **(B)** NO_2.

function, only subjects living in the current residential site for more than one year were included in the statistical analysis.

The association between each air pollutant with respiratory function indices was first examined. From the correlation between air pollutants, the two-pollutant model was used to identify the most significant pollutant. All of the models were adjusted for a set of variables chosen based on previous biologic and epidemiologic knowledge. These variables included age, sex, height, weight, smoking status (past or current smoker and pack-year), diagnosed asthma or chronic obstructive pulmonary disease (COPD), educational attainment, and season of respiratory function test. An investigation of a potential interaction between the effects of $PM_{2.5}$ and $PM_{2.5-10}$ on lung function was done by calculating the p value of interaction term. A subgroup analysis excluding subjects with physician-diagnosed asthma and COPD was also performed to confirm the association between air pollution and lung function. Statistical significance was set at $p < 0.05$.

Results

The characteristics of study subjects. The residential locations of the participants were shown in Fig. 1, while their demographics and respiratory function indices were summarized in Table 1. There were 1241 elderly in this study (mean age, 70.5 years; male-to-female ratio, 0.73). Their mean BMI was 24.6 kg/m^2 and 42.8% had a BMI >25 kg/m^2. Among them, 8.6% were current smokers and 11.3% were former smokers, with a median time from quitting smoking of 18.5 years. The mean cumulative pack-years of current and former smokers were 30.6 and 18.3, respectively. The prevalence of diagnosed asthma with airway symptoms in the past year and COPD were 2.0% and 1.9%, respectively.

The distribution of air pollution at residential sites. Distributions of the 2015 annual concentrations of six air pollutants were shown in Table 2. The mean residential $PM_{2.5}$ was 26 $\mu g/m^3$, which exceeded the National Ambient Air Quality Standard of Taiwan of 15 $\mu g/m^3$. However, the mean NO_2, CO, O_3, and SO_2, concentrations were below the national regulated levels. The $PM_{2.5}$ and NO_2 inter-quartile ranges (IQR) were wide, 10 $\mu g/m^3$ and 9.9 ppb compared to their mean concentrations of 26 $\mu g/m^3$ and 16.5 ppb, respectively. Moreover, $PM_{2.5}$ level was highly correlated with $PM_{2.5-10}$ (r = 0.82) and SO_2 (r = 0.81) levels, whereas $PM_{2.5-10}$ level was moderately correlated with SO_2 (r = 0.63) (Table 3). The 10-fold cross-validated R^2 values of the Kriging estimation of $PM_{2.5}$, PM_{10}, NO_2, CO, O_3, and SO_2 were 0.61, 0.50, 0.63, 0.28, 0.20 and 0.61, respectively.

The effect of air pollution on lung function, single-pollutant model. Estimations of the association between each pollutant and respiratory function indices were shown in Table 4. Both $PM_{2.5}$ and $PM_{2.5-10}$ were significantly associated with decrements in FVC, FEV_1, and $FEF_{25\%}$. On the other hand, $PM_{2.5-10}$ had negative associations with $FEF_{25-75\%}$ and $FEF_{50\%}$, while SO_2 had relatively weak associations with FVC, $FEV_{1,}$ and $FEF_{25\%}$. An IQR change in $PM_{2.5}$ was associated with 106.38 ml (4.47%) decrease in FVC and 73.30 ml (3.90%) decrease in FEV_1. An IQR change in $PM_{2.5-10}$ was associated with 101.22 ml (4.25%), 91.23 ml (4.85%), and 104.44 ml/s (5.58%)

	Mean (SD) or %	
	Male	Female
Number	522	719
Demographics		
Age, yr	70.91 (4.38)	70.16 (4.07)
Body height, cm	163.22 (6.18)	154.24 (6.69)
Body weight, kg	66.19 (9.40)	58.13 (9.77)
Body mass index	24.83 (3.11)	24.39 (3.48)
Education level		
Low(primary school or less)	38.12	48.82
Medium (middle or high school or equivalent)	45.02	44.65
High (university degree or more)	16.86	6.54
Smoking status, %		
Never	61.30	93.74
Current	14.75	4.17
Former	23.95	2.09
Pack-years*	23.33 (16.44)	25.04 (18.35)
Physician diagnosed asthma, %	2.87	1.39
Physician diagnosed COPD, %	2.49	1.39
Lung function indices		
FVC, ml	2872.89 (560.99)	2026.23 (417.74)
FEV1, ml	2235.00 (482.24)	1622.52 (336.17)
$FEF_{25\sim75\%}$, ml/s	2138.03 (849.44)	1675.52 (636.93)
$FEF_{25\%}$, ml/s	5054.14 (1680.46)	3761.57 (1098.84)
$FEF_{50\%}$, ml/s	2869.41 (1118.19)	2248.80 (831.12)
FEF75%, ml/s	811.53 (413.43)	645.83 (332.55)
FEV_1/FVC	0.78 (0.08)	0.80 (0.07)
Season of lung function test, %		
Spring (March-May)	52.11	49.65
Summer (June-August)	43.10	45.20
Fall (September-November)	1.15	1.53
Winter (December-February)	3.64	3.62

Table 1. Characteristics of the elderly who participated in the Taiwan Aging Cohort Study, 2015–2016 (n = 1241). *Among current or former smokers.

	Mean	Median	IQR	Minimum	Maximum
Exposures in 2015					
$PM_{2.5}$, μg/m^3	26.02	24.53	10.00	17.05	35.33
$PM_{2.5-10}$, μg/m^3	18.01	16.54	7.29	10.74	30.21
NO_2, ppb	16.54	15.79	9.93	8.63	21.62
CO, ppm	0.55	0.45	0.33	0.34	0.73
O_3, ppb	27.03	27.10	1.68	25.80	30.40
SO_2, ppb	3.24	3.21	0.23	1.76	4.59

Table 2. Distributions of air pollution exposure in residences of the elderly (n = 1241). Definition of abbreviations: IQR, interquartile range; $PM_{2.5}$, particulate matter with aerodynamic diameter of 2.5 μm; $PM_{2.5-10}$, particulate matter with aerodynamic diameter of 2.5–10 μm; NO_2, nitrogen dioxide; CO, carbon monoxide; O_3, ozone; SO_2, sulphur dioxide.

decrease in FVC, FEV_1, and $FEF_{25-75\%}$, respectively. The association between air pollution and lung function indices remained in the subgroup without physician-diagnosed asthma and COPD (Supplementary Table S1).

Two-pollutant model to clarify the most hazardous air pollutant. The two-pollutant model was used to adjust for the potential confounding effects of co-pollutants (Table 5). The effect of $PM_{2.5}$ on FVC remained consistently significant, as well as the effects of $PM_{2.5-10}$ on FEV_1, $FEF_{25-70\%}$, $FEF_{25\%}$, and $FEF_{50\%}$. The effect of SO_2 on respiratory function was insignificant after adjusting for particulate matters. There was no significant synergistic interaction between the effect of $PM_{2.5}$ and $PM_{2.5-10}$ on lung function (Supplementary Table S2).

	PM$_{2.5}$	PM$_{2.5-10}$	NO$_2$	CO	O$_3$	SO$_2$
PM$_{2.5}$	1	0.820**	0.001	−0.224**	0.109*	0.807**
PM$_{2.5-10}$		1	−0.272**	−0.473**	0.364**	0.629**
NO$_2$			1	0.967**	−0.879**	0.363**
CO				1	−0.862**	0.117**
O$_3$					1	−0.249**
SO$_2$						1

Table 3. Correlations of air pollutants for the year 2015 in residences of the elderly (n = 1241). Abbreviations: PM$_{2.5}$, particulate matter with aerodynamic diameter of 2.5 μm; PM$_{2.5-10}$, particulate matter with aerodynamic diameter of 2.5–10 μm; NO$_2$, nitrogen dioxide; CO, carbon monoxide; O$_3$, ozone; SO$_2$, sulphur dioxide. $^*p < 0.001$; $^{**}p < 0.0001$.

	FVC	FEV$_1$	FEV$_1$/FVC
PM$_{2.5}$	**−106.38 (23.01)******	**−73.30 (18.97)*****	0.005 (0.004)
PM$_{2.5-10}$	**−101.22 (25.84)******	**−91.23 (21.23)******	−0.003 (0.004)
NO$_2$	0.54 (28.93)	9.74 (23.80)	0.003 (0.005)
CO	28.58 (28.55)	28.48 (23.48)	0.001 (0.005)
O$_3$	−15.00 (26.17)	−18.40 (21.52)	−0.003 (0.004)
SO$_2$	**−14.60 (4.18)*****	**−8.68 (3.44)***	0.001 (0.001)
	FEF$_{25-75\%}$	**FEF$_{25\%}$**	**FEF$_{50\%}$**
PM$_{2.5}$	−26.75 (36.57)	**−420.99 (67.33)******	−87.33 (48.05)
PM$_{2.5-10}$	**−104.44 (40.88)***	**−495.67 (75.33)******	**−168.51 (53.71)****
NO$_2$	28.65 (45.60)	74.71 (85.25)	0.22 (60.00)
CO	31.08 (45.01)	**217.89 (83.94)****	17.85 (59.22)
O$_3$	−43.32 (41.23)	−99.83 (77.08)	−43.88 (54.25)
SO$_2$	2.21 (6.61)	**−74.47 (12.18)******	−7.17 (8.70)

Table 4. Association between each ambient air pollutant and lung function indices, in a single-pollutant model (n = 1241). $^*p < 005$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$. The models were adjusted by age, sex, body height, body weight, diagnosed asthma and COPD, educational attainment, smoking status (e.g. current or past smoker, cumulative pack-year of smoking), and season of lung function test. The regression coefficients and standard errors were estimated for every interquartile range increase in each pollutant, 10 μg/m^3 for PM$_{2.5}$, 7.29 μg/m^3 for PM$_{2.5-10}$, 9.93 ppb for NO$_2$, 0.33 ppm for CO, 1.68 ppb for O$_3$, and 0.23 ppb for SO$_2$.

	FVC	FEV$_1$	FEV$_1$/FVC	FEF$_{25-75\%}$	FEF$_{25\%}$	FEF$_{50\%}$
PM$_{2.5}$						
with PM$_{2.5-10}$	**−94.58***	−22.89	**0.02****	**131.70***	−187.05	90.49
with NO$_2$	**−106.63******	**−73.82*****	0.005	−27.87	**−424.67******	−87.53
with CO	**−105.41******	**−71.43*****	0.005	−23.24	**−402.79******	−87.73
with O$_3$	**−105.99******	**−72.47*****	0.005	−23.89	**−416.61******	−84.81
with SO$_2$	**−113.84****	**−94.69****	0.001	−97.73	**−254.33***	−150.11
PM$_{2.5-10}$						
with PM$_{2.5}$	−16.57	**−70.74***	**−0.02****	**−222.33****	**−328.24****	**−249.50****
with NO$_2$	**−107.47******	**−90.71******	−0.003	**−104.36***	**−509.51******	**−179.07****
with CO	**−110.61*****	**−98.37******	−0.004	**−113.35***	**−503.95******	**−198.49*****
with O$_3$	**−109.21*****	**−96.51******	−0003	**−101.77***	**−524.44******	**−174.39****
with SO$_2$	**−73.37***	**−91.25*****	**−0.011***	**−172.55*****	**−342.63*****	**−218.25****
SO$_2$						
with PM$_{2.5}$	1.70	4.88	0.001	16.21	−38.05	14.33
with PM$_{2.5-10}$	−7.62	0.005	**0.002***	**18.63***	**−41.86****	13.61
with NO$_2$	**−17.89*****	**−11.34****	0.001	0.53	**−96.66******	−8.77
with CO	**−16.09*****	**−9.92****	0.001	1.35	**−84.30******	−8.02
with O$_3$	**−16.70*****	**−10.41****	0.001	0.22	**−86.35******	−10.05

Table 5. The association between each ambient particulate air pollutant and lung function indices, in a two-pollutant model (n = 1241). $^*p < 005$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$. The models were adjusted for age, sex, body height, body weight, diagnosed asthma and COPD, educational attainment, smoking status (e.g. current or past smoker, cumulative pack-year of smoking), season of lung function test, and co-pollutants. The regression coefficients were estimated for every interquartile range increase in each pollutant.

In the subgroup analysis of subjects without obstructive lung diseases, the effect of $PM_{2.5}$ on FVC, and $PM_{2.5-10}$ on $FEF_{25-70\%}$, $FEF_{25\%}$, and $FEF_{50\%}$ were similar after adjusting for co-pollutants (Supplementary Table S3).

Discussion

The results show significant negative effects of long-term exposure to both ambient $PM_{2.5}$ and $PM_{2.5-10}$ on lung function among Taiwanese elderly living in four geographic areas. There is a wide distribution of PM concentrations and different effects of $PM_{2.5}$ and $PM_{2.5-10}$ on lung function parameters when using the two-pollutant model. Long-term $PM_{2.5}$ exposure mainly decreases the vital capacity of lung function, whereas $PM_{2.5-10}$ has a stronger negative effect on airway function. Overall, for every IQR (10 μg/m^3) increase in $PM_{2.5}$, FVC is reduced by 106.38 ml (4.47%) and for every IQR (7.29 μg/m^3) increase in $PM_{2.5-10}$, FEV_1 and $FEF_{25-75\%}$ are reduced by 91.23 ml (4.85%) and 104.44 ml/s (5.58%), respectively.

The exposure-response relationship of $PM_{2.5}$ on lung function is larger than in previous research conducted in the area of a relatively lower level of air pollution. The results here reveal that each 10 μg/m^3 increase in $PM_{2.5}$ reduces FVC and FEV1 by 106.38 ml (4.47%) and 73.30 ml (3.90%), respectively. Adar *et al.*[13] reported the association between $PM_{2.5}$ and lung function in the Multi-Ethnic Study of Atherosclerosis (MESA). The MESA recruited middle-aged adults and elderly (45~84 years of age) in six U.S. states. The mean 1-year $PM_{2.5}$ exposure of participants was approximately 14 μg/m^3. Their results revealed that every 10 μg/m^3 increase in $PM_{2.5}$ reduced FVC and FEV_1 by 108 ml (3.3%) and 48 ml (2%), respectively. The larger effect size in relatively more highly polluted area underscores the need for an active policy to cut ambient $PM_{2.5}$ in highly polluted areas.

The current study reveals a stronger effect of $PM_{2.5-10}$ on lung function parameters related to conductive airways than $PM_{2.5}$. Prior experiments on respiratory drugs have disclosed much higher deposition rates of coarse particles on extrathoracic and upper bronchial regions of respiratory tract than fine particles[14]. As for the lower bronchial region, there seems to be similar preference for the deposition of fine and coarse particles. Our study showed the preferential effect of $PM_{2.5-10}$ on FEV_1 and MMEF. Upon lung function parameters, FEV_1 and FEV_1/FVC ratio generally represent larger airway function and MMEF to smaller airway function. In other words, the observed effect of $PM_{2.5-10}$ on FEV_1 in this study echoes previous evidences disclosing its dominant deposition in larger airways, but its effect on mid-expiratory flow also suggests an impact of ambient $PM_{2.5-10}$ down to lower bronchial region.

Although fine PM has been considered highly dangerous, evidence shows that ambient coarse PM also causes several health hazards, e.g. increased blood pressure[15], heart rate variability[16], respiratory morbidity and mortality[17], emergency visit for asthma[18], and neural biomarkers[19]. Some studies also show the lung function effects of PM_{10} or $PM_{2.5}$[20], but information remains very limited for $PM_{2.5-10}$[7]. The multi-center European meta-analysis, ESCAPE, has found that a 10 μg/m^3 increase in long-term exposure to PM_{10}, but not in $PM_{2.5}$ and $PM_{2.5-10}$, is associated with approximately 1.4% and 1.5% decreases in FEV_1 and FVC, respectively[21]. In a cross-sectional study in southern China, areas with an average $PM_{2.5}$ of 23–75 μg/m^3 demonstrate a stronger $PM_{2.5}$ effect on FEV_1 and FVC than PM_{10}[22], suggesting that fine PM has the main effect on lung function. The inconsistent results may be due to the varying compositions of ambient PM, weather conditions, and co-pollutants in different geographic areas. Results of the present study finding may trigger more study interests regarding the health effects of $PM_{2.5-10}$. Given the differences in sources and formation mechanisms between fine and coarse PM, various environmental strategies or policies should be integrated to minimize overall PM-related health problems.

In this study, there are different patterns of $PM_{2.5}$-and $PM_{2.5-10}$-related lung function impairments. In the single-pollutant model, there are non-significant positive and negative associations for $PM_{2.5}$ and $PM_{2.5-10}$, respectively, with FEV_1/FVC ratio, suggesting the restrictive effect of $PM_{2.5}$ and the obstructive effect of $PM_{2.5-10}$. In the two-pollutant model, the consistent effects of $PM_{2.5}$ on FVC and $PM_{2.5-10}$ on FEV_1 and $FEF_{25-75\%}$ further suggest the anatomic tropism of various sized PM. Whether ambient PM restricts or obstructs lung function remains controversial in epidemiologic research.

The Normative Aging Study of elderly men reveals that the effect of long-term black carbon exposure is stronger for FEV_1 than for FVC[23], suggesting an obstructive pattern. A recent study in southern China has demonstrated a significant obstructive effect of long-term $PM_{2.5}$ exposure[22], while the cross-sectional analysis of the SAPALDIA study shows a stronger effect of PM_{10} on FVC than on FEV_1[24]. This points to a restrictive effect. The ESCAPE meta-analysis has observed a significantly stronger effect of PM_{10} on FVC than FEV_1[21], also suggesting a restrictive pattern. In the same study, further looking into the non-significant results of $PM_{2.5}$, $PM_{2.5}$ absorbance (an indicator of black carbons), and $PM_{2.5-10}$, there is a tendency for a restrictive effect of $PM_{2.5}$ and obstructive effects of $PM_{2.5}$ absorbance and $PM_{2.5-10}$. More studies are needed to determine whether the specific size or composition of PM can lead to different lung function impairments.

Overall, this study does not show any statistically significant obstructive or restrictive effect of PM by FEV_1/FVC ratio, but rather size-specific effects on parameters of vital capacity (FVC) or airway function (FEV_1 and $FEF_{25-75\%}$). A recent nationwide survey of schoolchildren aged 6–15 years in Taiwan also reveals similar findings: a non-significant trend of a positive association between FEV_1/FVC ratio and $PM_{2.5}$, especially in children aged 11–15 years, and a negative association between FEV_1/FVC ratio and $PM_{2.5-10}$[6]. Based on previous deposition models in humans[7–10], there is no clear boundary for the deposition of various sized PM on the tracheobronchial airway or alveolar region. During light exercise, any sized inhalable PM can deposit in every part of the respiratory system, with a higher proportion of coarse PM depositing in the tracheobronchial region than in the alveolar region, whereas fine PM is deposited mostly in the alveolar region. Thus, PM of various sizes may theoretically have varying proportional effects on each part of the intra-thoracic airways. However, the FEV_1/FVC ratio mainly measures the airway obstruction in the larger airways. Additional examinations, including total lung capacity and lung diffusing capacity, may improve the assessment of $PM_{2.5}$ effects on alveolar regions.

This study has some strengths. First, the relatively lengthy residential duration (>5 years in 92% of the participants) in our study population may improve the accuracy of long-term exposure assessments. Second, the elder population tends to spend most time at home and has smaller daily activity catchment area. This also improves our assessment accuracy, compared to younger and working population. Third, the high spatial heterogeneity and wide range of PM exposure level in our study population allowed the associations of PM and lung function to be well documented (Table 4). Fourth, the study was conducted in areas with high density of air monitoring stations. This reduces the misclassification from Kriging interpolation. Lastly, standardized protocol and uniform spirometers with regular calibration were used to ensure a reliable lung function measurement.

In this study, we chose Kriging interpolation for exposure estimation. One study has demonstrated better estimation performances of Kriging than the inverse distance weighting (IDW) or the nearest monitor estimation method on estimating PM_{10}, NO_2, CO, O_3, and SO_2[25]. The major limitation of kriging is that it does not consider environmental factors, such as land use and meteorological conditions[26]. The land-use regression (LUR) model may solve above problem and provide high local resolution. However, the generalizability of LUR is often concerned[27]. Hence, this method was not chosen since our participants were enrolled from four different geographic areas. In addition, satellite-based remote sensing approach[28] was not feasible due to the high missing rates of the satellite-based aerosol optical depth measurements in Northern Taiwan due to meteorological conditions and cloud contamination. Finally, the accuracy of Kriging interpolation for $PM_{2.5}$ and PM_{10} (10-fold cross-validated R^2 0.61 and 0.50, respectively) in this study was not inferior to land-use regression estimation adopted from Wu *et al.*[29] (0.57 for $PM_{2.5}$ and 0.50 for $PM_{2.5-10}$). In conclusion, we considered Kriging interpolation an acceptable choice among current available methods.

Nonetheless, this study has some limitations that should be noted. First, given the cross-sectional design, caution has to be taken in determining a causal relationship. Further longitudinal studies are warranted to confirm the results. Second, due to the lack of chemical analysis of PM, only the health effect by mass concentration can be evaluated. The specific contribution of each source to the observed effect cannot be concluded. In the Taipei area, the main source of PM_{10} is soil dust (34%), followed by vehicle emissions (25%) and secondary aerosols (24%). In contrast, the main source of $PM_{2.5}$ is from vehicle emissions (33%), followed by industrial emissions (23%), secondary aerosols (22%), and soil dust (20%)[29]. A study in Chiayi reveals that the main source of $PM_{2.5}$ is secondary aerosols (33%), followed by traffic exhaust (16%), the petrochemical industry (9%), and agricultural burning (8%)[30]. Another study in Kaohsiung City demonstrates that the main source of $PM_{2.5}$ is traffic exhaust (18–54%), followed by secondary aerosols (30–45%) and agricultural burning (13–17%)[31]. Information regarding the geographic distribution of $PM_{2.5-10}$ is limited. Long-term monitoring of particle composition in the epidemiologic survey areas should be done in the future to examine specific sources with related health effects. Lastly, the range of ozone exposure among the study subjects is quite narrow. This reduces the detectability of a exposure-response relationship, even though evidence has shown the negative effect of ozone on lung function[6,32,33].

In conclusion, this study demonstrates that long-term exposure to both ambient $PM_{2.5}$ and $PM_{2.5-10}$ at residential sites is associated with reduced lung function among the elderly (aged $\geq$65 years). The observed exposure-response relationship of $PM_{2.5}$ on respiratory function in this study was larger than in previous one conducted in a lower polluted country. Moreover, there are different effects on lung function by $PM_{2.5}$ and $PM_{2.5-10}$, the former with stronger effect on vital capacity and the later on airway parameters. These results emphasize the constant need for stricter control of air pollution, including both fine and coarse PM, and for more studies on long-term health outcomes, especially among the vulnerable population.

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Author Contributions

C.H.C., H.C.C. and Y.L.L.G. designed the study. D.C., K.Y.L., W.Y.L., J.I.Y. and K.W.T. recruited study subjects and collected data. C.D.W. performed exposure assessment. C.H.C. and Y.L.L.G. performed the analyses and wrote the manuscript. All authors proof-read the manuscript.

Additional Information

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