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Acute effects of air pollutants on pulmonary function among students: a panel study in an isolated island

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Abstract

Background: Many epidemiological studies on the health effects of air pollutants have been carried out in regions with major sources such as factories and automobiles. However, the health effects of air pollutants in regions without major sources remain unclear. This study investigated the acute effects of ambient air pollution on pulmonary function among healthy students in an isolated island without major artificial sources of air pollutants.

Methods: A panel study was conducted of 43 healthy subjects who attended a school in an isolated island in the Seto Inland Sea, Japan. We measured the forced expiratory volume in 1 s (FEV_1) and peak expiratory flow (PEF) every morning for about 1 month in May 2014. Ambient concentrations of particulate matter ≤ 2.5 μm in diameter ($PM_{2.5}$), particulate matter between 2.5 and 10 μm in diameter ($PM_{10-2.5}$), black carbon (BC), ozone (O_3), and nitrogen dioxide (NO_2) were measured. The associations between the concentrations of air pollutants and pulmonary function were analyzed using mixed-effects models.

Results: A decrease in FEV_1 was significantly associated with BC concentrations (−27.28 mL [95%confidence interval (CI): −54.10,−0.46] for an interquartile range (IQR) increase of 0.23 μg/m^3). The decrease in PEF was significantly associated with indoor O_3 concentrations (−8.03 L/min [95% CI:−13.02,−3.03] for an IQR increase of 11 ppb). Among subjects with a history of allergy, an increase in $PM_{2.5}$ concentrations was significantly associated with low FEV_1. In subjects with a history of asthma, an inverse association between the indoor O_3 concentration and pulmonary function was observed.

Conclusions: Our results demonstrate that increases in BC and O_3 concentrations have acute effects on the pulmonary function among students in an isolated island without major artificial sources of air pollutants.

Keywords: Allergy, Asthma, Air pollution, Isolated island, Pulmonary function, Panel study

Background

Many studies have reported the influence of air pollutants on the respiratory system [1–7]. Among air pollutants, particulate matter ≤ 2.5 μm in diameter ($PM_{2.5}$) induces an inflammatory response of the airway when inhaled, reducing the pulmonary function [8–11]. In addition, it is known that exposure to black carbon (BC), a component of $PM_{2.5}$, impairs the lung function in children [12]. Many studies involving patients with respiratory diseases, such as asthma [13–15] and chronic obstructive pulmonary

disease (COPD) [16, 17], have been carried out to evaluate the acute effects of air pollution. In addition, these studies have been primarily conducted in urban areas with a high concentration of air pollutants, involving factories and automobiles [18, 19]. Furthermore, most studies adopted concentrations at monitoring stations in the neighborhood to evaluate the influence of air pollutants on the respiratory system.

However, the results of studies among patients with specific diseases or epidemiological studies in areas with a high concentration of air pollutatnts are not always adaptable for a general population. Few epidemiological studies have evaluated the health effects of changes in the concentration of air pollutants in an environment

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where healthy persons live. Furthermore, the duration of indoor daily activities is longer than that of outdoor activities; therefore, when concentrations at monitoring stations in the neighborhood were used, exposure assessment may not have been accurately performed.

In this study, we repeatedly performed pulmonary function tests of healthy subjects in an isolated island without major artificial sources of air pollutants, and evaluated the acute effects of changes in the concentrations of air pollutants measured in indoor and outdoor spaces on the respiratory system among the subjects.

Methods

Study design and subjects

Yuge Island is an isolated island in the Seto Inland Sea, Japan (Fig. 1). Pulmonary function tests among students were conducted every day between May 12 and June 9, 2014. In addition, the atmospheric environment was measured during the same period. On this island, road traffic is light, but there may be little influence of automobile exhausts. Furthermore, there is no large factory, and there are no artificial sources of air pollutants other than ships; the island may be a clean-air area. However, recently, the influence of transported air pollutants derived from the Asian Continent has been indicated [20]. To investigate the relationship between the atmospheric environment and pulmonary function, we conducted pulmonary function tests among subjects who had stayed in Yuge Island over a long period of time; students attending a school on this island were requested to participate in this study. The subjects were 43 students from whom written informed consent was obtained (aged 15–16 years, mean: 15.1 years, 29 males and 14 females). Prior to this study, its protocol was

Fig. 1 Location of Yuge Island in the Seto Inland Sea of Japan

approved by the Ethics Review Board of Hyogo College of Medicine.

Assessment of the effects on health

Using a standard questionnaire [21], respiratory symptoms and the presence or absence of a history of asthma or allergy were evaluated. Subjects who selected "Yes" to the question "Have you ever been diagnosed with asthma?" were regarded as having a history of asthma. Those who selected "Yes" to the question "Have you ever been diagnosed with allergic rhinitis?" or "Have you ever been diagnosed with pollinosis?" were regarded as having a history of allergy.

For pulmonary function testing, an electronic peak flow meter (Vitalograph 2110, Vitalograph Ltd., Buckingham, U.K.) was delivered to each subject, and self-measurement of the peak expiratory flow (PEF) and forced expiratory volume in 1 s (FEV_1) was conducted before the start of the first lesson every morning from Monday until Friday.

Measurement of the atmospheric environment

To measure the atmospheric environment, an automatic particulate matter-measuring device (SPM-613D, Kimoto Electric Co., Ltd., Osaka, Japan) was installed on the roof of the school, and $PM_{2.5}$, particulate matter between 2.5 and 10μm in diameter ($PM_{10-2.5}$), and BC were measured continuously. In addition, the outdoor concentrations of ozone (O_3) and nitric oxide (NO_2) were measured using a passive sampler (Ogawa & Co., Ltd., Kobe, Japan) and a filter badge NO_2 (Advantec Co. Ltd., Tokyo, Japan), respectively. The sampler and badge were exchanged every 24 h on Monday to Friday for measurement, and 72-h measurement was conducted on weekends. Furthermore, the indoor concentrations of O_3 and NO_2 were measured in school classrooms, where the students had stayed for most of each school day, as described for outdoor measurement. The indoor concentration of $PM_{2.5}$ was measured serially using a digital dust indicators (Model LD-5, Sibata Scientific Technology Ltd., Tokyo, Japan) in the classroom.

Statistical analysis

The relationships between the indoor and outdoor concentrations of $PM_{2.5}$, O_3, and NO_2 were expressed as correlation coefficients. Those between the results of a pulmonary function test and the concentrations of air pollutants were evaluated using a mixed effect model with the rate of change per interquartile range (IQR) increase of each pollutant for 24 h before a pulmonary function test after adjusting for the atmospheric temperature, humidity, and subject's height. Furthermore, the analyses were performed using two-pollutant models to adjust for potential confounding effects of co-pollutants, for outdoor

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and indoor air pollutants, respectively. A *p*-value of 0.05 was regarded as significant. For analysis, we used SPSS 22 software (IBM Co., Armonk, NY, U.S.A.).

Results

The background characteristics of the subjects are shown in Table 1. A total of 868 pulmonary function tests were conducted. The means ± standard deviations of PEF and FEV_1 were 390.1 ± 110.2 L/min and 2.48 ± 0.74 L, respectively. Of the subjects, 7 (16.3%) had a history of asthma, and 19 (44.2%) had a history of allergy without asthma. Seventeen subjects (39.5%) did not have either history. During the study period, no subject developed respiratory symptoms, such as cough, sputum, or wheezing.

The mean daily indoor/outdoor concentrations of air pollutants during the study period are shown in Table 2. The mean outdoor concentration of $PM_{2.5}$ was 30.9 ± 12.5 μg/m^3. Those of $PM_{10-2.5}$ and BC were 22.7 ± 15.4 and 0.55 ± 0.22 μg/m^3, respectively. The maximum outdoor concentration of $PM_{2.5}$ was 61.6 μg/m^3, which was measured on the day with yellow sand carried from China to Japan. On the same day, the concentration of $PM_{10-2.5}$ was also high (53.8 μg/m^3). The mean indoor concentration of $PM_{2.5}$ was 17.0 ± 9.6 μg/m^3.

There were strong positive correlations between the outdoor and indoor concentrations of $PM_{2.5}$ and NO_2 ($r = 0.82$ and 0.92, respectively). However, the correlation between those of O_3 was weak ($r = 0.42$) (Fig. 2). The mean indoor concentrations of $PM_{2.5}$, O_3, and NO_2 were lower than the outdoor values.

The associations between the concentrations of air pollutants and changes in parameters of pulmonary function during the study period are shown in Table 3. FEV_1 decreased significantly in relation to an increase in the BC concentration (−27.28 mL [95% confidence interval (CI):−54.10,−0.46] per IQR increase of 0.23 μg/m^3). The PEF reduced significantly in relation to an increase in the indoor O_3 concentration (−8.03 L/min [95% CI:−13.02,−3.03] per IQR increase of 11.0 ppb). There was no significant correlation between the concentrations of the other pollutants and changes in pulmonary function.

We performed analyses using two-pollutant models to adjust for confounding effects of co-pollutants. Additional file 1: Table S1 shows the estimated changes in PEF and FEV_1 associated with an IQR increase of each pollutant [see Additional file 1]. The FEV_1 showed a significant decrease in relation to an increase in BC after adjustment for outdoor O_3. The association between PEF and indoor O_3 was also significant after adjustment for indoor $PM_{2.5}$ or NO_2. Furthermore, PEF reduced significantly in relation to an increase in outdoor $PM_{2.5}$ or BC, after adjustment for outdoor NO_2.

The associations between the concentrations of air pollutants and PEF with respect to the presence or absence of a history of asthma or allergy are shown in Fig. 3(a). In subjects with a history of allergy, PEF reduced significantly with an increase in the indoor concentration of $PM_{2.5}$ (−6.71 L/min [95% CI:−13.36, −0.06] per IQR increase). In those with a history of asthma, PEF reduced significantly with an increase in the indoor concentration of O_3 (−22.6 L/min [95% CI:−41.08,−4.13] per IQR increase). On the other hand, the PEF reduced significantly with an increase in the indoor concentration of O_3 in those without either history (−8.84 L/min [95% CI:−16.28,−1.40] per IQR increase). In those with a history of allergy, FEV_1 reduced significantly with an increase in the outdoor concentration of $PM_{2.5}$ (−70.0 mL [95% CI:−130.1,−9.94] per IQR increase) (Fig. 3(b)). In addition, FEV_1 reduced significantly with an increase in the indoor concentration of O_3 in subjects with a history of asthma (−130.3 mL [95% CI:−243.5,−17.2] per IQR increase).
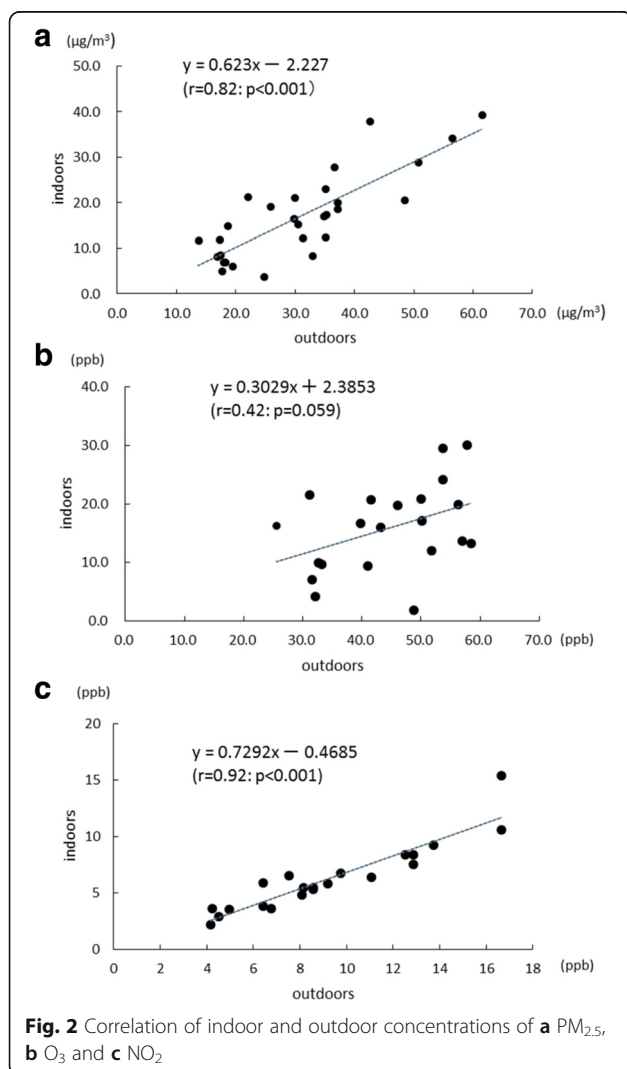
Discussion

Even in an isolated island without artificial sources of air pollutants, there were changes in the atmospheric concentrations of air pollutants, indicating that changes in the concentration of BC have an acute influence on the pulmonary function in healthy students. The indoor concentration of O_3 more markedly influenced pulmonary function compared with its outdoor concentration. In subjects with a history of asthma, pulmonary function reduced significantly with an increase in O_3 concentration. In those with a history of allergy, it reduced significantly with an increase in $PM_{2.5}$ concentration. These results suggested that subjects with these histories were more susceptible to changes in the concentrations of air pollutants.

Although we thought that this island in the Seto Inland Sea should be a clean-air area, the concentration of $PM_{2.5}$ was considerably high in the island. It was thought that the high concentrations recorded were largely due to transported air pollutants including yellow sand and the emissions from marine ships. Allen et al. showed that

Table 1 Characteristics of study subjects

	Male (n = 29)	Female (n = 14)	Total (n = 43)
Height, mean (SD) (cm)	166.4 ± 6.8	156.9 ± 5.1	163.3 ± 7.7
PEF (L/min)	420.8 ± 110.2	320.7 ± 73.7	390.1 ± 110.2
FEV_1 (L)	2.66 ± 0.75	2.10 ± 0.55	2.48 ± 0.74
Measurements of pulmonary function (n)	(594)	(274)	(868)

SD standard deviation; *PEF* peak expiratory flow; *FEV$_1$*, forced expiratory volume in 1 s

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Table 2 The 24-h mean concentrations of outdoor and indoor air pollutants and meteorological parameters during the study period

	n	Mean	SD	Minimum	Median	Maximum	IQR
Outdoor air pollutants							
PM$_{2.5}$ (µg/m^3)	29	30.9	12.5	13.7	30.6	61.6	18.4
PM$_{10-2.5}$ (µg/m^3)	29	22.7	15.4	6.0	16.2	54.2	24.2
BC (µg/m^3)	29	0.55	0.22	0.26	0.49	1.25	0.23
O$_3$ (ppb)	21	44.6	10.3	25.7	46.1	58.5	20.8
NO$_2$ (ppb)	21	9.2	3.8	4.2	8.6	16.7	6.3
Indoor air pollutants							
PM$_{2.5}$ (µg/m^3)	29	17.0	9.6	3.7	16.5	39.3	12.6
O$_3$ (ppb)	21	15.9	7.5	1.9	16.2	30.0	11.0
NO$_2$ (ppb)	21	6.3	3.0	2.2	5.8	15.3	4.2
Meteorological parameters							
Temperature (℃)	29	20.2	2.1	15.8	19.8	23.9	3.6
Relative humidity (%)	29	71.5	11.1	52.0	69.0	92.0	15.5

SD standard deviation; *IQR* interquartile range; *PM$_{2.5}$* particulate matter ≤ 2.5 µm in diameter; *PM$_{10-2.5}$* particulate matter between 2.5 and 10 µm in diameter; *BC* black carbon; *O$_3$* ozone; *NO$_2$* nitrogen dioxide

Fig. 2 Correlation of indoor and outdoor concentrations of **a** PM$_{2.5}$, **b** O$_3$ and **c** NO$_2$

PM$_{2.5}$ are transported over long distances and affects distant clean-air areas [22]. It was also reported that transported air pollutants and emissions from marine ships affect the levels of air pollution in Kyushu, Japan [23, 24]. If the emission from marine ships contribute to air quality in the island, the concentration of sulfur dioxide may be also high. However, the concentrations have not been measured around the island.
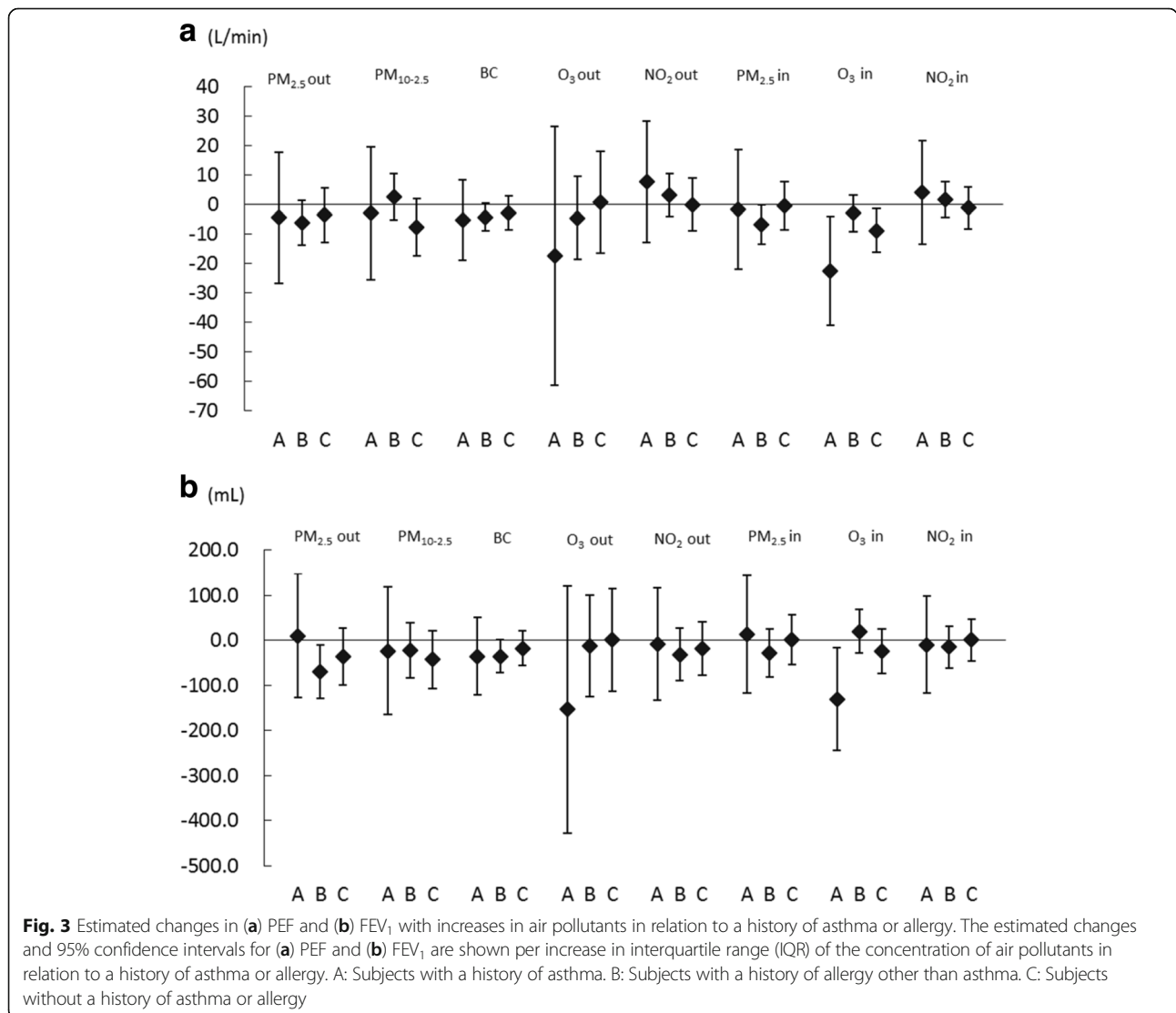
The results of this study showed that pulmonary function reduced significantly with an increase in the atmospheric concentration of BC, and the association was still significant after adjustment for O$_3$. Huang et al. reported that a pulmonary function test in healthy adults after they stayed in a transport hub of a big city for 2 h showed a significant decrease in FEV$_1$ related to an increase in BC concentration [25]. Patel et al. conducted a study among school children in New York, and indicated that symptoms, such as wheezing and shortness of breath, deteriorated with an increase in BC concentration [26]. The results of these studies were consistent with those of our study. Diesel emission gas contains a large volume of BC [27]. A study reported that when persons were exposed to diesel emission gas, the bronchial mucosal neutrophil and mast cell counts increased, inducing transient increases in the number of inflammatory cells in the airway and cytokine levels [28]. With an increase in BC concentration, an inflammatory response in the airway may have occurred, thereby reducing pulmonary function. The area investigated in this study was an isolated island with light traffic, which unlike urban areas, and had relatively low concentration of BC. Our results suggested that an increase in BC concentration influences pulmonary function even in such an area with a low air pollutant concentrations. Huang et al. evaluated adults

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Table 3 Associations between air pollutants and pulmonary function during the study period

	PEF (L/min)			FEV$_1$ (mL)		
	Change[a]	95% CI	P-Value	Change[a]	95% CI	P-Value
Outdoor air pollutants						
PM$_{2.5}$	−4.57	(−10.67, 1.52)	0.141	−41.19	(−84.38, 1.99)	0.062
PM$_{10-2.5}$	−2.71	(−9.04, 3.62)	0.401	−37.50	(−81.80, 6.79)	0.097
BC	−3.53	(−7.31, 0.25)	0.067	−27.28	(−54.10, −0.46)	0.046
O$_3$	−3.84	(−15.42, 7.74)	0.515	−30.93	(−112.84, 50.99)	0.459
NO$_2$	2.18	(−3.67, 8.02)	0.466	−28.23	(−69.40, 12.95)	0.179
Indoor air pollutants						
PM$_{2.5}$	−3.21	(−8.63, 2.20)	0.245	−9.58	(−48.50, 29.34)	0.629
O$_3$	−8.03	(−13.02, −3.03)	0.002	−20.14	(−55.36, 15.09)	0.262
NO$_2$	0.81	(−3.96, 5.59)	0.738	−9.88	(−43.22, 23.46)	0.561

PEF peak expiratory flow; *FEV$_1$* forced expiratory volume in 1 s; *CI* confidence interval; *PM$_{2.5}$* particulate matter ≤ 2.5 μm in diameter; *PM$_{10-2.5}$* particulate matter between 2.5 and 10 μm in diameter; *BC* black carbon; *O$_3$* ozone; *NO$_2$* nitrogen dioxide
[a]Mean changes in PEF or FEV$_1$ associated with an increase in the interquartile range of each air pollutant

Fig. 3 Estimated changes in (**a**) PEF and (**b**) FEV$_1$ with increases in air pollutants in relation to a history of asthma or allergy. The estimated changes and 95% confidence intervals for (**a**) PEF and (**b**) FEV$_1$ are shown per increase in interquartile range (IQR) of the concentration of air pollutants in relation to a history of asthma or allergy. A: Subjects with a history of asthma. B: Subjects with a history of allergy other than asthma. C: Subjects without a history of asthma or allergy

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exposed to air pollutants for 2 h in a previous study [25]. In our study, the subjects were adolescent students who attended school for many hours. Because this survey was conducted in an isolated island, the subjects resided both in the island and along the coast. As the 1-month survey was carried out in such a place, the influence of exposure to air pollutants on daily living could be evaluated accurately. Furthermore, most subjects were healthy, and the results of our study may be representative.

The indoor concentration of O_3 was more markedly associated with pulmonary function compared with its outdoor concentration, and the effect of O_3 was still significant after adjustment for $PM_{2.5}$ or NO_2. O_3 exhibits acute effects on the lungs [29]. When the indoor concentration of O_3 increased, PEF decreased significantly. However, there was no significant relationship with an increase in the outdoor concentration of O_3. Altug et al. reported that the PEF among elementary school children decreased significantly with an increase in the concentration of O_3 [30]. McConnell et al. performed a 5-year follow-up survey of 3535 children without asthma, and indicated that 265 were newly diagnosed with asthma during the follow-up, suggesting that high-intensity exercise in an area with a high concentration of O_3 promotes the onset of childhood asthma [31]. Furthermore, Amadeo et al. reported that, even at an O_3 concentration lower than the reference value presented in the WHO guidelines, PEF decreased with an increase in the concentration of O_3, suggesting the acute effects of O_3 on the pulmonary function of children [32]. Pulmonary function reduces with an increase in O_3 concentration, because O_3 may increase inflammation of the airway as a potent acidic pollutant [10, 33]. Intra-pulmonary O_3 uptake was reported to peak in the terminal bronchioles [34]. In our study, the relationship with the indoor concentration of O_3 and pulmonary function was marked. Gaseous substances, such as O_3, are sometimes generated indoors; therefore, their concentrations in living spaces should be measured and used for exposure assessments.

Neither the indoor nor outdoor concentrations of $PM_{2.5}$ were significantly associated with PEF and FEV_1 among all the subjects in a single-pollutant model. However, after adjustment for outdoor NO_2, PEF significantly decreased with an increase in the outdoor concentration of $PM_{2.5}$. Moreover, PEF decreased significantly with an increase in BC after adjustment for NO_2. These findings may be due to the interactions between NO_2 and other air pollutants. The results suggested acute effects related to changes in the concentrations of O_3 and $PM_{2.5}$ in subjects with a history of asthma or allergy. In those with a history of allergy, the PEF and FEV_1 significantly reduced when the indoor and outdoor concentrations of $PM_{2.5}$ increased, respectively. With respect to the acute effects of $PM_{2.5}$, Huang et al. reported that FEV_1

decreased by –0.15% (95% CI: –0.28, –0.02%) when the exposure concentration for 2 h increased by 10 μg/m^3 [25]. Bernals et al. indicated that allergic airway diseases are not merely disorders of the immune system, and that allergic diseases primarily arise from airway epithelium defects resulting from immaturity or caused by environmental insults [35]. In our study, pulmonary function may also have reduced through such a pathophysiological mechanism. Based on the results of this study, there was no relationship between $PM_{10-2.5}$ and changes in pulmonary function. $PM_{10-2.5}$ is deposited in the nasal cavity, pharynx, and upper airway when it is inhaled. However, $PM_{2.5}$ reaches the bronchiolar and alveolar levels in the lungs because its particle diameter is small. A previous study reported that the influence of $PM_{2.5}$ on the respiratory system was more marked than that of $PM_{10-2.5}$ [36]. Based on the results of this study, there was no relationship between the $PM_{2.5}$ concentration and PEF or FEV_1 in subjects with a history of asthma, but this was possibly because the number of subjects was small.

In subjects with a history of asthma, PEF and FEV_1 decreased significantly with an increase in the indoor concentration of O_3. In these subjects, the two parameters decreased slightly with an increase in the outdoor concentration of O_3. Mortimer et al. reported that PEF in the morning decreased with an increase in O_3 concentration in children with asthma [37]. In our study, when analyzing the results with respect to medical histories, PEF was associated with an increase in O_3 concentration in subjects other than those with a history of allergy. There was no significant difference in those with a history of allergy, but the reason was unclear.

There was no association between an increase in NO_2 concentration and pulmonary function. In power plant workers exposed to NO_2, pulmonary functions were reduced significantly [38]. Gauderman et al. indicated that the odds ratio of asthma was 1.83 (95% CI: 1.04–3.22) when the outdoor concentration of NO_2 increased by 5.7 ppb (IQR) [39]. Furthermore, Liu et al. conducted a study among children with asthma, and reported that an increase in NO_2 concentration significantly reduced pulmonary function [40]. The concentration of NO_2 measured in our study was relatively low; therefore, there may have been no influence on the respiratory system.

We had conducted the survey in the same area in the autumn of 2013, and found negative associations between pulmonary function and the concentrations of $PM_{2.5}$, NO_2, and BC among subjects with a history of asthma [41]. In the present study, to estimate the exposure to air pollutants accurately, we conducted measurements of the indoor concentrations of air pollutants in addition to outdoor concentrations. The subjects in the present study were different from those in the previous

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one, and this survey was conducted during spring. In the results of this study, an inverse association between pulmonary function and the concentrations of air pollutants among subjects with a history of asthma or allergy, which was compatible with the previous study. Therefore, subjects with a history of asthma or allergy were considered to be more susceptible to air pollutants. These adverse effects of air pollution may be modified by medication for asthma or allergy. However, in this study, information on the medication taken by the subjects was not obtained. The interaction with medication should be further evaluated.

This study has several limitations. One is that the number of subjects was small, resulting in an insufficient detection power; therefore, the influence of air pollution may have been underestimated. However, pulmonary function tests were conducted every morning, and a significant reduction in pulmonary function related to increases in BC or O_3 concentrations was observed, even though the number of subjects was relatively small. The second limitation is that the study period was short and was limited to one season. It has been reported that the concentrations and sources of air pollutants have seasonal variations. In the future, a large-scale survey involving a larger number of subjects should be conducted for a longer period. The third limitation is that only PEF and FEV_1 were used as pulmonary function parameters. Although inflammation of the airway may be involved in a reduction of pulmonary function, it was not tested in this study. In the future, the inflammatory state of the airway should be evaluated objectively in addition to pulmonary function tests.

Conclusion

In an isolated island without major artificial sources of air pollutants, changes in the concentrations of air pollutants acutely influenced the pulmonary function of healthy subjects. The results suggest that gaseous substances, such as O_3, are sometimes generated indoors, and that the indoor concentration of O_3 more markedly influences pulmonary function compared with its outdoor concentration. In subjects with a history of allergy, pulmonary function reduced with an increase in the concentration of $PM_{2.5}$.

Additional file

Additional file 1: Table S1. Associations between air pollutants and pulmonary function during the study period in each single- and two-pollutant model. (DOCX 23 kb)

Abbreviations

BC: Black carbon; FEV_1: Forced expiratory volume in 1 s; IQR: Interquartile range; NO_2: Nitrogen dioxide; O_3: Ozone; PEF: Peak expiratory flow; $PM_{10-2.5}$: Particulate matter between 2.5 and 10 μm in diameter; $PM_{2.5}$: Particulate matter ≤ 2.5 μm in diameter

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