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Original article

Association between pulmonary function and daily levels of sand dust particles assessed by light detection and ranging in schoolchildren in western Japan: A panel study

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Abbreviations:
ADS, Asian dust storm; CI, confidence intervals; IQR, interquartile range; LIDAR, Light Detection and Ranging; NO_2, nitrogen dioxide; O_x, ozone; PEF, peak expiratory flow; PM_{10}, particulate matter smaller than 10 micro meter; $PM_{2.5}$, particulate matter smaller than 2.5 micro meter; PTA, Parent Teacher Association; SD, standard deviation; SO_2, sulfur dioxide; SPM, suspended particle matter

ABSTRACT

Background: An important aspect of sand dust emissions in association with respiratory disorders is the quantity of particulate matter. This is usually expressed as particulate matter less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$). However, the composition of PM_{10} and $PM_{2.5}$ varies. Light detection and ranging is used to monitor sand dust particles originating in East Asian deserts and distinguish them from air pollution aerosols. The objective of this study was to investigate the association between the daily levels of sand dust particles and pulmonary function in schoolchildren in western Japan.
Methods: In this panel study, the peak expiratory flow (PEF) of 399 schoolchildren was measured daily from April to May 2012. A linear mixed model was used to estimate the association of PEF with the daily levels of sand dust particles, suspended particulate matter (SPM), and $PM_{2.5.}$
Results: There was no association between the daily level of sand dust particles and air pollution aerosols, while both sand dust particles and air pollution aerosols had a significant association with SPM and $PM_{2.5}$. An increment of 0.018 km^{-1} in sand dust particles was significantly associated with a decrease in PEF (−3.62 L/min; 95% confidence interval, −4.66 to −2.59). An increase of 14.0 $\mu g/m^3$ in SPM and 10.7 $\mu g/m^3$ in $PM_{2.5}$ led to a significant decrease of −2.16 L/min (−2.88 to −1.43) and −2.58 L/min (−3.59 to −1.57), respectively, in PEF.
Conclusions: These results suggest that exposure to sand dust emission may relate to pulmonary dysfunction in children in East Asia.
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Introduction

Many epidemiological studies have suggested an association between atmospheric particulate matter levels and respiratory and cardiovascular morbidity and mortality.[1,2] In children with asthma, short-term exposure to air pollutants can decrease pulmonary function and increase respiratory symptoms.[3,4] Turbulent winds raise large quantities of dust from desert sand and are an important source of particulate matter. A large sand dust emission in East Asia,

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which is referred to as an Asian dust storm (ADS), originates in the deserts of Mongolia, northern China, and Kazakhstan and is the second strongest dust emission worldwide.[5] ADS most frequently occurs from March to May, and data suggests that they have lasted until late autumn in recent years. ADS is a source of air pollution, because the dust contains chemicals, metals, microorganisms, and ions.[6–8]

ADS is a serious health concern because of the associated heavy pollution and has been associated with an increase in mortality, emergency treatment for cardiovascular diseases, and hospitalization for pneumonia.[9–11] We have shown that ADS has a significant relationship with symptoms and pulmonary dysfunction in adult patients with asthma[12,13]; furthermore, it has been associated with an increased risk of hospitalization and acute respiratory tract symptoms in children with asthma.[14,15] ADS decreases the peak expiratory flow (PEF) in children with mild asthma,[15] and exposure to metals bound to ADS particles also decreases pulmonary function in healthy children.[16] On the other hand, the criteria for ADS days is currently unclear and differ among countries. Therefore, different studies used different definitions of ADS days. Several studies used particulate matter smaller than 2.5 μm ($PM_{2.5}$) or particulate matter less than 10 μm (PM_{10}) to investigate the association between ADS and health disorders. However, $PM_{2.5}$ and PM_{10} contain air pollution aerosols other than sand dust.

Air pollution consists of particulate matter, existing solid or liquid, and gaseous matter such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3). Particulate matter can be classified into two groups; non-spherical particles, which are mineral dust particles and spherical particles such as organic aerosols and inorganic sulfates and nitrates.[17,18] Light Detection and Ranging (LIDAR) depolarization measurements performed simultaneously at two wavelengths can be used to identify non-spherical dust particles and spherical particles.[17,18] Although the LIDAR system is unable to differentiate the size of particulate matter, it can be used to measure the level of mineral dust particles as airborne sand dust particles and non-mineral dust particles as air pollution aerosols in real time. LIDAR measurements for the detection of a potential ADS are continuously acquired in 23 locations in Japan, South Korea, China, Mongolia, and Thailand, and these data permit investigation of the association between pulmonary function and daily exposure to sand dust particles.

We conducted this study to investigate the association between pulmonary function in children and ADS using LIDAR data for daily sand dust levels in western Japan. We also studied the relationship between pulmonary function and air pollution aerosols. To the best of our knowledge, this is the first study to assess the association between pulmonary function in children and daily levels of sand dust particles and air pollution aerosols assessed using LIDAR measurements in East Asia.

Methods

Study design

In this panel study, PEF of schoolchildren was monitored daily in the morning from March to May 2012, the period during which ADS events are most frequent in Japan. March, which is generally spring vacation time, was used as a trial period for the children to familiarize with the monitoring procedure. The study was performed in Matsue, the capital city of Shimane Prefecture, Southwest Japan. This city houses approximately 200,000 individuals and covers an area of 530.2 km^2. All 401 fourth grade students aged 8 and 9 years in four of a total of 35 elementary schools in Matsue City in 2012 were enrolled. The 4 elementary schools were within 10 km of each other, and all subjects lived within a radius of 1 km of the schools.

Gender, height, weight, and the presence of asthma, allergic rhinitis, allergic conjunctivitis, atopic dermatitis, and food allergies were recorded in March 2012. The subjects were considered to have asthma if they met any of the following criteria in the past 12 months: diagnosis of asthma by a pediatrician, presence of wheezing, use of asthma medication, and regular visits to a hospital for asthma. The subjects were considered to have allergic rhinitis, allergic conjunctivitis, atopic dermatitis, and/or food allergy if they met any of the following criteria in the past 12 months: diagnosis of any of these conditions by a pediatrician, use of medication for any of these conditions, and regular visits to a hospital for any of these conditions. The study was approved by the institutional ethics committee (Ethics Committee of the Faculty of Medicine, Tottori University, Approval Number 1764). We asked the Matsue City Board of Education for their help and received approval to submit the study to the schools. The study was also approved by the Parent Teacher Association (PTA) of each elementary school. The children and their parents were informed by teachers and provided written consent.

PEF monitoring

The children and teachers were taught how to measure PEF before the start of the study. From March to May 2012, with the exception of Saturdays, Sundays, and public holidays, all children measured their PEF daily, in the morning using a peak flow meter (Mini-Wright, Harlow, England, American Thoracic Society scale). All children went to school on foot and were potentially exposed to any air pollutants. The children recorded their best PEF value from three attempts after arriving at school between 8 AM and 9 AM.

Measurement of air pollutant levels

LIDAR is installed in Matsue City and is used to monitor the concentration of sand dust particles and air pollution aerosols for the Japanese Ministry of the Environment. LIDAR systems measure the aerosol levels at 15-min intervals by distinguishing between non-spherical and spherical dust particles.[17,18] LIDAR systems measure the levels of spherical and non-spherical particles using extinction coefficient, which is a measure of how strongly a substance absorbs light. Extinction coefficient is proportional to the reciprocal of visibility, and a non-spherical dust particles level of 0.1 km^{-1} equals a visibility range of 10 km.[19] When the level of suspended particulate matter (SPM) is 0.1 mg/m^3, the visibility range is 10 km. The daily level is determined on the basis of the median value of 96 measurements over a 24-h period from midnight of one day to midnight of the following day.[17,18]

Particulate matter is classified into several categories according to its size. PM_{10} is defined as any particle measuring less than l0 μm in diameter with a 50% cut-off and $PM_{2.5}$ as any particle measuring less than 2.5 μm diameter with the same cut-off as PM_{10}.[20] In Japan, SPM is defined under the National Air Quality Standard as any particle with a diameter of less than 10 μm with a 100% cut-off.[20] The theoretical 50% cut-off diameter for SPM is assumed to be approximately 7 μm.[21] The particle diameter of SPM measured in Japan is intermediate to those classified under $PM_{2.5}$ and PM_{10} parameters. Although the daily fluctuations of SPM are similar to those of $PM_{2.5}$,[22] the constituents of particulate matter could differ among countries. The Japanese Ministry of the Environment monitors the levels of SPM instead of PM_{10}. The concentrations of SPM, $PM_{2.5}$, SO_2, NO_2, and O_3 as well as LIDAR data are also monitored by the Japanese Ministry of the Environment in Matsue City. These data were used to examine the relationship between changes in PEF and air pollutant levels.

Statistical analysis

Linear mixed models that accounted for associations among repeated measurements within a subject were used to estimate the effect of exposure to sand dust particles, air pollution aerosols, SPM, and $PM_{2.5}$ on the daily PEF of children.[23,24] The linear mixed models included a random intercept for subjects in the analysis, individual characteristics (gender, height, weight, asthma, allergic rhinitis, allergic conjunctivitis, atopic dermatitis, and food allergy), meteorological variables such as daily temperature, humidity, and atmospheric pressure, gaseous air pollution (SO_2, NO_2, and O_3), and other parameters of sand dust particles, air pollution aerosols, SPM, and $PM_{2.5}$ deviated from the evaluation. Estimates are given as the absolute difference in PEF values per interquartile range (IQR) change in exposure, with 95% confidence intervals (CIs). Linear mixed model analyses were performed using R ver. 3.0.3 (R Foundation for Statistical Computing, Vienna, Austria). Associations among sand dust particle, air pollution aerosol, and SPM, and $PM_{2.5}$ levels were assessed by linear regression analysis using SPSS software (Japanese version 20.0 for windows; IBM SPSS Japan Inc., Tokyo, Japan). All quoted *P*-values are two-sided, with a significance level of 0.05.

Results

Subject characteristics

A total of 401 children were recruited. Two were subsequently excluded because they failed to maintain a daily record of PEF. The characteristics of the remaining 399 children are shown in Table 1.

Air pollutant levels and the association among each air pollutant

The daily levels of sand dust particles and air pollution aerosols are shown in Figure 1. There was no association between sand dust particles and air pollution aerosols (Fig. 2), while both sand dust particles and air pollution aerosols showed a significant association with SPM and $PM_{2.5}$.

PEF

The results for changes in PEF values for an IQR increase in the levels of sand dust particles, air pollution aerosols, SPM, and PM2.5 are presented in Table 2. Sand dust particles and air pollution aerosol levels were significantly associated with a decrease in PEF, with an increase of 0.018 km^{-1} in sand dust particles and 0.065 km^{-1} in air pollution aerosols decreasing PEF by −3.26 L/min and −4.62 L/min, respectively. SPM and PM2.5 levels were significantly associated with a decrease in PEF, with increases of 14.0 μg/m3 in SPM and 10.7 μg/m3 in PM2.5 decreasing PEF by −2.16 L/min and −2.58 L/min, respectively. Multivariate analyses were used to evaluate the associations between daily PEF values (after exposure to SPM, PM2.5, sand dust particles, and air pollution aerosols) and allergic diseases; the results revealed no significant associations. For example, the results of the association between PEF values after sand dust exposure and allergic diseases were as follows: asthma [−16.3 L/min; 95% CI, −32.9 to 0.4; P = 0.06], allergic rhinitis (−7.0 L/min; 95% CI, −19.5 to 5.5; P = 0.27), allergic conjunctivitis (−3.9 L/min; 95% CI, −38.8 to 30.9; P = 0.83), atopic dermatitis (−5.6 L/min; 95% CI, −21.3 to 10.2; P = 0.49), and food allergy (0.4 L/min; 95% CI, −23.3 to 23.9; P = 0.98).

Table 1
Characteristics of the 399 children included in this study.

Gender, Male/Female	205/194
Height (cm)	132.3 ± 5.94
Male	132.2 ± 5.51
Female	132.4 ± 6.41
Weight (kg)	29.5 ± 5.83
Male	29.6 ± 6.23
Female	29.3 ± 5.40
Allergic disease (Number)	
Asthma	38
Allergic rhinitis	78
Allergic conjunctivitis	8
Atopic dermatitis	44
Food allergies	19

Data are shown as means ± SDs.

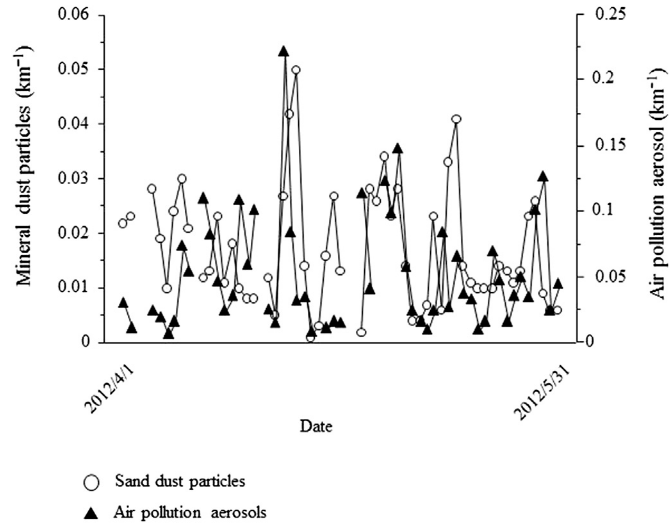

Fig. 1. Daily levels of sand dust particles and air pollution aerosols from April 1 to May 31, 2012. LIDAR failed to register data on April 3, 4, 11, 20, and May 2, 3 for the level of sand dust particles, and April 3, 4, 11, 20, 28, and May 2, 3, and 6 for that of air pollution aerosols.

Discussion

Several epidemiological studies have suggested an association of ADS with respiratory disorders.[9–11,14,25] However, at present, the definition of ADS days varies among countries, and this may cause differences in the assessment of the relationship between ADS and health disorders among studies. In addition, sand dust emissions, including ADS, are conventionally expressed as PM_{10} and $PM_{2.5}$, although these are a mixture of various components. LIDAR can quantify the diffusion of sand dust particles by distinguishing between non-spherical and spherical dust particles. To ensure accuracy, we studied the relationship between large sand dust emissions in East Asia (Southwest Japan) and pulmonary function in children using LIDAR data for daily sand dust levels. Our key finding was that increased levels of sand dust particles induced a decrease in pulmonary function in schoolchildren. The results also showed that SPM and $PM_{2.5}$ were significantly associated with a decrease in PEF, indicating a relationship between ADS and pulmonary function.

Thus far, there has been no method to monitor sand dust particles. Many studies used $PM_{2.5}$ and PM_{10} levels to estimate the association between sand dust emissions and health disorders. However, PM_{10} and $PM_{2.5}$ are a mixture of various components in addition to sand dust particles. Therefore, PM_{10} and $PM_{2.5}$ are insufficient to determine the quantity of sand dust particles. In contrast, LIDAR systems are a suitable method to measure the

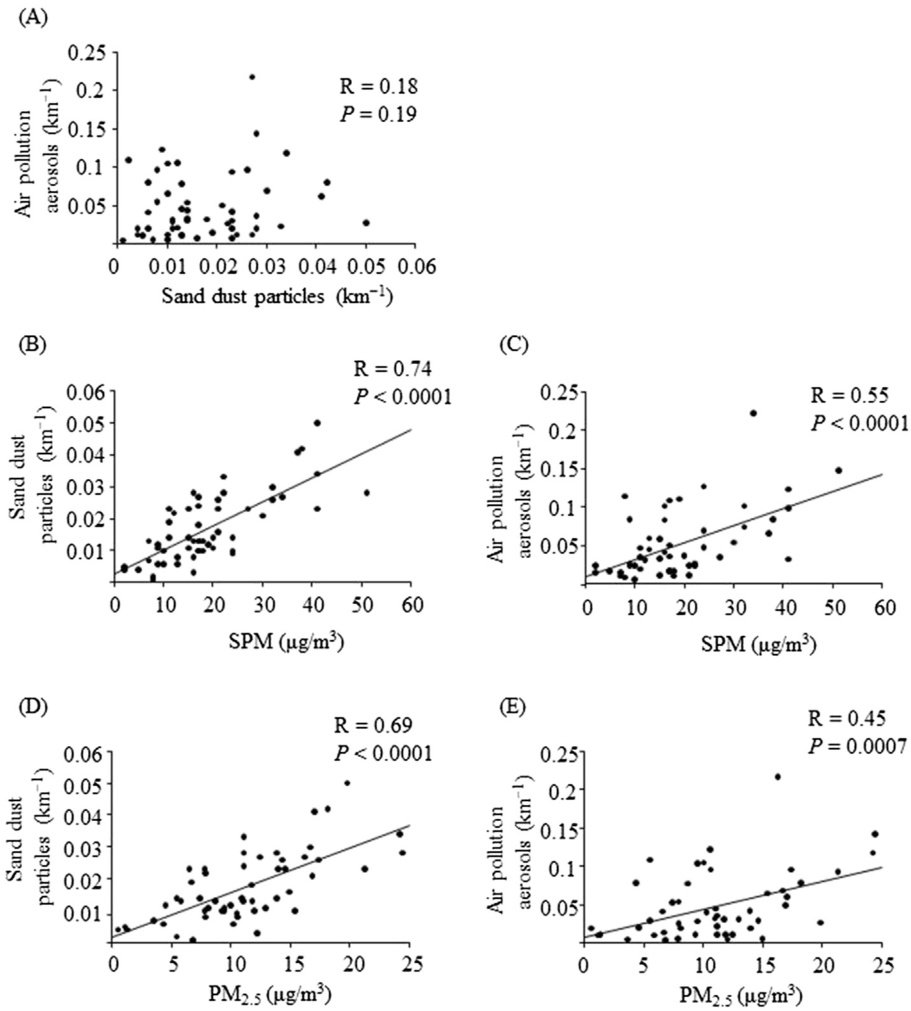

Fig. 2. Associations of sand dust particles with air pollution aerosols (A), suspended particulate matter (SPM) (B), and particulate matter smaller than 2.5 μm ($PM_{2.5}$) (C). Association of air pollution aerosols with SPM (D) and $PM_{2.5}$ (E).

quantity of sand dust emissions from East Asian deserts and air pollution aerosols; however, they are unable to recognize the size of particulate matter. This study found that sand dust emissions from East Asian deserts were associated with pulmonary function in schoolchildren, although the significant associations did not persist.

The South Korean study did not find a significant relationship between ADS events and PEF in children without asthma using $PM_{2.5}$ and PM_{10} levels.[16] In contrast, in this study, the levels of sand dust particles, SPM, and PM2.5 were significantly associated with decreased PEF in children without asthma. This discrepancy may be because this study had four times as many subjects as the South Korean study. Our study was planned to have sufficient statistical power to test the hypothesis. Another cause may be the difference in composition of particulate matter between western Japan and Korea because the effects of particulate matter on production of pro-inflammatory cytokine differed with composition.[26]

LIDAR systems lack defined criteria for heavy dust days. Kanatani *et al.* defined one as a daily (24-h) median sand dust particle level of >0.1 km^{-1}, which equaled 100 $\mu g/m^3$ of SPM, and found a significant association with heavy dust exposure and hospital admission in children with asthma.[14] Another study determined a moderate dust day as 0.066 km^{-1} and a heavy dust day as 0.105 km^{-1} to estimate the association between sand dust emissions and emergency ambulance dispatches.[27] They found that heavy dust days were associated with an increase in emergency dispatches from all causes and cardiovascular disease, whereas moderate dust days showed no association. During this study, the daily median level never exceeded 0.06 km^{-1}. Low level exposure to sand dust emissions may at least have a potential to induce minor pulmonary dysfunction in children, but it is unable to increase emergency ambulance dispatches and hospital admissions in children with asthma. It may be necessary to classify the risk levels of LIDAR data, as done for other air pollutants.

Table 2
Association of PEF with IQR increases in the levels of sand dust particles, air pollution aerosols, SPM, and $PM_{2.5}$ according to multivariate analyses using linear mixed models.

Exposure metric	IQR	Change in PEF (L/min)	95% CI	*P*-value
Sand dust particles	0.018 km^{-1}	−3.62	−4.66, −2.59	<0.0001
Air pollution aerosols	0.065 km^{-1}	−4.62	−5.59, −3.64	<0.0001
SPM	14.0 $\mu g/m^3$	−2.16	−2.88, −1.43	<0.0001
$PM_{2.5}$	10.7 $\mu g/m^3$	−2.58	−3.59, −1.57	<0.0001

IQR, interquartile range; CI, confidence interval; PEF, peak expiratory flow; SPM, suspended particulate matter; $PM_{2.5}$, particulate matter smaller than 2.5 μm in diameter.

NO_2, O_3, and SO_2 are gaseous air pollutants, not airborne particles. Non-mineral dust particles are identified as air pollution aerosols by LIDAR. Few have investigated the association of pulmonary function in children with air pollution aerosols except PM_{10}, $PM_{2.5}$, and SPM. To the best of our knowledge, this is the first study to show that an increased level of air pollution aerosols determined by LIDAR is clearly linked with decreased pulmonary function in children.

Both sand dust particles and air pollution aerosols showed significant associations with PM_{10} and $PM_{2.5}$. However, there was no significant association between sand dust particles and air pollution aerosols. Onishi *et al.* suggested that heavy dust events originating from deserts in East Asia can be classified into three types on the basis of LIDAR data: Type 1 events with high levels of aerosolized air pollutants, Type 2 events with high levels of sand dust particles relative to those of aerosolized air pollutants, and Type 3 events with very low levels of aerosolized air pollutants.[8] Sand dust emissions in East Asia contain chemicals, metals, microorganisms, and ions from urban or industrial pollutant emissions in many regions.[6–8,10] When the levels of both sand dust particles and air pollution aerosols are high, the decrease in pulmonary function may be more severe. In future, it may be necessary to study the synergistic effects of sand dust particles and air pollution aerosols in East Asia on pulmonary function.

Nasopharyngeal dysfunction, such as allergic rhinitis, plays an important role in bronchoconstriction.[28] Onishi *et al.* found that an increase in air pollutant levels on ADS days affect the skin.[29] Park and Yoo found a relationship between ADS occurrence and PEF in South Korean children with asthma, but other South Korean study was unable to find any relationship between ADS events and PEF in children without asthma.[15,16,30] There is a relationship between atopic disposition and airway hyperresponsiveness in children.[31] The influence of air pollutants on airway may differ depending on whether allergic diseases are present. Therefore, we also adjusted for allergic diseases while analyzing for the association of air pollutants with PEF. In addition, although a previous study reported that gender influences the risk of wheezing and the prevalence of asthma in childhood,[32] but we found no association between gender and asthma in our study.

There are several limitations in the study. First, the number of children with asthma may be small. Second, we were unable to diagnose asthma on the basis of airway hyperresponsiveness to methacholine and reversible airflow limitation. Third, we did not investigate diseases except asthma, allergic rhinitis, allergic conjunctivitis, atopic dermatitis, and food allergies. Fourth, missing PEF values due to absence from school were excluded from data analysis. However, this intermittent missing data was statistically independent and did not cause any serious biases in the results. Finally, this study period was limited. We were also unable to assess the seasonal variation in the association of sand dust particles with SPM and $PM_{2.5}$. Further study is needed to estimate the relationship between sand dust particles and pulmonary function throughout the year.

In conclusion, we found a significant association between pulmonary function in schoolchildren and daily levels of sand dust particles. SPM and $PM_{2.5}$ also showed significant negative associations with PEF in children. These findings suggest that sand dust emissions in East Asia may exacerbate pulmonary dysfunction in children.

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Conflict of interest

The authors have no conflict of interest to declare.

Authors' contributions

MW, JK, HS, and ES designed the study. MW and HNo wrote the manuscript. MW, KK, TT, HNa, and AY contributed to data collection. MW and HNo performed the statistical analysis and interpretation of the results. MW, HNo, and ES contributed to critical revision of important intellectual content. All authors read and approved the final manuscript.

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