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Exposure to Fine Particles by Mine Tailing and Lung Function Effects in a Panel of Schoolchildren, Chañaral, Chile

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Abstract

There is much literature on the effects of fine particulate matter ($PM_{2.5}$) on respiratory and cardiovascular health. However, few studies have evaluated the impact of $PM_{2.5}$ on a population living in the vicinity of a massive deposit of mine tailings. A longitudinal panel study was performed to evaluate the association between exposure to $PM_{2.5}$ and acute effects on lung function in schoolchildren from November 2012 to May 2013. Ambient levels of $PM_{2.5}$ and its metal composition were measured. Lung function was evaluated using spirometric testing. Associations were quantified using GEE multilevel analysis controlling for confounders by using different lag time periods. The chemical characterization of $PM_{2.5}$ had high levels of S > Na > Cl > Ca > Si > Fe > Al > Mg > K > Cu > Ti > and Zn, which would be associated with metals present in tailings. We found a negative association between the temporal variation of $PM_{2.5}$ and changes in lung function specifically on forced vital capacity. Our results suggest that schoolchildren exposed to fine particulate matter from tailings deposited in the bay of Chañaral have their forced vital capacity decreased, which would affect their present and future lung development, increasing the risk of developing chronic respiratory diseases.

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Keywords

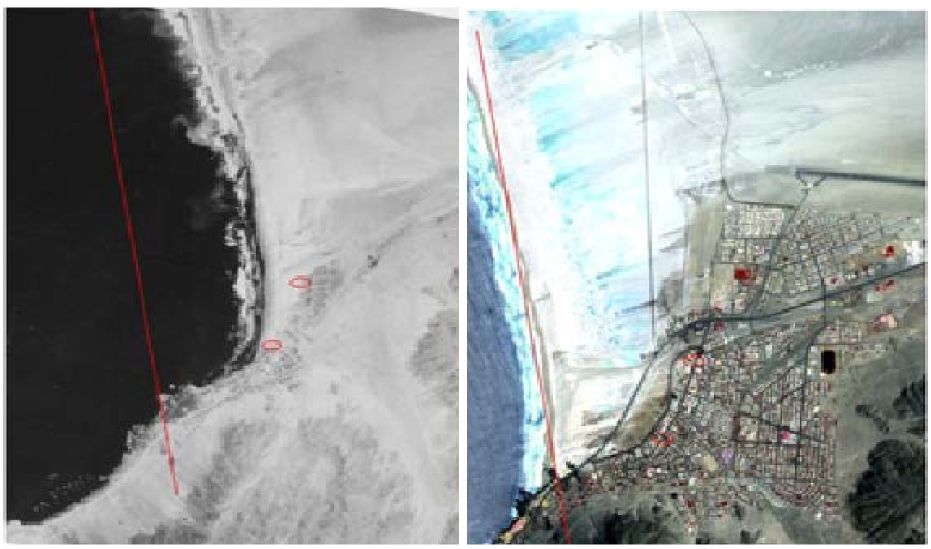
Mine Tailings, Fine Particulate Matter, Heavy Metals, Lung Function, Schoolchildren

1. Introduction

Particulate matter is a complex mixture of solid particles and liquid droplets found in the air, which comes from various natural and anthropogenic sources. This form of pollutant can have different sizes and can be composed of many types of materials and chemicals [1] [2]. Numerous epidemiological studies have found that the exposure to PM, especially the fine fraction ($PM_{2.5}$) has adverse effects on human health, especially for vulnerable populations [1] [3] [4]. Children are more vulnerable than adults to the effects of exposure to polluted air, due to their stage of physical growth, immature immune system, and developing respiratory organs with a more susceptible and reactive respiratory epithelium [3] [5]. Extensive evidence has associated exposure to $PM_{2.5}$ from vehicular traffic and fuel burning with impaired pulmonary function and increased respiratory complaints on children [3] [4] [6]-[11]. However, few studies have reported on the effects of PM from the soil and dust of mine tailings [12] [13].

Chile is one of the largest copper producers worldwide, and therefore copper is one of the country's major sources of economic income of the country [14]. Most mines are in the central and northern Chile, distributed along the Cordillera de Los Andes. El Salvador is an open-pit mine, located at 2600 m above sea level (26˚15' South Lat. S.; 69˚ West Long). The chemical composition of this mineral corresponds to cuprous primary porphyry mineralization, which one is characterized by alkali feldspar-biotite-anhydrite-chalcopyrite and bornite-chalcopyrite-pyrite mineral assemblages [15]. As a result of the mining operations, between 1939 and 1975, more than 150×10^6 Mg of tailing were discharged continuously into the Rio Salado without any treatment, being deposited in the bay of Chañaral. This modified the coastline, expanding the area of the beach significantly and causing a heavy siltation and pollution of the bay, directly affecting more than 20 km of coastline and covering about 12 km^2 [16] [17] (**Figure 1**). This resulted in pollution of tailings sands rich in Cu, Fe, As, Zn, Cn, Pb, As, Hg, Mo and other heavy metals [18] [19]. Coastal winds carry the particulate material contamination over the town of Chañaral. Neary and Garcia-Chevesich report a high incidence of cancers and skin, respiratory, and eye diseases that would be associated with exposure to particulate matter as a result of prevailing coastal winds [17].

The objective of the present study was to evaluate the relationship between lung function and exposure to environmental $PM_{2.5}$, among a panel of schoolchildren living near a beach highly contaminated with mine tailings.



(a) (b)

Figure 1. (a) Oblique photography trimetrogon taken in 1948; (b) SPOT satellite image of 2006. The figure on the left shows the approximate position of the original coast (red line).

2. Materials and Methods

2.1. Study Design and Location

A longitudinal panel study was performed using a spatially representative sample of children aged 6 to 15 years residing in Chañaral, Atacama Region, Chile (**Figure 2**), during the period from November 2012 to May 2013. Chañaral has a surface area of 5772 km^2, with a population of 13,543 inhabitants, according to the 2002 census and projected for 2012 is 12,570 inhabitants. The area's main commercial activity is mining, followed by fishing. Geographically, Chañaral has arid desert conditions with scarce rainfall, resulting in sparse vegetation. The local prevailing winds are west to east. The general dryness of the desert environment, combined with the circulation of winds, promotes suspension and transport of dust from the mine tailings towards the valleys [17].

2.2. Sample Design and Subjects

The sampling frame for the study was all schoolchildren aged 6 to 15 years attending all elementary schools in the city of Chañaral (n = 1896). The estimated sample required was 115 children, assuming an average effect size of −0.04 L/min of decreased lung function for each 1 μg/m^3 increase in PM concentration, with the significance criterion set at 5% and a statistical power of 80% [20]. The sample size was increased by 20% to adjust for attrition. Therefore, the final estimated sample size was n = 158.

To ensure spatial representativeness, we used a stratified sampling design based on Neyman's optimal allocation, with 3 strata according to the perpendicular distance of a child's house from the beach (**Figure 3**). Schoolchildren were selected within these strata by systematic random sampling.

2.3. Data Collection

Sociodemographic and health variables. After signing the informed consent document, the parent or legal guardian of the participant responded to a questionnaire to collect the sociodemographic data, health history, and information about environmental pollutant exposure in the household [21].

Particulate matter and meteorological variables. PM levels were measured for 182 days by a certified company (CESMEC S.A) using a monitoring station with adequate coverage of the target area, located in the city of Chañaral (Latitude 26˚20'17.54"S Longitude 70˚36'57.58"O) (**Figure 3**). TERMO® 5014i equipment for mea-

Figure 2. Map of Chile and Chañaral, Atacama region. Source: Adapted of geographic atlas of Chile and the world, Ed. Vicens Vives, Santiago 2009.

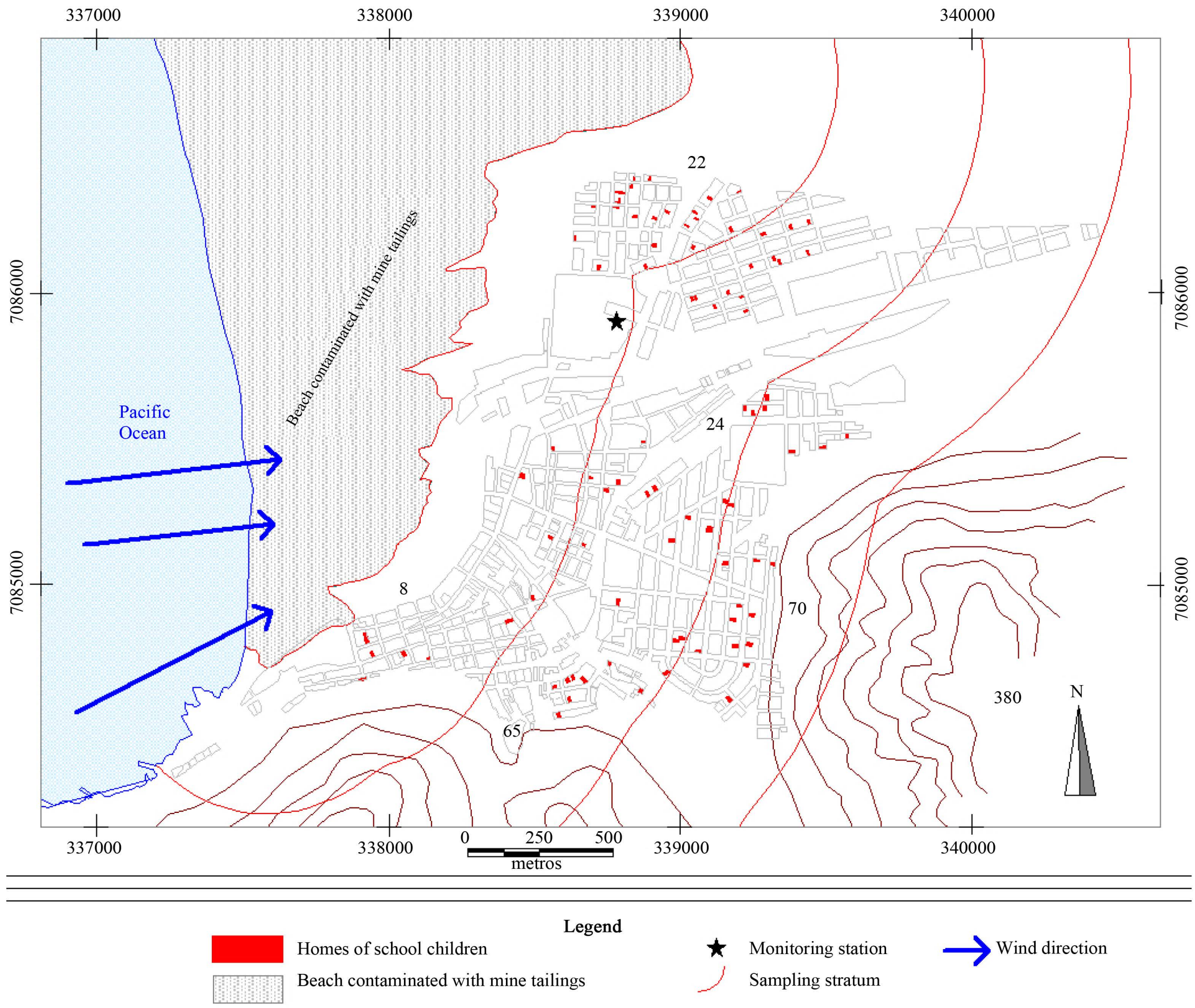


Figure 3. Dividing lines of the strata and location of households of schoolchildren participating and the monitoring station, Chañaral, Atacama Region, Chile 2012-2013.

suring $PM_{2.5}$ was used. Furthermore, a meteorological station at the same location was used to record wind velocity, temperature, relative humidity, solar radiation, barometric pressure, and precipitation. The concentration of metals in $PM_{2.5}$ filters was determined with X-ray Florescence XRF an EPA approved methods [22].

Lung function. The children underwent spirometry testing during the school day (morning) at their respective schools, approximately every 2 weeks, from November 12, 2012 to May 10, 2013. Personnel were trained according to the international norms issued by the American Thoracic Society (ATS) guidelines [23], translated and adapted by the Chilean Society of Respiratory Diseases in 2006 [24]. A portable Easy One Spirometer® was used for the measurements. Forced vital capacity maneuvers were performed. Spirometric curves that met ATS acceptability and reproducibility criteria were selected for analysis [24]. At least 3 maneuvers were performed. If the first 3 maneuvers did not meet acceptability and reproducibility criteria, up to 8 maneuvers were performed. Forced expiratory volume in 1 second (FEV_1), forced vital capacity (FVC), peak expiratory flow (PEF), and forced expiratory flow during the middle portion of the FVC (FEF_{25-75}) were recorded.

Anthropometric measurements: Were carried out two weeks before began the functional lung measurements by trained personnel. In this occasion, schoolchildren participated in training for the lung function testing.

2.4. Statistical Analysis

Descriptive and exploratory analyses were performed on the database. The relationships between the variables were examined using correlations, scatter plots, and box plots. PM concentration levels throughout the study period were analyzed, and lags were established to study its effect on the lung function at time 0 (lag0) as well as the effect of the average, 75th percentile, and maximum values for the 4, 12, and 24 hours prior to the test (lag4 avg, lag12 avg, lag24 avg, lag4 P75, lag12 P75, lag24 P75, lag4 max, lag12 max, lag24 max). Associations between PM and lung function values were studied using a multi-level model of repeated measures nested within schoolchildren, we used Generalized Estimating Equations (GEE) [25] with an unadjusted and adjusted analyses. Analyses were performed using the STATA 11.1 program.

2.5. Ethical Issues

This study was approved by the Ethic Committee for Human Research from the Faculty of Medicine at the University of Chile and funded by the Chilean National Fund for Research and Development in Health (CONICYT-FONIS: N˚ SA11|2244).

3. Results

We invited 158 children (and their parents) to participate, via meetings to provide information about the study's purpose and participation requirements. We were able to recruit 119 children, 9 of whom (7.5%) abandoned the study, of which 6 did so before completing the questionnaire, and 3 before starting the measurements. Therefore, 110 children were followed. **Figure 3** shows the location of the homes of the participating schoolschildren. The anthropometric and sociodemographic data for the 110 participants are shown in **Table 1**. The majority of children were male (58.18%), and average age at recruitment was 11.2 years (SD = 2.7). The anthropometric variables showed similar distributions for both sexes, with no significant differences. For both the mother and the father of the children, the most common education level category was 9 to 12 years (58.18% and 48.18%, respectively), followed by the category 8 or fewer years of education. Smoking prevalence of at the time of the questionnaire was similar for the father and mother of the child. Asthma and rhinitis prevalence was 9.1%, and 10.9%, respectively.

The spirometry values for the children are presented in **Table 2**. Spirometry values increased progressively with age's groups; there were significant differences for all spirometry values between age groups, as well as between sexes. There were no significant differences between groups according to asthma and rhinitis diagnosis, education level or smoking status of parents.

Table 3 shows the average levels by minute as well as the 24-hour average for the PM and meteorological variables during the study period. The $PM_{2.5}$ levels by minute showed a range of 0.01 to 172.5 μg/m^3. The meteorological variables showed narrower ranges of variability. There were no extreme temperatures recorded during the study period; furthermore, the relative humidity and barometric pressure were relatively stable and showed no relationship with PM variation. **Figure 4** displays a time series for the 24-hour average (daily) $PM_{2.5}$ concentrations and wind velocities as well as the 25th and 75th percentiles (P25, P75) of the daily measurements for these variables throughout the study period, along with Chilean norms for 24-hour average $PM_{2.5}$ concentration. As shown, the variability of the wind velocity was higher during the first 3 months of the study, corresponding with the higher PM levels recorded for the same period. The 24-hour average of $PM_{2.5}$ exceeded the Chilean norm of 50 μg/m^3 only one occasion.

The chemical composition of the environmental PM_{10} in Chañaral during the study period was analyzed as part of another study, and therefore we will not go into detail here regarding the procedures and analyses performed to determine these values. Briefly, the average concentrations of metals and metalloids found in the PM_{10} in Chañaral were, in descending order: Cl > Si > S > Ca > Al > Fe > K > Cu > Mg > Ti > Zn; comparatively, these average levels are higher than those reported in other studies carried out in the central and northern zones of Chile [26] [27]. On the other hand, to $PM_{2.5}$ the descending order were S > Na > Cl > Ca > Si > Fe > Al > Mg > K > Cu > Ti > and Zn.

Table 4 shows the regression coefficients and 95% confidence intervals for the average associations between $PM_{2.5}$ concentration and lung function in GEE models. We fitted this model including only 105 schoolchildren because 5 subjects abandoned the study during the first weeks of follow-up. There were significant negative associations between $PM_{2.5}$ levels and the lung function variables analyzed. The regression coefficients represent the average decrease in lung function values for a 1-unit increase in $PM_{2.5}$ concentration. In the unadjusted model, lag12 max $PM_{2.5}$ concentration was negatively associated with decreased FEV_1 (β −0.75 ml, 95% CI −1.4,

Table 1. Anthropometric and sociodemographic characteristics of the schoolchildren studied. Chañaral, Atacama region, Chile, 2012-2013.

Anthropometric Measures	Average	SD
Age, years	11.2	2.7
Height, cm	144.2	15.5
Weight, kg	44.4	13.2
Body Mass Index (BMI)	20.9	3.5
Sociodemographic Characteristics	**n**	**%**
Male	64	58.18
Mother's education level		
8 years or less	20	18.18
9 to 12 years	64	58.18
13 years or more	13	11.82
Don't know/no answer	13	11.82
Father's education level		
8 years or less	23	20.91
9 to 12 years	53	48.18
13 years or more	17	15.45
No answer	17	15.45
Smoking status of mother		
Never smoked	36	32.73
Current smoker	36	32.73
Ex-smoker	25	22.72
Don't know/no answer	13	11.82
Smoking status of father		
Never smoked	29	26.37
Current smoker	40	36.36
Ex-smoker	18	16.36
Don't know/no answer	23	20.91
Asthma diagnosis		
Yes	10	9.09
No	79	71.82
Don't know/no answer	21	19.09
Rhinitis diagnosis		
Yes	12	10.91
No	79	71.82
Don't know/no answer	12	17.27
Type of school		
Private	10	9.09
Municipal	100	90.91
Strata		
Strata 1 (<600 mts)	44	40
Strata 2 (600 - 1200 mts)	60	54.55
Strata 3 (>1200 mts)	6	5.45

SD: standard deviation.

−0.03) *i.e*. for every 1 unit increase in the maximum concentration of 12 hour $PM_{2.5}$ decreases the FEV_1 0.75 ml with a confidence interval between −1.4 and −0.03 ml, which it does not include the value of invalidity (0) allows us to conclude the negative association is significant and not due to chance; lag4 and lag12 avg $PM_{2.5}$ were also negatively associated with FVC (β −2.42 ml, 95% CI −4.7, −0.1; and β −5.07 ml, 95% CI −8.9, −1.1, respectively), as were lag4, lag12, and lag24 max $PM_{2.5}$ levels (β −1.74 ml, 95% CI −2.7, −0.8; β −1.90 ml, 95% CI −2.8, −1.01; and β −2.01 ml, 95% CI −2.9, −1.03, respectively). In the unadjusted analysis, the only flow value showing a significant negative association with PM was PEF, which was negatively associated with lag24

Table 2. Lung function values of the schoolchildren during the study period. Chañaral, Atacama region, Chile, 2012-2013.

	n*	n**	FEV_1 (ml)	FVC (ml)	PEF (ml/sec)	FEF_{25-75} (ml/sec)
			Average (SD)	Average (SD)	Average (SD)	Average (SD)
≤9 years	28	136	1706.5 (408.01)	2081.8 (472.5)	3719.5 (1093.3)	1802.8 (624.2)
9 to 11 years	24	113	2018.7 (402.5)	2385.3 (420.0)	4561.3 (915.3)	2344.2 (768.9)
11 to 13 years	22	111	2378.8 (364.7)	2898.04 (432.5)	5097.1 (1156.1)	2487.6 (722.6)
>13 years	36	151	3385.4 (706.6)	3983.7 (916.0)	7012.2 (1511.9)	3692.3 (934.1)
Total	110	511	2417.7 (838.4)	2888.2 (984.7)	5177.9 (1763.5)	2629.6 (1068.3)

*Number of schoolchildren; **Number of spirometry tests. SD: standard deviation, FEV_1 (ml): forced expiratory volume during the first second (milliliter), FVC (ml): forced vital capacity (milliliters), PEF (ml/sec): peak expiratory flow (milliliters/seconds), FEF_{25-75} (ml/sec): forced expiratory flow 25 - 75 (milliliters/seconds).

Table 3. Particulate matter and meteorological variables during the study period. Chañaral, Atacama Region, Chile, 2012-2013.

	N	**Average (SD)**	**P25**	**P50**	**P75**	**Min - max**
Measurements during the study period*						
$PM_{2.5}$ (μg/m³)	207,519	17.15 (15.24)	7.88	13.58	23.08	0.01 - 172.5
Temperature (˚C)	260,832	18.39 (2.71)	16.51	18.07	20.14	10.44 - 27.35
Relative humidity (%)	260,832	70.13 (8.93)	63.85	71.27	77.26	34.33 - 89.9
Wind velocity (m/s)	260,832	2.59 (1.80)	1.10	2.19	3.93	0 - 10.26
Barometric pressure (mmHg)	260,832	757.23 (1.53)	756.2	757.2	758.2	751.8 - 762.5
24-hour average**						
$PM_{2.5}$ (μg/m³)	182	13.63 (5.86)	10.7	12.5	14.8	4.3 - 50.1

*By minute; **By day. SD: standard deviation. P25: 25th percentile, P50: 50th percentile, P75: 75th percentile, min - max: minimum - maximum, PM: particulate matter, μg/m³: micrograms/cubic meters, ˚C: degrees Celsius, m/s: meters/second, mmHg: millimeters of mercury.

Table 4. Regression coefficients [unadjusted and adjusted] for a 1-unit increase in $PM_{2.5}$ level (CI 95%) on lung function values in schoolchildren of Chañaral, Atacama region, Chile, 2012-2013.

	FEV_1 (ml)		**FVC (ml)**		**PEF (ml/sec)**		**FEF_{25-75} (ml/sec)**	
	$Coef_{unadj}$ IC 95%	$Coef_{adj}$* IC 95%	Coefunadj IC 95%	$Coef_{adj}$* IC 95%	$Coef_{unadj}$ IC 95%	$Coef_{adj}$* IC 95%	$Coef_{unadj}$ IC 95%	$Coef_{adj}$* IC 95%
$PM_{2.5}$								
lag0	1.08 (−2.3, 0.2)	−1.22 (−2.5, 0.1)	−1.63 (−3.4, 0.1)	−1.77 (−3.6, 0.03)	−1.67 (−6.2, 2.8)	−2.19 (−6.7, 2.3)	−0.55 (−3.9, 2.8)	−0.72 (−4.1, 2.6)
lag4 avg	−0.79 (−3.0, 1.4)	−0.38 (−2.6, 1.8)	**−2.42 (−4.7, −0.1)**	−1.88 (−4.2, 0.4)	−0.37 (−6.9, 6.1)	0.66 (−5.8, 7.1)	2.21 (−2.7, 7.1)	2.93 (−1.9, 7.8)
lag12 avg	−2.05 (−4.8, 0.7)	−0.47 (−3.2, 2.2)	−5.07 (−8.9, −1.1)	−3.47 (−7.2, 0.2)	−1.30 (−10.2, 7.6)	1.95 (−7.3, 11.2)	5.13 (−1.8, 12.1)	7.71 (−0.1, 15.2)
lag24 avg	0.30 (−1.9, 2.5)	−0.77 (−3.1, 1.6)	−0.85 (−3.7, 2.1)	−2.71 (−6.3, 0.9)	3.79 (−4.2, 11.8)	2.35 (−6.5, 11.2)	2.73 (−2.4, 7.9)	3.41 (−2.0, 8.8)
lag4 P75	0.07 (−1.4, 1.5)	0.86 (−0.6, 2.3)	−1.07 (−2.6, 0.5)	−0.14 (−1.6, 1.3)	−2.25 (−7.4, 2.9)	−0.32 (−5.3, 4.7)	2.96 (−0.7, 6.6)	3.92 (−0.2, 7.6)
lag12 P75	0.51 (−2.4, 3.4)	2.06 (−0.8, 4.9)	0.01 (−3.3, 3.3)	1.87 (−1.5, 5.2)	−0.44 (−10.3, 9.3)	3.67 (−6.1, 13.4)	4.47 (−2.5, 11.4)	6.25 (−0.8, 13.3)
lag24 P75	0.14 (−3.6, 3.9)	0.52 (−3.5, 4.6)	1.91 (−3.1, 6.8)	2.33 (−2.7, 7.4)	−4.36 (−16.8, 8.1)	−3.16 (−15.8, 9.5)	2.04 (−7.8, 11.9)	3.49 (−7.1, 14.1)
lag4 max	−0.66 (−1.5, 0.2)	0.14 (−0.8, 1.1)	**−1.74 (−2.7, −0.8)**	−0.81 (−1.7, 0.2)	−1.98 (−5.1, 1.1)	0.06 (−3.1, 3.2)	1.09 (−1.3, 3.5)	−2.24 (−0.2, 4.6)
lag12 max	**−0.75 (−1.4, −0.03)**	0.13 (−0.6, 0.8)	**−1.90 (−2.8, −1.01)**	**−0.96 (−1.8, −0.1)**	−2.61 (−5.3, 0.1)	−0.51 (−3.2, 2.1)	1.63 (−0.4, 3.6)	2.89 (−0.7, 5.0)
lag24 max	−0.72 (−1.5, 0.1)	0.16 (−0.7, 1.1)	**−2.01 (−2.9, −1.03)**	**−1.19 (−2.3, −0.1)**	**−2.93 (−5.7, −0.1)**	−0.96 (−3.8, 1.9)	1.86 (−0.3, 4.0)	3.47 (−1.2, 5.7)

*GEE model adjusted for age, sex, weight, wind speed, ambient temperature; Significant values in bold. FEV_1 (ml): forced expiratory volume in one second (ml), FVC (ml): forced vital capacity (milliliters), PEF (mL/sec): peak expiratory flow (milliliters/second), FEF_{25-75} (mL/sec): forced expiratory flow 25 - 75 (milliliters/second). $Coef_{unadj}$: unadjusted coefficient, $Coef_{adj}$: adjusted coefficient, PM: particulate matter, μg/m³: microgram/cubic meter, P75: 75th percentile.

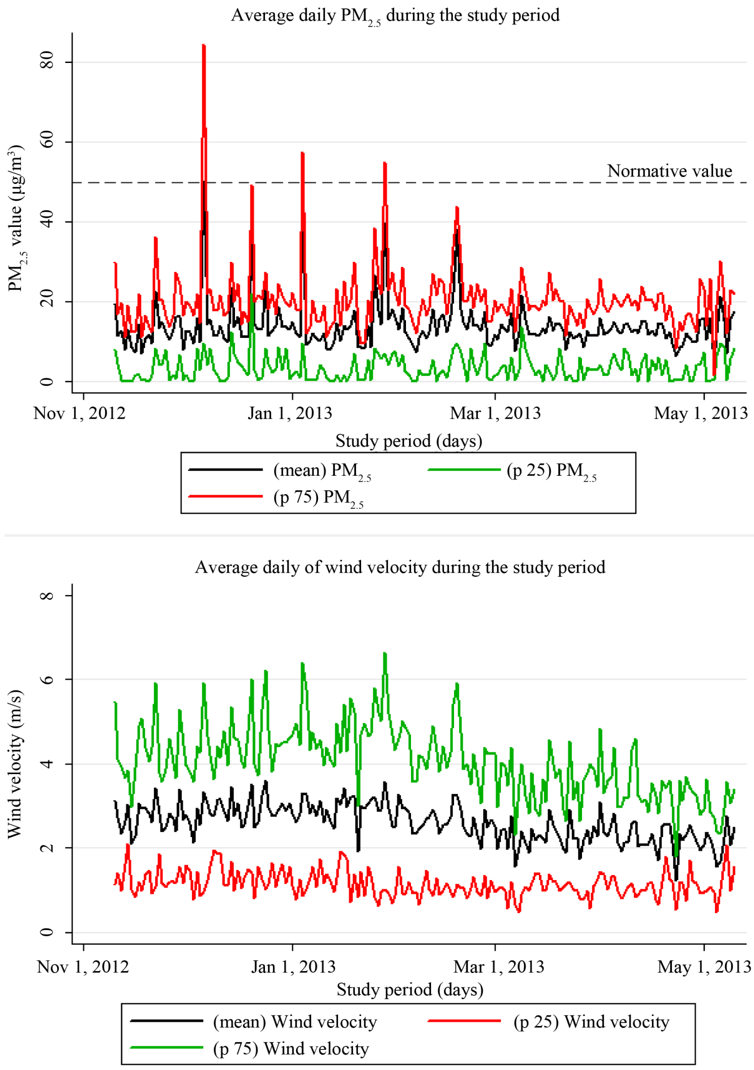


Figure 4. Descriptive time series showing 24-hour $PM_{2.5}$ and wind velocity values during the study period. Chañaral, Atacama region, Chile, 2012-2013.

max $PM_{2.5}$ concentration (β −2.93 ml/sec, 95% CI −5.7, −0.1). After adjusting for age, sex, weight, environmental temperature, and wind speed, only the negative associations between lag12 max and lag24 max $PM_{2.5}$ levels and FVC remained significant. Non-significant relationship with lung function was observed when we fitted a model considering the distance of households of schoolchildren to tailings deposit (as a continuous variable and according to categories of strata), the diagnosis of asthma and rhinitis as well as parental smoking were considered (data not shown).

4. Discussion

In order to study the short-term effect of environmental exposure to PM on lung function values, we found a negative association between environmental exposure to PM and spirometry values, in an urban population of schoolchildren living near a beach contaminated with mine tailings. This decrease in lung function was especially marked for FVC impairment associated with fine particulate matter exposure ($PM_{2.5}$).

In other studies with similar panel designs, the PM value most commonly reported has been the median of 24-h average concentrations during the period studied. For $PM_{2.5}$, the median 24-h concentration in this study (12.5 µg/m^3) moderately exceeded the value reported by Trenga *et al.* [11] at 11.2 µg/m^3 for a residential area in Seattle, United States and markedly exceeded the value reported by Dales *et al.* at 6.5 µg/m^3 for an area affected by heavy truck traffic in Windsor, Canada [8]; however, a study performed by Moshammer *et al*. in a zone exposed to industrial pollution and vehicular traffic in Linz, Austria [6] reported a median value of 15.79 $\mu g/m^3$, exceeding the value reported in the present study.

Due to the controversy of suggesting that central site measurements may not be representative of individual or residential community exposure, Trenga *et al*. studied the differences between concentrations measured in the central site and those measured immediately outside personal residences. The author found a strong correlation between the two values (r = 0.77) [11]. This finding is very important, as most studies on the health effects of air pollution rely on central site measurements, including the present study.

The average metal and metalloid concentrations found in the PM_{10} in Chañaral were generally greater than those reported by other studies in different cities and mining zones in northern Chile and are consistent with the metal measured for this population in different studies [17] [18] [26] [28]. Several studies in animal models suggest that the bioavailable metal transition is one the primary determinants of the acute inflammatory response for both the combustion source and ambient PM samples [2] [29]-[31]. Genotoxic and epigenotoxic effects on human bronchial epithelial cells have been reported due to variable concentrations of transition metals and organic compounds [32] [33].

Pulmonary development, immune function, and respiratory response to various air pollutants are interrelated via complex multifactorial processes [34], possibly explaining the high degree of variability for lung function values reported.

The results of the association analysis for PM and lung function are largely consistent with the literature. However, the type of measure reported varies by study. Some authors have reported changes in lung function for each 10 $\mu g/m^3$ of change in PM or change in interquartile range (IQR) of PM, while other authors have focused on variations in spirometry values as compared to predicted values. Furthermore, the time lags used vary among studies, making it difficult to compare results. $PM_{2.5}$ was negatively associated with FEF_{25-75} in the study by Trenga *et al*., carried out on children with asthma, and with FEV_1 and PEF in the study by Moshammer *et al*., carried out on healthy children in Linz, Austria. Dales *et al*. only studied FEV_1 values in asthmatic children, finding a negative association with 12-h lag $PM_{2.5}$ concentration. In our study, we found negative unadjusted associations between FEV_1 and 12-h lag maximum $PM_{2.5}$ concentration and between PEF and 24-h lag maximum $PM_{2.5}$ concentration, which is consistent with the findings reported by Moshammer *et al*. in healthy children. The same authors also found a marked association between average and maximum 4 and 12-h lag $PM_{2.5}$ levels with FVC as well as 24-h lag maximum levels with FVC.

Most of the significant associations found with $PM_{2.5}$ levels were for FVC. This measure is the maximum capacity of air expelled during a forced expiration and represents a concrete indicator of pulmonary capacity. Decreased FVC indicates a restrictive ventilatory defect. One of the causes described in the literature for this type of limitation is inhalation of organic and inorganic dust. However, the findings in this study represent acute variation in FVC rather than a progressive decrease in function over time. To confirm the long-term effects of exposure, it would be necessary to extend the study to follow the children for several more years. The sample of schoolchildren studied was mostly healthy, and the associations between PM concentration and lung function did not vary according to asthma or rhinitis diagnosis; that is, exposure to increased $PM_{2.5}$ levels impairs respiratory function in the short-term regardless of asthma or rhinitis diagnosis.

While changes in lung function as a result of chronic exposure become evident at more advanced ages, the fact that we found associations between short-term $PM_{2.5}$ exposure and lung function indicates that schoolchildren in Chañaral are currently affected by the exposure. Further chronic effects may emerge during adulthood. Moreover, given that the $PM_{2.5}$ studied contained metallic particles, long-term exposure may have other silent and cumulative effects not only on the respiratory system but also on other organs due to bio-accumulation of heavy metals.

These findings underscore the need for further studies in communities exposed to air pollution from various sources in order to uncover other acute or chronic effects of exposure to pollution from mine tailings.

5. Conclusion

The present study is the first report of the respiratory health effects of exposure to PM from mine tailings among the inhabitants of Chañaral. Increased $PM_{2.5}$ levels associated with toxic metals affect the respiratory function of schoolchildren living in the city and the variation in FVC suggests that these children may be vulnerable to effects of long-term exposure. Measures to control or decrease exposure in this population are needed, and we hope that the evidence reported here will contribute to such efforts.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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