Long-term impact of coal mine fire smoke on lung mechanics in exposed adults

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Abstract
Background and objective: In 2014, a 6-week-long fire at the Hazelwood coal mine exposed residents in the adjacent town of Morwell to high concentrations of fine particulate matter with an aerodynamic diameter < 2.5 μm (PM2.5). The long-term health consequences are being evaluated as part of the Hazelwood Health Study.

Methods: Approximately 3.5–4 years after the mine fire, adults from Morwell (n = 346) and the comparison town Sale (n = 173) participated in the longitudinal Respiratory Stream of the Study. Individual PM2.5 exposure was retrospectively modelled. Lung mechanics were assessed using the forced oscillation technique (FOT), utilizing pressure waves to measure respiratory system resistance (Rrs) and reactance (Xrs). Multivariate linear regression was used to evaluate associations between PM2.5 and transformed Rrs at 5 Hz, area under the reactance curve (AX5) and Xrs at 5 Hz controlling for key confounders.

Results: There were clear dose–response relationships between increasing mine fire PM2.5 and worsening lung mechanics, including a reduction in post-bronchodilator (BD) Xrs5 and an increase in AX5. A 10 μg/m3 increase in mine fire-related PM2.5 was associated with a 0.015 (95% CI: 0.004, 0.027) reduction in exponential (Xrs5) post-BD, which was comparable to 4.7 years of ageing. Similarly, the effect of exposure was associated with a 0.072 (0.005, 0.138) increase in natural log (lnAX5) post-BD, equivalent to 3.9 years of ageing.

Conclusion: This is the first study using FOT in adults evaluating long-term respiratory outcomes after medium-term ambient PM2.5 exposure to coal mine fire smoke. These results should inform public health policies and planning for future events.

KEYWORDS
air pollution, coal mine fire, environmental lung disease, forced oscillation technique, lung mechanics, particulate matter, respiratory, smoke

INTRODUCTION

Ambient air particulate matter (PM) exposure, from sources including vehicle exhaust, industry, biomass fuels and wildfires, collectively account for an estimated 7.5% of all deaths globally in 2016. In particular, fine PM with a median aerodynamic diameter < 2.5 μm (PM2.5) infiltrates deep into the peripheral lung. Short-term (days) exposure to PM2.5 has been shown to be associated with cardiovascular and respiratory morbidity and mortality. Guo et al. showed in a large cohort study that long-term ambient PM2.5 exposure was consistently associated with reduced lung function, accelerated annual lung function decline and an increased risk of developing chronic obstructive pulmonary disease (COPD) in adults. Similarly, in a review, Li et al. showed an association with long-term exposure to ambient air pollution levels and increased incidence of respiratory symptoms in children.

The long-term sequelae of fine particle exposures on lung function, particularly from medium exposure episodes (weeks to months) such as landscape fires, have not been well characterized. Studies of wildfires predominantly use secondary data such as hospitalization and emergency presentations to identify respiratory associations.
Although long-term exposure to indoor coal burning has been found to be associated with worsening respiratory symptoms, reduced lung function and COPD in adults, much remains unknown regarding the impact of coal mine fires on human lung health. Addressing the gaps in the current available evidence is critical, given the increasing incidence of catastrophic wildfires globally attributable to climate change.

The forced oscillation technique (FOT) is a methodology used to measure lung mechanics. FOT may be able to detect early changes in peripheral airway function that spirometry cannot. To our knowledge, no study has assessed the long-term impact of PM$_{2.5}$ from exposure to coal mine fires, wildfires or biomass fuel smoke in adults using FOT.

In February 2014, embers from nearby bush fires started a fire in the Hazelwood open-cut brown coal mine, located in the Latrobe Valley, south-eastern Australia. It was an unprecedented event that generated significant air pollution from coal mine fire smoke over 6 weeks, particularly affecting residents in the adjacent town of Morwell. The most exposed population at the time numbered approximately 14,000. This resulted in considerable community concerns about the potential long-term health effects of smoke exposure.

The Hazelwood Health Study (www.hazelwoodhealthstudy.org.au) was established to investigate the potential health effects in people who were exposed to smoke from the mine fire. The Hazelinks Stream of the Hazelwood Health Study utilized hospital emergency presentations and admissions data to show that hospitalization for respiratory conditions increased during the first month of the mine fire. The Adult Survey Stream of the Hazelwood Health Study$^{11}$ compared self-reported health outcomes between the most exposed community and an unexposed sample more than 2 years after the event. The Adult Survey found increasing risks of respiratory symptoms, particularly cough, phlegm and wheeze, related to the mine fire exposure.$^{12}$ This analysis aimed to further investigate the association between exposure to mine fire smoke and long-term lung function as assessed by FOT, 3.5–4 years after the event.

**METHODS**

**Study design and setting**

The Respiratory Stream of the Hazelwood Health Study is a longitudinal follow-up study of selected participants from the Adult Survey.$^{11,13}$ The study was conducted between August and December 2017 in Morwell (exposed), and between January and March 2018 in the nearby town of Sale (unexposed). Refer Appendix S1 in the Supporting Information for an explanation of the selection of Sale as the comparator town. Study data were collected and managed using REDCap (Research Electronic Data Capture)$^{14}$ electronic data capture tools hosted at Monash University, Australia.

**Participant recruitment and sample collection**

Participants were eligible for the Respiratory Stream of the Hazelwood Health Study if they had completed the Adult Survey, were at least 18 years of age on 9 February 2014 and had lived in the study area at the time of the mine fire. Adult Survey participants were excluded from the Respiratory Stream if they had specified no further contact, were of unknown age or sex or were aged over 90 years. Participants were further excluded where a contraindication to spirometry was identified—including recent surgery, myocardial infarction, pneumothorax, pulmonary embolism, open pulmonary tuberculosis or known aneurysms.$^{15}$

A target sample size of 339 from Morwell and 170 from Sale was derived based on the ability to detect a 5 ml/year or greater forced expiratory volume in 1 s (FEV$_1$) decline in exposed compared with non-exposed participants using a two-sample $t$-test with a two-sided $p$-value of 0.05 and 80% power. A weighted random sample (to correct for lower response rate in some subgroups of participants, such as young people) of 1346 Adult Survey participants was invited for assessment of their respiratory function. Participants reporting an asthma attack or current asthma medication use in the Adult Survey were oversampled (40%) to provide ability for further evaluation in an asthmatic sample. Response bias was evaluated and corrected using statistical weighting (Appendix S2 in the Supporting Information) and sensitivity analysis using unweighted data.

Invitation to participate was by mail, email and/or short message service (SMS), and recruitment continued until the target sample size was achieved (Figure 1).

**Participant characteristics**

Participant characteristics such as age, sex, ethnicity, employment status and smoking history were collected via questionnaires. Participants were classified as non-smokers (<100 cigarettes in their lifetimes), ex-smokers (current non-smokers with >100 cigarettes in their lifetimes) or current smokers.$^{16}$ Height and weight were measured by a trained personnel during the study visit. Education level and occupational exposures (employment in dusty or polluted environments for at least 6 months) were obtained from the
Adult Survey. Self-reported asthma status was captured via a modified European Community Respiratory Health Survey questionnaire. Participants were identified as having spirometry consistent with COPD if post-bronchodilator (BD) ratio of FEV₁ to forced vital capacity (FEV₁/FVC) < lower limit of normal (fifth percentile) using the Global Lung Initiative spirometry reference values.

Exposure assessment

Retrospective modelling of the spatial and temporal distribution of mine fire-related PM₂.₅ concentrations by the Australian Commonwealth Scientific and Industrial Research Organisation Oceans & Atmosphere was used due to the absence of ground-level air pollution monitoring at the beginning of the mine fire. Please refer Appendix S3 in the Supporting Information for a more detailed explanation of PM₂.₅ modelling. Individual level mean daily PM₂.₅ exposures over the mine fire period (51 days, between 9 February and 31 March 2014) were estimated through linking time-location diary data (reported in the Adult Survey) with the modelled fire-related PM₂.₅ exposure data as described by Johnson et al.

Clinical outcome measures

Respiratory testing was performed by the same trained respiratory scientists at both sites using standard operating procedures in line with the current respiratory measurement standards where available. Spirometry was measured using the EasyOne Pro Lab Respiratory Analysis System (ndd Medical Technologies AG, Zürich, Switzerland) in line with the international standards. FOT parameters were measured using the Tremoflo C-100 device (Thorasy, Montreal, Canada) in line with the current standards at the time of testing (see Appendix S4 in the Supporting Information for details). Parameters reported for FOT included respiratory system resistance and reactance at a frequency of 5 Hz (Rrs₅ and Xrs₅, respectively), the area under the reactance curve (AX₅) and resonant frequency (Fres). Data were imputed where acceptability criteria were not met or coherence <0.80 for 5 Hz or <0.90 at 11 or 19 Hz. Tests were performed before and 10 min after the administration of a short-acting BD (300 µg salbutamol). BD use in the previous 24 h was recorded, as BDs were unable to be withheld prior to assessment due to ethical reasons.

Statistical analysis

Statistical weighting was developed and applied to all analyses to correct for over-sampling of asthmatics as well as possible attrition bias from the Adult Survey to clinical follow-up; see details in Appendix S2 in the Supporting Information. Descriptive statistics were used to compare patient characteristics and clinical outcomes between non-exposed Sale participants as well as the tertiles of PM₂.₅ exposure level in Morwell (low, medium or high exposure). Crude statistical significance was assessed using Pearson chi-square tests for categorical measures and t-tests for continuous measures.

Multivariate linear regression models were fitted to analyse the association between mean PM₂.₅ exposure and outcomes, controlling for key confounders including age, height, weight, sex, smoking status, self-reported asthma and/or COPD, employment, education level and occupational exposure. Standardized z-scores and % predicted for FOT outcome variables were not used in the analysis due to poor regression model fit and high proportions of participants outside of reference prediction range (mostly due to older age and heavier weight). Therefore, possible outcome transformation methods and non-linear associations were explored using both Box–Cox transformation and fractional polynomial regression models. The best outcome transformation method was identified as logarithmic transformations for Rrs₅, AX₅ and Fres and exponential transformation for Xrs₅. Additional non-linearity was not observed between transformed outcomes and predictors such as age, weight and height. Missing data were addressed using multiple imputation using chained equations. Due to the lack of a low or no exposure sample in Morwell, as well as possible differences between Morwell and Sale participants, two sets of regression models were carried out for each outcome variable: Model 1 including a binary variable indicating township of participant (Morwell or Sale), and Model 2 excluding this variable. Sensitivity analyses were performed with unweighted and complete case models as well as models including only Morwell participants. Statistical analyses were performed using Stata version 16 (Stata Corporation, College Station, Texas 2016).
RESULTS

Participant characteristics and PM$_{2.5}$ exposure

This cross-sectional analysis included all participants in the first round of Respiratory Stream data collection, which comprised a total of 519 participants (346 from Morwell and 173 from Sale). Refer Figure 1 for flow chart of participants.

Table 1 shows the participant characteristics by exposure level to mine fire smoke. The mean (SD) PM$_{2.5}$ exposure levels for non-exposed (Sale) and for Morwell (low, medium and high exposure groups) were 0.1 (0.4), 5.9 (1.8), 11.5 (1.5) and 27.8 (10.3) μg/m$^3$, respectively. There were differences between exposure groups for gender distribution and weight, with those in the high exposure group having a higher proportion of males and heavier weight. Other participant characteristics were comparable between exposure groups. Refer Table S1 in the Supporting Information for characteristics of participants versus non-participants.

PM$_{2.5}$ exposure and lung function

As FOT variables are dependent on sex, age, height and weight, unadjusted results were not included in the analysis. As shown in Figure 2 and Table S2 in the Supporting Information, all outcome variables were skewed and displayed slightly larger variation in baseline compared to post-BD outcomes. A clear dose–response pattern was observed between exposure level and FOT outcomes. Results from multivariate linear regression analysis (Table 2) revealed a negative association between increasing mine fire-related PM$_{2.5}$ exposure and post-BD reactance at 5 Hz, with Morwell included or excluded as a predictor. With Morwell excluded as a predictor, a 10 μg/m$^3$ increase in mine fire-related PM$_{2.5}$ was associated with 0.015 reduction in post-BD exponential transformed Xrs5. This was equivalent to 4.7 years of ageing estimated in the regression model (as shown in Table S3 in the Supporting Information, the estimated effect of 10 years of ageing was 0.032, therefore equivalent years of ageing was calculated as 0.015 ÷ 0.032 = 4.7). When Morwell was excluded as a predictor,

**TABLE 1** Participant characteristics by exposure group

| Characteristic                  | Sale N = 173 | Morwell low exposure N = 109 | Morwell medium exposure N = 113 | Morwell high exposure N = 124 | p-Value |
|---------------------------------|--------------|------------------------------|---------------------------------|-----------------------------|---------|
| Age group (years)               |              |                              |                                 |                             |         |
| 18–44                           | 44 (22%)     | 36 (26%)                     | 36 (30%)                        | 35 (25%)                    | 0.74    |
| 45–64                           | 74 (42%)     | 43 (44%)                     | 43 (37%)                        | 50 (37%)                    |         |
| 65+                             | 55 (36%)     | 30 (29%)                     | 34 (34%)                        | 39 (38%)                    |         |
| Gender                          |              |                              |                                 |                             |         |
| Male                            | 62 (36%)     | 43 (46%)                     | 46 (43%)                        | 62 (56%)                    | 0.02    |
| Caucasian/white                 | 171 (99%)    | 108 (99%)                    | 112 (100%)                      | 123 (99%)                   | 0.92    |
| Employed                        | 89 (47%)     | 44 (38%)                     | 46 (40%)                        | 50 (35%)                    | 0.34    |
| Higher education$^a$            | 107 (63%)    | 56 (57%)                     | 54 (54%)                        | 74 (64%)                    | 0.39    |
| BMI (kg/m$^2$)                  |              |                              |                                 |                             |         |
| Underweight/normal (BMI < 25)   | 40 (24%)     | 23 (20%)                     | 21 (18%)                        | 15 (11%)                    | 0.06    |
| Overweight (25 ≤ BMI < 30)      | 66 (38%)     | 35 (33%)                     | 31 (29%)                        | 35 (30%)                    |         |
| Obese (BMI ≥ 30)                | 67 (38%)     | 51 (47%)                     | 61 (53%)                        | 74 (59%)                    |         |
| Smoking status                  |              |                              |                                 |                             |         |
| Non-smoker                      | 82 (49%)     | 58 (52%)                     | 60 (54%)                        | 49 (36%)                    | 0.10    |
| Ex-smoker                       | 66 (39%)     | 35 (33%)                     | 34 (33%)                        | 51 (47%)                    |         |
| Current smoker                  | 25 (12%)     | 16 (15%)                     | 19 (13%)                        | 24 (17%)                    |         |
| Asthma and/or COPDb$^b$         | 73 (37%)     | 58 (41%)                     | 57 (40%)                        | 63 (39%)                    | 0.96    |
| Historical occupational exposure| 64 (37%)     | 43 (44%)                     | 44 (39%)                        | 54 (46%)                    | 0.47    |

| Mean (SD)                      | Mean (SD)    | Mean (SD)                    | Mean (SD)                       | Mean (SD)                   |
|---------------------------------|--------------|------------------------------|---------------------------------|-----------------------------|
| Age (years)                     | 57.3 (20.0)  | 54.7 (14.3)                  | 54.5 (15.3)                     | 56.7 (14.7)                 | 0.50    |
| Height (cm)                     | 166.5 (11.2) | 166.0 (9.6)                  | 166.4 (8.8)                     | 167.1 (7.9)                 | 0.86    |
| Weight (kg)                     | 81.2 (24.4)  | 86.7 (22.7)                  | 86.8 (20.2)                     | 88.8 (17.0)                 | 0.009   |
| PM$_{2.5}$ exposure (μg/m$^3$)  | 0.1 (0.4)    | 5.9 (1.8)                    | 11.5 (1.5)                      | 27.8 (10.3)                 |         |

Abbreviations: COPD chronic obstructive pulmonary disease; PM$_{2.5}$, particulate matter with an aerodynamic diameter < 2.5 μm.

$^a$Certificate, university or other tertiary institute degree.

$^b$Spirometric COPD and/or self-reported asthma attack in the last 12 months.
regression analysis suggested that increased exposure to mine fire-related PM$_{2.5}$ was associated with increased area under the post-BD reactance curve (AX5). The effect of exposure was associated with a 0.072 increase in ln(AX5) post-BD, being equivalent to 3.9 years of ageing (see Table S4 in the Supporting Information, effect of 10 years of ageing was estimated to be 0.185). More detailed regression results for post-BD Xrs5 and AX5 are shown in Tables S3 and S4 in the Supporting Information. An association between increasing PM$_{2.5}$ exposure and BD response in exponential transformed Xrs5 was also seen (see Tables 2 and S5 in the Supporting Information for details). Sensitivity analyses (results not shown) suggest that results from unweighted/un-imputed models and models including Morwell participants only were highly consistent with the main findings.

**DISCUSSION**

Assessment of participants nearly 4 years after the Hazelwood coal mine fire revealed an association between medium-term mine fire-related PM$_{2.5}$ exposure and more negative respiratory system reactance (Xrs5), specifically...
measured after the administration of BD. To the best of our knowledge, this represents the first study using FOT analysis in adults to evaluate longer term respiratory function after a medium-term PM$_{2.5}$ exposure related to coal mine fire smoke.

The mechanism for the more negative reactance (a marker of the compliance of the respiratory system) is unclear. Previous studies of long-term exposure to air pollution and PM$_{2.5}$ have shown associations with increased respiratory morbidity and airflow obstruction. Separately, it has been shown that measurements of reactance at 5–6 Hz via FOT are sensitive to airway closure and expiratory flow limitation in subjects with obstruction. A possible mechanism for the association seen between medium-term exposure PM$_{2.5}$ and Xrs5 in this study may be early peripheral airway changes that occur with airflow limitation or accelerated lung ageing.

Interestingly, the association between PM$_{2.5}$ and Xrs5 was only observed in the post-BD data. A possible explanation for this finding is that participants were recruited from a general population with varying states of lung health and by assessing participants’ post-BD, variability of bronchomotor tone was minimized across participants allowing assessment of fixed pulmonary abnormalities. That is, the assessment of the relationship between PM$_{2.5}$ and Xrs5 could be undertaken without the confounding effects of bronchomotor tone.

Importantly, these findings in adults are similar to the findings in children within the Hazelwood Health Study Early Life Followup Stream. Shao et al. demonstrated that infant or in utero exposures to coal mine fire emissions were associated with long-term impairment of lung reactance, with increased average PM$_{2.5}$ being significantly associated with worsening area under the reactance curve—a complementary parameter in the evaluation of reactance. Similarly, abnormalities in oscillography parameters were found in subjects with lower respiratory symptoms, after acute exposure to pollution from the 9/11 terrorist attacks, where spirometry was insensitive.

The study has several strengths. Unlike observational studies that have used only secondary data (such as hospitalization) to assess respiratory health, this research has built upon previously collected hospitalization and self-reported symptom data with the inclusion of objective measures of lung mechanics. A further strength of this study was the inclusion of individual estimates of PM$_{2.5}$ exposure utilizing a combination of detailed time-location diaries and spatially and temporally resolved modelling of PM$_{2.5}$ concentrations based on coal combustion and weather conditions.

However, the study also has some limitations. The study endeavoured to account for all relevant potential confounding factors in our analysis, such as age, gender, weight, BMI, education status, tobacco and occupational exposures, and included sampling weights to account for attrition bias. However, it is feasible that some of the observed results

**TABLE 2** Summary of multivariate linear regressions of FOT parameters—Regression coefficients ($\beta$) and 95% CI

| Mean exposure model (PM$_{2.5}$ per 10 $\mu$g/m$^3$) | Model 1 (including township as a confounder) | Model 2 (excluding township as a confounder) |
|-----------------------------------------------|---------------------------------------------|---------------------------------------------|
| | $\beta$-Coefficient (95% CI) | $p$-Value | $\beta$-Coefficient (95% CI) | $p$-Value |
| Baseline$^a$ | | | | |
| Baseline ln(Rrs5) | $-0.003$ (–0.035, 0.029) | 0.87 | $-0.001$ (–0.028, 0.026) | 0.95 |
| Baseline exp(Xrs5) | $-0.009$ (–0.024, 0.006) | 0.23 | $-0.008$ (–0.020, 0.005) | 0.23 |
| Baseline ln(AX5) | $0.030$ (–0.056, 0.116) | 0.50 | $0.038$ (–0.034, 0.109) | 0.31 |
| Baseline ln(Fres) | $0.001$ (–0.030, 0.032) | 0.97 | $0.006$ (–0.019, 0.032) | 0.62 |
| Post-BD$^b$ | | | | |
| Post-BD ln(Rrs5) | $0.011$ (–0.018, 0.041) | 0.45 | $0.012$ (–0.013, 0.036) | 0.34 |
| Post-BD exp(Xrs5) | $-0.018$ (–0.032, –0.003) | 0.015 | $-0.015$ (–0.027, –0.004) | 0.011 |
| Post-BD ln(AX5) | $0.063$ (–0.017, 0.144) | 0.12 | $0.072$ (0.005, 0.138) | 0.034 |
| Post-BD ln(Fres) | $0.017$ (–0.010, 0.045) | 0.22 | $0.021$ (–0.001, 0.044) | 0.07 |
| Difference between baseline and post-BD | | | | |
| Difference in ln(Rrs5) | $0.012$ (–0.010, 0.034) | 0.27 | $0.012$ (–0.006, 0.029) | 0.20 |
| Difference in exp(Xrs5) | $-0.009$ (–0.018, 0.000) | 0.047 | $-0.008$ (–0.015, –0.001) | 0.032 |
| Difference in ln(AX5) | $0.030$ (–0.026, 0.086) | 0.30 | $0.032$ (–0.013, 0.078) | 0.17 |
| Difference in ln(Fres) | $0.014$ (–0.008, 0.037) | 0.21 | $0.013$ (–0.005, 0.032) | 0.15 |

Abbreviations: AX5, area under the reactance curve from 5 Hz; BD, bronchodilator; COPD, chronic obstructive pulmonary disease; exp, exponential; FOT, forced oscillation technique; Fres, resonant frequency; ln, natural log; Rrs5, respiratory system resistance at 5 Hz; Xrs, respiratory system reactance at 5 Hz.

$^a$Regression models adjusted for age, gender, height, weight, employment, education, smoking status, asthma and COPD status, work exposure and township of the resident (Morwell or Sale). Whether the participants had taken a BD prior to their assessment was also controlled for in the models of FOT outcomes at baseline, as well as difference between baseline and post-BD. Model 2: identical to Model 1 except township was not included as a confounder. Missing data, including 41 records for post-BD Rrs5, post-BD Xrs5 and post-BD AX5, 42 records for post-BD Fres and six records for education level, were imputed using multiple imputation with chained equations.

$^b$Model 1 adjusted for age, gender, height, weight, employment, education, smoking status, asthma and COPD status, work exposure and whether participants had BD prior to the test. Missing data, including 44 records for baseline Rrs5, baseline Xrs5 and baseline AX5, 48 records for baseline Fres and six records for education level, were imputed using multiple imputation with chained equations.
occurred by chance or were influenced by unknown con-
ounding factors or factors influencing participation in the
study. Furthermore, at this stage in the study, we only have
cross-sectional data on lung mechanics. Future follow-up of
the Hazelwood Health Study Respiratory Stream partici-
pants will better inform an investigation of the long-term
implications of medium-duration coal mine fire-related
smoke exposure on respiratory mechanics and lung health.

In conclusion, a clear dose–response association was
observed between medium-duration PM$_{2.5}$ exposure levels
from ambient coal mine fire smoke and a more negative
respiratory system reactance in this cohort. This study
adds new findings to the literature on the lung health
effects of medium-term PM$_{2.5}$ exposure. These inform
public health policy and planning for future coal mine
fires or similar medium-duration PM$_{2.5}$ generating pollu-
tion events such as the recent megafires in Australia and
the United States. Longitudinal data are required to con-
firm the findings of this study and to better understand
the association of coal mine fire smoke and altered respi-
ratory system reactance and potential accelerated lung
ageing in exposed populations.

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CONFLICT OF INTERESTS
This study was previously presented online at the virtual
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HUMAN ETHICS APPROVAL DECLARATION
The Monash University Human Research Ethics Committee
approved the Hazelwood Health Study: Cardiovascular and
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