OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

Meta-Analysis of the Impact of Ambient Particulate Matter on Lung Function Across the Lifespan

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ABSTRACT

The main aim of this meta-analysis was to gather information from studies regarding how air quality is correlated with lung function by measuring spirometry values (FEV_1 and FVC), classified according to age. Although numerous investigations have found a general association between air quality and respiratory health, there remains a scarcity of research that quantitatively compares pooled effect sizes across different stages of life. Some single studies have discovered, nevertheless, an association between lung health values and air quality. The object of this meta-analysis, therefore, has been to deeply investigate existing evidence pertaining to a connection relating lung health issues to exposure of particulate matter such as PM2.5 and PM10. Meta-analysis has been achieved through a separation of age groups and a calculation of averages, Z-scores, and P-values by attempting to establish how strong of a connection exists, if at all. Since all P values, having been estimated for each age group, have been <0.01, it has been possible to establish a negative relationship between lung health and air pollution from a very young age until older ages. A deficit of 2.19% among children, a deficit of 31.2 mL among adults, and a deficit of 1.08% among the elderly have been found for every 10 µg/m³ of exposure, emphasizing how different age groups are affected by air pollution and the importance of public health intervention in this area.

INTRODUCTION

The human respiratory system is susceptible to air pollution due to its large surface area and continuous exposure to the environment. Because particulate matter (PM) is undetectable by the body's filtration mechanisms, it is an example of a pollutant that endangers the health of the respiratory system. In humans, coarse particulate matter like PM10 is typically found in the main bronchi, whereas fine particulate matter like PM2.5 is typically located near the alveolar sacs. Particulate matter penetrates deeply in both situations, which may restrict airflow and lower lung volume due to oxidative stress.

While the effects of air pollution appear to be widely acknowledged, there appears to be a lack of thorough data that, when taking age into account through a numerical comparison, connects these biological risks to contaminants. Spirometry will be employed in this work as an efficient numerical comparison to address this. To be clear, spirometry measures forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) to identify obstructive and restrictive lung abnormalities. However, research that does not divide the populations would not be an accurate picture of the problem at hand due to the significant variations between children, adults, and the elderly. Thus, this paper will describe how a rise in air pollution affects these three stages of life differently, if at all. This study looks at pooled effect sizes, Z-scores, and significant values (P-values) for child, adult, and senior populations in order to provide a clear, comparative assessment of risk over the life cycle.

METHODS

To complete the initial statistical synthesis, an inverse-variance weighted random-effects meta-analysis was conducted for the age groups of Children (≤18 years), Adults (18–65 years), and Elderly (>65 years). Even though I^2 and τ^2 values are more commonly utilized for measurements of heterogeneity, these are not presented because of the low number of studies included within each age-stratified group. Therefore, these values could not be taken into consideration for a specific variance interpretation.

2.1 Systematic Search and Selection of Studies

For systematic reviews, the PRISMA criteria were adhered to in order to identify the best data. To find accurate and pertinent peer-reviewed articles that were published recently (between 2013 and 2025), this strategy required searching PubMed, Google Scholar, and Web of Science. Furthermore, to ensure that the final result was grounded in quantitative data, only research that provided scalable regression coefficients were taken into account.

2.2 Linear Scaling Calculation

The regression coefficients from each investigation were standardized to a similar 10 $\mu g/m^3$ increment in order to maintain uniformity and equal comparison. This scale was required because many of the included studies had certain interquartile ranges (IQRs) to their increment. The following formula was used to apply the scaling:

$$\beta_{scaled} = \beta_{reported} \times \left(\frac{10}{reported\ increment}\right)$$

2.3 Statistical Synthesis

The Inverse-Variance Method was used to determine the β_{pooled} after the β_{scaled} was computed. In order to give studies with more accurate results more weight in the final meta-analysis, the Inverse-Variance Method was selected for this investigation. The following formula was used to calculate the weight (w) for each study “i” based on standard errors:

$$w_i = \frac{1}{SE_i^2}$$

Following the computation of each study's weight, weighted averages were used to determine the pooled effect size, as indicated by the following formula:

$$\beta_{pooled} = \frac{\Sigma\left(w_i \times \beta_{scaled,i}\right)}{\Sigma w_i}$$

2.4 Derivation of Z-scores and P-values

The following formula was used to calculate the Standard Error of the Pooled Estimate in order to guarantee the accuracy of the study's findings:

$$SE_{pooled} = \sqrt{\frac{1}{\Sigma w_i}}$$

Following the calculation of the β_{pooled}, Z-scores were determined using the following equation to determine how many standard deviations the β_{pooled} is from zero:

$$Z = \frac{\beta_{pooled}}{SE_{pooled}}$$

To test the null hypothesis, a two-tailed P-value with 95% confidence was obtained using the normal distribution and the Z-scores for each group of individuals through the formula below:

$$\beta_{pooled} \pm \left(1.96 \times SE_{pooled}\right) = 95\%\ CI$$

To guarantee high confidence in the final conclusions and confidence intervals, a significance level of 0.01 was selected.

STUDY PROFILES

The demographics within each study were examined to ensure that the studies that were included were pertinent to the objective of this investigation. The European ESCAPE project, which provided pediatric data using a reliable technique, included Gehring et al. (2013), which was utilized for the children's pool. The Framingham Heart Study cohort, one of the most reputable medical records, was used by Rice et al. (2016) for the children's pool as well. The identical cohort was used by Rice et al. (2015) for the adults' pool. To ensure that the pooled estimates were not limited to a specific location, Adams et al. (2015), which was also used for the adults' pool, complemented the Rice et al. (2015) cohort with a wide European demographic range. Wang et al. (2019), which focused on a longitudinal viewpoint, had a varied age range of participants in the older adults' pool. Last but not least, Elbarbary et al. (2020) used a cohort from Wave 1 of the World Health Organization, which was also used for the pool of older adults, to cover people from low and middle-income countries. When combined, these studies offer a reliable sample for assessing how particulate matter affects lung health and function.

RESULTS

The studies examined within the children's strata in Table 1 consistently show that children's exposure to PM2.5 and PM10 is associated with statistically significant impairments in FEV_1 and FVC growth trajectories. PM2.5 exposure is associated with a significant decrease in FEV_1 volume in adults, as shown in Table 2, and a deterioration in the FEV_1/FVC ratio in the elderly, as shown in Table 3.

The preliminary meta-analysis results, which are displayed in the tables below, support these relationships with significant statistical significance across all age groups.

Table 1. Children:

Studies pooled using FEV_1 percent predicted

Study	Original Pollutant & β	Standardized β per 10 $\mu g/m^3$ PM2.5	95% Confidence Interval	Weight in Pooling
Gehring et al. (2013)	PM2.5: -1.77% [-3.34, -0.18) per 5 $\mu g/m^3$	-3.54%	[-6.68%, -0.36%]	22.2%
Rice et al. (2016)	PM10: -1.81% [-3.50, -0.12] per 10 $\mu g/m^3$	-1.81%	[-3.50%, -0.12%]	77.8%

Table 2. Adults:

Studies pooled using FEV_1 in mL

Study	Original Pollutant & β	Standardized β per 10 $\mu g/m^3$ PM2.5	95% Confidence Interval	Weight in Pooling
Rice et al. (2015)	PM2.5: -13.5 mL [-26.6, -0.3) per 2 $\mu g/m^3$	-67.5 mL	[-133.0, -1.5]	10.4%
Adam et al. (2015)	PM2.5: -13.5 mL [-24.7, -2.3] per 5 $\mu g/m^3$	-27.0 mL	[-49.4, -4.6]	89.6%

Table 3. Older Adults:

Studies pooled using FEV_1/FVC ratio in percent

Study	Original Pollutant & β	Standardized β per 10 μg/m³ PM10	95% Confidence Interval	Weight in Pooling
Wang et al. (2019)	PM2.5: -0.57% [-1.05, -0.09) per 5 μg/m³	-1.14%	[-2.10%, -0.18%]	4.8%
Elbarbary et al. (2020)	PM2.5: -2.81% [-3.37, -2.25] per 26.1 μg/m³	-1.08%	[-1.29%, -0.86%]	95.2%

Table 4. Final Pooled Results:

Age Group	Pollutant	Outcome	Pooled β	95% Confidence Interval	Z-score	P-value
Children	PM2.5/PM10	FEV_1 in % predicted	-2.19%	[-3.69%, -0.70%]	-2.89	0.004
Adults	PM2.5	FEV_1 in mL	-31.2 mL	[-52.4 mL, -10.0 mL]	-2.89	0.004
Older Adults	PM2.5	FEV_1/FVC ratio in %	-1.08%	[-1.29%, -0.87%]	-10.11	<0.0001

DISCUSSION

Based on the findings of this meta-analysis, it can be said that poor lung function is associated with inferior air quality across all three age groups. A 10 μg/m³ increase in particulate matter exposure is linked to a 2.19% expected deficit in FEV_1% in children, a 31.2 mL deficit in FEV_1 in adults, and a 1.08% decrease in the FEV_1/FVC ratio in the elderly, according to an analysis of the pooled estimates in Table 4. The validity of the conclusions was demonstrated by the fact that all of these values were statistically significant in each age group ($P < 0.01$).

These results in each age group show that lung development is affected by particulate matter. A deficit of 2.19% in FEV_1% throughout children is very alarming because it occurs at a critical development stage. Moreover, this could impair the potential maximum functions of the pulmonary system, leading to potential vulnerability of the fragility of the system. The 31.2 mL of FEV_1 deficiency in adults shows an accelerated decline of lung function that goes beyond aging, potentially hindering the ability of an adult to live an active life. For the elderly, it seems that despite their age, their ratio of FEV_1/FVC has deteriorated by 1.08%, showing a trend towards an obstructive pattern and being prone to potential chronic disorders.

LIMITATIONS

There are various restrictions on this meta-analysis. After normalization, the synthesis combines two pollution measurements which are PM2.5 and PM10 while assuming a comparable mass-based effect. However, the deposition is determined by the size of the particles. Physiological heterogeneity results from the fact that smaller particles, such as PM2.5, penetrate the deep alveoli while coarser particles, such as PM10, frequently deposit in the upper tracheobronchial airways. Research that used non-linear modeling or only reported categorical means was not taken into account in the publication because the analysis was limited to studies that provided regression coefficients. Furthermore, confounding variables like different exposures from jobs, socioeconomic status, and secondhand smoking in the original cohorts could result in pooled estimate differences even though there was a stratification by age. Lastly, only particle matters like PM2.5 and PM10 were the focus of this study. Therefore, additional research is necessary to examine other important contaminants, including ozone and nitrogen dioxide.

CONCLUSION

In summary, air pollution has a detrimental and statistically significant influence on lung health as determined by spirometry. This effect persists throughout life but is most vulnerable during childhood and old age. The meta-analysis's large, pooled effect sizes and P-values provide compelling quantitative evidence for enhancing air quality to safeguard respiratory health in people of all ages.

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