Published in final edited form as:
Epidemiology. 2010 March ; 21(2): 215–223. doi:10.1097/EDE.0b013e3181cb41f7.

Estimating error in using ambient PM2.5 concentrations as proxies for personal exposures

Christy L. Avery[1], **Katherine T. Mills**[1], **Ronald Williams**[2], **Kathleen A. McGraw**[3], **Charles Poole**[1], **Richard L. Smith**[4], and **Eric A. Whitsel**[1,5]

[1]Department of Epidemiology; The University of North Carolina at Chapel Hill; Chapel Hill, NC

[2]U.S. Environmental Protection Agency, National Exposure Research Laboratory; Research Triangle Park, NC

[3]Health Sciences Library; The University of North Carolina at Chapel Hill; Chapel Hill, NC

[4]Department of Statistics and Operations Research; The University of North Carolina at Chapel Hill; Chapel Hill, NC

[5]Department of Medicine; The University of North Carolina at Chapel Hill; Chapel Hill, NC

Abstract

Background—Several methods have been used to account for measurement error inherent in using ambient concentration of particulate matter < 2.5 μm/m^3 ($PM_{2.5}$) as a proxy for personal exposure. Such methods usually rely on the estimated correlation between ambient and personal $PM_{2.5}$ concentrations (*r*). These studies have not been systematically and quantitatively assessed for publication bias or heterogeneity.

Methods—We searched seven electronic reference databases for studies of the within-participant correlation between ambient and personal $PM_{2.5}$.

Results—We identified 567 candidate studies, eighteen (3%) of which met inclusion criteria and were abstracted. The studies were published between 1999 and 2008, representing 619 non-smoking participants aged 6–93 years in seventeen European and North American cities. Correlation coefficients (median 0.54; range 0.09–0.83) were based on a median of eight ambient-personal $PM_{2.5}$ pairs per participant (range 5 to 20) collected over 27 to 547 days. Overall, there was little evidence for publication bias (funnel plot symmetry tests: Begg's log rank test, P=0.9; Egger's regression asymmetry test, P=0.2). However, strong evidence for heterogeneity was noted (Cochran's Q test for heterogeneity, $P < 0.001$). European locales, eastern longitudes in North America, higher ambient $PM_{2.5}$ concentrations, higher relative humidity, and lower between-participant variation in *r* were associated with increased *r*.

Conclusions—Characteristics of participants, studies, and the environments in which they are conducted may affect the accuracy of ambient $PM_{2.5}$ as a proxy for personal exposure.

Corresponding Author: Christy Avery, Department of Epidemiology, University of North Carolina Chapel Hill, Bank of America Center, 137 E. Franklin St., Suite 306, Chapel Hill, NC 27514, (919) 966-8491 (voice), (919) 966-9800 (fax), christy_avery@unc.edu.

Several studies have examined methods of accounting for the effects of error associated with the use of ambient particulate matter (PM) concentrations as proxies for personal PM exposure.[1–3] Investigators from the National Morbidity and Mortality and Air Pollution Study,[4] for example, compared regression calibration and multi-stage Poisson regression. Although such strategies are potentially useful, the comparison relied on estimates of the cross-sectional association between personal and ambient PM_{10} concentrations in a convenience sample of five panel studies representing 292 participants from four geographic locations. A five-study convenience sample is potentially problematic, as non-random study selection may provide biased inferences.[5] Also, cross-sectional PM correlations may be weaker than longitudinal, within-person PM correlations, due to inter-individual variation in behaviors influencing exposure.[6–8]

There has not been a systematic and quantitative review of studies of the ambient-personal $PM_{2.5}$ correlation and, perhaps more importantly, the modifying effects of participant, study and environment characteristics. Thus, there are no summary estimates of the correlation that could be used to adjust for the error inherent in using ambient $PM_{2.5}$ concentration as proxies for personal PM exposure. To address this gap, we systematically and quantitatively reviewed the literature estimating within-participant, ambient-personal $PM_{2.5}$ correlations and determined the extent and sources of measurement error inherent in using ambient $PM_{2.5}$ as a surrogate for personal exposure. These results will facilitate quantification of bias resulting from the use of ambient $PM_{2.5}$ as a proxy for personal exposure in a Women's Health Initiative (WHI) ancillary study, the Environmental Epidemiology of Arrhythmogenesis in the WHI.

METHODS

Systematic Review Strategy

We searched for studies of the within-participant, ambient-personal or outdoor-personal $PM_{2.5}$ correlation considering all document types, languages, and publication dates. On 12 November 2007 we searched PubMed (1950 to date), ISI Web of Science (1955 to date), ISI BIOSIS Previews (1969 to date), CSA Environmental Sciences and Pollution Management (1967 to date), Toxline (1965 to date), and Proquest Dissertations & Theses (1861 to date). STN EMBASE (1974 to date) was searched on 14 December 2007.

We used the following strategy to search PubMed: (PM 2.5 OR PM2.5 OR PM25 OR PM 25 OR fine particle*) AND (ambient OR outdoor OR outdoors OR outside OR exterior OR external OR background OR fixed site*) AND (individual OR personal) AND (correlat* OR associat* OR relat* OR compar* OR pearson OR spearman). The same four sets of keywords were adapted for input into Web of Science, BIOSIS, Environmental Sciences, Toxline, and EMBASE. The Dissertations & Theses search required only the first three sets of keywords to create a result set small enough for review.

Citations were downloaded to an electronic reference manager (EndNote X1®, Thomson Reuters), duplicates were removed, and secondary references were added. The citations were independently reviewed with respect to three inclusion criteria: measurement of ambient $PM_{2.5}$, measurement of personal $PM_{2.5}$, and estimation of the within-participant, ambient-personal $PM_{2.5}$ correlation. We extracted study, participant and environment characteristics from all articles meeting inclusion criteria. Study characteristics included journal of publication, publication date, setting, study dates, sample size, duration, timing (consecutive, non-consecutive), lower limit of $PM_{2.5}$ detection, number (minimum, mean) of paired $PM_{2.5}$ measures, and correlation metric (Pearson, Spearman). Participant characteristics included age (mean, minimum, maximum), percent female, and the presence of comorbidities (pulmonary, cardiovascular, multiple, none). Environmental characteristics included the mean, median and standard deviation of $PM_{2.5}$ concentrations (ambient, personal); the within-participant, ambient-personal $PM_{2.5}$ correlation coefficients and corresponding number of paired measurements; season; average distance to ambient monitor; monitor type; air exchange rate; percent of time using air conditioning; and percent of time with windows open. Discrepant exclusions and extractions were adjudicated by consensus. We requested supplemental data from authors by electronic mail as needed. City-specific longitudes and latitudes were obtained from the GEOnet Names Server (http://earthinfo.nga.mil/gns/html/whatsnew.htm#C3). Meteorologic data were obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climateresearch.html).

Statistical analysis

Uniform measures of association for the j^{th} study were estimated from the personal-ambient $PM_{2.5}$ correlations measured within each of the i^{th} participants. We converted each within-participant correlation coefficient (r_i) to its variance-stabilizing, Fisher's z-transform $(Z_{r_i})=\frac{1}{2}\log_e\left(\frac{1+r_i}{1-r_i}\right)$.[9] Estimates of the within-participant variance $(v_i)=\frac{1}{n_i-3}$ and between-participant variance $(\tau_j^2)=\frac{Q_j-(k_j-1)}{c}$ for the j^{th} study were estimated from the number of paired personal-ambient $PM_{2.5}$ measurements for each participant (n_i), the number of participants per study (k_j), the weighted sum of squared errors $(Q_j)=\sum_{i=1}^{k}(n_i-3)(Z_{r_i}-\overline{Z}_{r_i})^2$, and a constant $(c)=\sum_{i=1}^{k}(n_i-3)-\frac{\sum_{i=1}^{k}(n_i-3)^2}{\sum_{i=1}^{k}(n_i-3)}$. The transformed effect size for the j^{th} study is given by $\overline{Z}_j=\frac{\sum_{i=1}^{k}w_iZ_{r_i}}{\sum_{i=1}^{k}w_i}$ with weights $(w_i)=\left(\frac{1}{n_i-3}+\tau_j^2\right)^{-1}$, standard errors $(S_j)=\sqrt{\frac{1}{\sum_{i=1}^{k}w_i}}$ and study-specific weights $W_j=\left(\frac{1}{S_j}\right)^2$.[10] Negative τ^2 estimates were set to 0. Fixed-effects summary estimates were approximated using the median correlation coefficient and the average number of paired measurements for two studies[11,12] that did not provide participant-specific correlation coefficients.

Funnel plot asymmetry was assessed using a plot of W_j versus $\bar{Z}_j$, the adjusted rank correlation and regression asymmetry tests,[13,14] and a non-parametric "trim and fill" method that imputes hypothetically missing results due to publication bias.[15] In the absence of publication bias, plots of W_j versus $\bar{Z}_j$ usually resemble a symmetrical funnel with the more precise estimates forming the spout and the less precise estimates forming the cone, while low P values associated with the former tests (P_{Begg}; P_{Egger}) give evidence of asymmetry.

Inter-study heterogeneity was evaluated using a plot[16] of $\frac{\overline{Z}_j}{S_j}$ versus $\frac{1}{S_j}$ and Cochran's Q test.[17] The plot and test are related, in that the position of the j^{th} study along the vertical axis illustrates its contribution to the Q test statistic. In the absence of heterogeneity, all studies fall within the 95% confidence limits and for the Cochran Q test $P_{Cochran} > 0.1$.

Variation in the strength and precision of $\bar{Z}_j$ across levels of the study, environment, and participant characteristics was first assessed by estimating a summary random-effects estimate of $\bar{Z}$ within each study, environment and participant category.[18] We also constructed a series of univariable random-effects meta-regression models to relate each study, environment, and participant characteristic to differences in $\bar{Z}$ Lastly, a multivariable random-effects meta-regression model and a backwards-elimination strategy were used to evaluate ten characteristics of study, participant, and environment routinely available in epidemiologic studies of $PM_{2.5}$ health effects: latitude, longitude, presence of comorbidities, mean age, percent female, mean ambient $PM_{2.5}$, relative humidity, sea level pressure, and mean temperature. Interval-scale characteristics were analyzed before and after dichotomization at their medians unless noted otherwise. All analyses were performed using STATA (College Station, TX). To facilitate interpretation, estimates of $\bar{Z}$ were back-transformed to their original metric r after data analysis.

RESULTS

Our systematic review identified 567 candidate studies for screening. Of these studies, eighteen (3%) met criteria for critical appraisal and were abstracted. Abstracted studies were published between 1999 and 2008 (Table 1). The studies they described were set in seventeen North American and European cities, ten states or provinces and four countries, with 68% performed in the U.S. (eFigure, http://links.lww.com). The studies were conducted between 1995 and 2002. The mean study duration was 2.0 months (range 0.9 to 18.2), a period in which 79% of the studies collected $PM_{2.5}$ data over consecutive days. During data collection, the studies recorded an average of eight (range 5 to 20) ambient and personal $PM_{2.5}$ concentration pairs per participant on which their Pearson (37%) and Spearman (63%) correlation coefficients were based (Table 1).

The studies represented 619 non-smoking participants aged 6–93 (median = 70) years, 60% of whom were female and 41% of whom did not report chronic pulmonary or cardiovascular disease (Table 2). Ambient $PM_{2.5}$ concentrations (range 8.3 to 25.2 ug/m^3) were lower than personal $PM_{2.5}$ concentrations (range 9.3 to 28.6 ug/m^3) overall, with a median personal-ambient $PM_{2.5}$ difference of 0 (range −9.0 to 16.3) (Table 3). The estimated $\bar{r}$ (median 0.54; range 0.09 to 0.83) and its standard deviation (median 0.12; range 0.04, 0.31) varied widely

(Table 3, rFigure 1), the latter reflecting variability in sample weights (median 82.7; range 10.3 to 552.0). Estimates of $_i$ were similarly variable among studies (median interquartile range (IQR) 0.38; range 0.22 to 1.04), as were temperature (range −6.0 to 24.6 °C) and relative humidity (range 44% to 87%), especially when comparing medians from single-season studies (44%).

Figure 2 provides a funnel plot of $\bar{Z}_j$, which suggests little evidence of asymmetry. This result is consistent with $P_{Begg} = 0.9$ and $P_{Egger} = 0.2$, but the "trim and fill" method imputed four hypothetically missing studies with $r < 0.15$. Figure 3, a Galbraith plot in which twelve correlation coefficients (44%) fell outside the 95% confidence bounds, provided strong evidence of heterogeneity. This evidence was consistent with $P_{Cochran} < 0.001$.

The interquartile range (IQR) of r_i (range dichotomized as ≥ 0.41 versus < 0.41) was the characteristic associated with the greatest difference in $\bar{r}$: −0.37 (95% CI = −0.53 to −0.20) (Figure 4). Other factors associated with increased $\bar{r}$ were studies conducted in Europe, studies with eastern longitudes in North America, higher mean ambient $PM_{2.5}$ concentrations, and higher relative humidity, although imprecision was noted. After restricting to North American studies, given the considerable heterogeneity by study locale and small number of European studies (n = 2), higher mean ambient $PM_{2.5}$ concentrations and higher relative humidity were the only characteristics predictive of $\bar{r}$ in multivariable meta-regression models ($P < 0.05$).

DISCUSSION

Surveys of human activity patterns suggest that people spend more than 85% of their time indoors,[19] where they are exposed to numerous sources of $PM_{2.5}$, with physical and chemical properties and toxicities that often differ from those of ambient $PM_{2.5}$.[20,21] Thus, estimates of personal $PM_{2.5}$ exposure based on ambient concentrations are associated with some degree of uncertainty. This has led to the suggestion that epidemiologic studies should use ambient PM as a surrogate only for outdoor PM exposure, not total exposure.[22–26] Nonetheless, certain studies are often cited to justify using ambient $PM_{2.5}$ concentrations as proxies for total personal $PM_{2.5}$ exposures.[8,27–29] These studies report strong within-participant ambient-personal $PM_{2.5}$ correlations. Other studies, which report ambient-personal $PM_{2.5}$ correlations as low as 0.10[30] are rarely cited.

Motivated by this apparent pattern of citations, we reviewed studies of the within-participant correlation between ambient and personal $PM_{2.5,}$ examining them for publication bias and heterogeneity. We found low potential for publication bias, although the "trim and fill" analysis imputed four hypothetically missing studies. These hypothetically-missing studies most likely represent unpublished findings because they differed considerably from the majority of the published literature, they could not be used to justify reliance on ambient $PM_{2.5}$ as a proxy for personal $PM_{2.5}$ exposure, or they were considered implausible. An alternative explanation is that they represent studies this meta-analysis did not identify, although this is less likely since we reviewed seven electronic reference databases, evaluated secondary sources, and did not apply any document type, language, or publication startingdate limitations. Indeed, this systematic review had all the features of a meta-analysis deemed necessary to ensure its sensitivity.[31–33]

Although there was little evidence for pronounced publication bias, we found strong evidence for heterogeneity in $\bar{r}$—evidence that contraindicated the estimation of a single summary measure to represent the entire literature. The direct associations between European locales and eastern longitudes in North America with $\bar{r}$ may reflect regional factors including higher urban $PM_{2.5}$ concentrations[34] or closer proximities to regulatory monitors. Furthermore, the direct associations of ambient $PM_{2.5}$ concentrations and relative humidity with $\bar{r}$ suggest an increased contribution of ambient $PM_{2.5}$ to personal exposures through activity patterns or increased air exchange. Regional differences in geographic, household, and personal factors may explain the indirect association between variation in r_i and $\bar{r}$, but further investigation was limited because these factors were uncommon, uncollected, or inconsistently reported. Similarly, we were unable to determine whether small ranges in personal or ambient $PM_{2.5}$ concentrations were associated with $\bar{r}$, as few studies reported participant-specific concentrations.

We did not find a strong association between temperature and $\bar{r}$, but the investigation included several multi-season studies. On the other hand, the scope of our investigation was limited by exclusion of twelve studies of the cross-sectional ambient-personal $PM_{2.5}$ correlation. Cross-sectional correlations are thought to be weaker than longitudinal, within-person correlations due to inter-individual variation in activities affecting exposure (e.g. spending time near smokers, cooking or cleaning).[6–8] A series of studies conducted in the Netherlands also found that ambient-personal PM correlations were stronger when analyses were conducted longitudinally.[35] Because studies of within-versus between-participant correlations address systematically different questions—the recognition of which precludes simultaneous evaluation[36]—the a priori exclusion of cross-sectional correlations was appropriate.

We were unable to determine whether associations based on summary data were good proxies for associations estimated using individual participant data.[37] One method to assess the validity of our conclusions and eliminate the potential for ecologic bias[38] would have been to evaluate individual participant data. A meta-analysis based on individual participant data also would allow for increased flexibility in analyses of heterogeneity and greater consistency of reporting.[39] Although such data were unavailable, the findings reported here were based on a large number of studies and have been interpreted cautiously.

The present meta-analysis focused on $PM_{2.5}$ although several European countries also regulate PM_{10}. It remains unclear whether findings for $PM_{2.5}$ extend to PM_{10}. The current meta-analysis also did not evaluate the association between ambient and personal concentrations of sulfate or elemental carbon, although these combustion products may better represent the influence of outdoor particles because their indoor sources are uncommon.[40–42] Nonetheless, the results presented here have potentially important implications for studies examining the health effects of $PM_{2.5}$ because methods for modifying regression equations to account for normally distributed measurement error are well established. Although the uniformity with which these results can be applied across study designs deserves additional consideration,[3,6–8,43] Crooks et al[44] recently described a Bayesian method for incorporating log-normal measurement error in a cross-sectional study of PM health effects. Log-normal distributions are believed more appropriate for PM, but the application of these methods requires knowledge of the conditional distribution of personal exposure given ambient exposure (specifically, the mean and standard deviation of the personal exposure distribution) as well as the ambient-personal $PM_{2.5}$ correlations described here.

Limitations notwithstanding, the present report reinforces the view that characteristics of participants, studies and the environments in which the studies are conducted affect the accuracy of ambient $PM_{2.5}$ as a proxy for personal exposure. The wide range in estimated correlations between personal and ambient $PM_{2.5}$, as well as the associations with participant, study, and environment characteristics, suggest that the potential for exposure misclassification can be substantial. Thus, these factors warrant greater scrutiny in studies utilizing ambient $PM_{2.5}$ as a proxy for personal exposure.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Sources of financial support: Supported by National Institutes for Environmental Health Sciences (R01-ES012238, P30-ES10126) and National Heart, Lung, and Blood (T32-HL007055) funding.

We thank Carry Croghan (US EPA) for assisting the authors in providing additional data analyses used in this report. Although this work has been reviewed by EPA and approved for publication, it may not necessarily reflect official Agency policy.

References

1. Brauer M, Brumm J, Vedal S, Petkau AJ. Exposure misclassification and threshold concentrations in time series analyses of air pollution health effects. Risk Anal. 2002; 22(6):1183–93. [PubMed: 12530788]
2. Yeh S, Small MJ. Incorporating exposure models in probabilistic assessment of the risks of premature mortality from particulate matter. J Expo Anal Environ Epidemiol. 2002; 12(6):389–403. [PubMed: 12415487]
3. Zeger SL, Thomas D, Dominici F, Samet JM, Schwartz J, Dockery D, Cohen A. Exposure measurement error in time-series studies of air pollution: concepts and consequences. Environ Health Perspect. 2000; 108(5):419–26. [PubMed: 10811568]
4. Dominici F, Zeger SL, Samet JM. A measurement error model for time-series studies of air pollution and mortality. Biostatistics. 2000; 1(2):157–75. [PubMed: 12933517]
5. Hunter, JE., Schmidt, FL. Correcting Error and Bias in Research Findings. 2. Sage Publications, Inc; 2004. Methods of Meta-Analysis.
6. Janssen NA, Hoek G, Brunekreef B, Harssema H, Mensink I, Zuidhof A. Personal sampling of particles in adults: relation among personal, indoor, and outdoor air concentrations. Am J Epidemiol. 1998; 147(6):537–47. [PubMed: 9521180]
7. Janssen NA, Hoek G, Harssema H, Brunekreef B. Childhood exposure to PM10: relation between personal, classroom, and outdoor concentrations. Occup Environ Med. 1997; 54(12):888–94. [PubMed: 9470897]

8. Janssen NAH, Hoek G, Harssema H, Brunekreef B. Personal exposure to fine particles in children correlates closely with ambient fine particles. Archives of Environmental Health. 1999; 54(2):95–101. [PubMed: 10094286]

9. Fisher, RA. Statistical methods for research workers. Edinburgh: Oliver & Boyd; 1925.

10. Field AP. Meta-analysis of correlation coefficients: a Monte Carlo comparison of fixed- and random-effects methods. Psychol Methods. 2001; 6(2):161–80. [PubMed: 11411440]

11. Kim D, Sass-Kortsak A, Purdham JT, Dales RE, Brook JR. Associations between personal exposures and fixed-site ambient measurements of fine particulate matter, nitrogen dioxide, and carbon monoxide in Toronto, Canada. J Expo Sci Environ Epidemiol. 2006; 16(2):172–83. [PubMed: 16175198]

12. Reid, CM. Assessment of Exposure to Selected Criteria Pollutants for Two Sensitive Population Cohorts in Atlanta, Georgia. Emory University; 2003.

13. Begg CB, Mazumdar M. Operating characteristics of a rank correlation test for publication bias. Biometrics. 1994; 50(4):1088–101. [PubMed: 7786990]

14. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997; 315(7109):629–34. [PubMed: 9310563]

15. Duval S, Tweedie R. Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. Biometrics. 2000; 56(2):455–63. [PubMed: 10877304]

16. Galbraith RF. A note on graphical presentation of estimated odds ratios from several clinical trials. Stat Med. 1988; 7(8):889–94. [PubMed: 3413368]

17. Cochran WG. The combination of estimates from different experiments. Biometrics. 1954; 73:526–30.

18. Berkey CS, Hoaglin DC, Mosteller F, Colditz GA. A random-effects regression model for meta-analysis. Stat Med. 1995; 14(4):395–411. [PubMed: 7746979]

19. Robinson, J., Nelson, WC. National human activity pattern survey data base. Research Triangle Park, NC: USEPA; 1995.

20. Monn C, Becker S. Cytotoxicity and induction of proinflammatory cytokines from human monocytes exposed to fine (PM2.5) and coarse particles (PM10-2. 5) in outdoor and indoor air. Toxicol Appl Pharmacol. 1999; 155(3):245–52. [PubMed: 10079210]

21. Wainman T, Zhang J, Weschler CJ, Lioy PJ. Ozone and limonene in indoor air: a source of submicron particle exposure. Environ Health Perspect. 2000; 108(12):1139–45. [PubMed: 11133393]

22. Mage D, Wilson W, Hasselblad V, Grant L. Assessment of human exposure to ambient particulate matter. J Air Waste Manag Assoc. 1999; 49(11):1280–91. [PubMed: 10589295]

23. McBride S, Williams R, Creason J. Bayesian hierarchical modeling of personal exposure to particulate matter. Atmospheric Environment. 2007; 41:6143–6155.

24. Wallace L, Williams R, Rea A, Croghan C. Continuous week long measurements of personal exposures and indoor concentrations of fine particles for 37 health-impaired North Carolina residents for up to four seasons. Atmospheric Environment. 2005; 40:399–414.

25. Wallace, L., Williams, R., Suggs, JC., Jones, P. Estimating contributions of outdoor fine particles to indoor concentrations and personal exposures: effects of household characteristics and personal activities. Washington, D.C: 2006.

26. Wilson WE, Suh HH. Fine particles and coarse particles: concentration relationships relevant to epidemiologic studies. J Air Waste Manag Assoc. 1997; 47(12):1238–49. [PubMed: 9448515]

27. Janssen NA, de Hartog JJ, Hoek G, Brunekreef B, Lanki T, Timonen KL, Pekkanen J. Personal exposure to fine particulate matter in elderly subjects: relation between personal, indoor, and outdoor concentrations. J Air Waste Manag Assoc. 2000; 50(7):1133–43. [PubMed: 10939207]

28. Sarnat JA, Koutrakis P, Suh HH. Assessing the relationship between personal particulate and gaseous exposures of senior citizens living in Baltimore, MD. J Air Waste Manag Assoc. 2000; 50(7):1184–98. [PubMed: 10939211]

29. Sarnat JA, Schwartz J, Catalano PJ, Suh HH. Gaseous pollutants in particulate matter epidemiology: confounders or surrogates? Environ Health Perspect. 2001; 109(10):1053–61. [PubMed: 11675271]

30. Adgate JL, Ramachandran G, Pratt GC, Waller LA, Sexton K. Longitudinal variability in outdoor, indoor, and personal PM2. 5 exposure in healthy non-smoking adults. Atmospheric Environment. 2003; 37(7):993–1002.

31. Moher D, Cook DJ, Eastwood S, Olkin I, Rennie D, Stroup DF. Improving the quality of reports of meta-analyses of randomised controlled trials: the QUOROM statement. Quality of Reporting of Meta-analyses. Lancet. 1999; 354(9193):1896–900. [PubMed: 10584742]

32. Oxman AD, Guyatt GH, Singer J, Goldsmith CH, Hutchison BG, Milner RA, Streiner DL. Agreement among reviewers of review articles. J Clin Epidemiol. 1991; 44(1):91–8. [PubMed: 1824710]

33. Shea BJ, Grimshaw JM, Wells GA, Boers M, Andersson N, Hamel C, Porter AC, Tugwell P, Moher D, Bouter LM. Development of AMSTAR: a measurement tool to assess the methodological quality of systematic reviews. BMC Med Res Methodol. 2007; 7:10. [PubMed: 17302989]

34. Rom, WN., Markowitz, S. Environmental and Occupational Medicine. 4. Lippincott Williams & Wilkins; 2006.

35. Janssen NA, Lanki T, Hoek G, Vallius M, de Hartog JJ, Van Grieken R, Pekkanen J, Brunekreef B. Associations between ambient, personal, and indoor exposure to fine particulate matter constituents in Dutch and Finnish panels of cardiovascular patients. Occup Environ Med. 2005; 62(12):868–77. [PubMed: 16299096]

36. Bland JM, Altman DG. Calculating correlation coefficients with repeated observations: Part 2--Correlation between subjects. BMJ. 1995; 310(6980):633. [PubMed: 7703752]

37. Lau J, Ioannidis JP, Schmid CH. Summing up evidence: one answer is not always enough. Lancet. 1998; 351(9096):123–7. [PubMed: 9439507]

38. Morgenstern H. Uses of ecologic analysis in epidemiologic research. Am J Public Health. 1982; 72(12):1336–44. [PubMed: 7137430]

39. Stewart LA, Tierney JF. To IPD or not to IPD? Advantages and disadvantages of systematic reviews using individual patient data. Eval Health Prof. 2002; 25(1):76–97. [PubMed: 11868447]

40. Brown KW, Sarnat JA, Suh H, Coull BA, Spengler JD, Koutrakis P. Ambient site, home outdoor and home indoor particulate concentrations as proxies of personal exposure. Journal of Environmental Monitoring. 2008; 10:1041–1051. [PubMed: 18728896]

41. Sarnat JA, Brown KW, Schwartz J, Coull BA, Koutrakis P. Ambient gas concentrations and personal particulate matter exposures: implications for studying the health effects of particles. Epidemiology. 2005; 16(3):385–95. [PubMed: 15824556]

42. Sarnat SE, Coull BA, Schwartz J, Gold DR, Suh HH. Factors affecting the association between ambient concentrations and personal exposures to particles and gases. Environ Health Perspect. 2006; 114(5):649–54. [PubMed: 16675415]

43. Schwartz J, Dockery DW, Neas LM. Is daily mortality associated specifically with fine particles? J Air Waste Manag Assoc. 1996; 46(10):927–39.

44. Crooks JL, Whitsel EA, Quibrera PM, Catellier DJ, Laio D, Smith RL. The effect of ignoring interpolation error on the inferred relationship between ambient particulate matter exposure and median RR interval in post-menopausal women. Epidemiology. 2008; 19(6):S127.

45. Ebelt ST, Petkau AJ, Vedal S, Fisher TV, Brauer M. Exposure of chronic obstructive pulmonary disease patients to particulate matter: relationships between personal and ambient air concentrations. J Air Waste Manag Assoc. 2000; 50(7):1081–94. [PubMed: 10939202]

46. Williams R, Suggs J, Creason J, Rodes C, Lawless P, Kwok R, Zweidinger R, Sheldon L. The 1998 Baltimore Particulate Matter Epidemiology-Exposure Study: part 2. Personal exposure assessment associated with an elderly study population. J Expo Anal Environ Epidemiol. 2000; 10(6 Pt 1): 533–43. [PubMed: 11140437]

47. Evans GF, Highsmith RV, Sheldon LS, Suggs JC, Williams RW, Zweidinger RB, Creason JP, Walsh D, Rodes CE, Lawless PA. The 1999 Fresno particulate matter exposure studies: comparison of community, outdoor, and residential PM mass measurements. J Air Waste Manag Assoc. 2000; 50(11):1887–96. [PubMed: 11111333]

48. Rodes CE, Lawless PA, Evans GF, Sheldon LS, Williams RW, Vette AF, Creason JP, Walsh D. The relationships between personal PM exposures for elderly populations and indoor and outdoor

concentrations for three retirement center scenarios. J Expo Anal Environ Epidemiol. 2001; 11(2): 103–15. [PubMed: 11409003]

49. Suh, H., Koutrakis, P., Chang, L. Characterization of the composition of personal, indoor, and outdoor particulate exposures. Harvard School of Public Health, Environmental Science and Engineering Program; Boston, MA: 2003. Report to the California Air Resources Board. Contract No. 98–330
50. Liu LJ, Box M, Kalman D, Kaufman J, Koenig J, Larson T, Lumley T, Sheppard L, Wallace L. Exposure assessment of particulate matter for susceptible populations in Seattle. Environ Health Perspect. 2003; 111(7):909–18. [PubMed: 12782491]
51. Williams R, Suggs J, Rea A, Leovic K, Vette A, Croghan C, Sheldon L, Rodes C, Thornburg J, Ejire A, Herbst M, Sanders W. The Research Triangle Park particulate matter panel study: PM mass concentration relationships. Atmospheric Environment. 2003; 37(38):5349–5363.
52. Noullett M, Jackson PL, Brauer M. Winter measurements of children's personal exposure and ambient fine particle mass, sulphate and light absorbing components in a northern community. Atmospheric Environment. 2006; 40(11):1971–1990.
53. Wu CF, Jimenez J, Claiborn C, Gould T, Simpson CD, Larson T, Liu LJS. Agricultural burning smoke in Eastern Washington: Part II. Exposure assessment. Atmospheric Environment. 2006; 40(28):5379–5392.

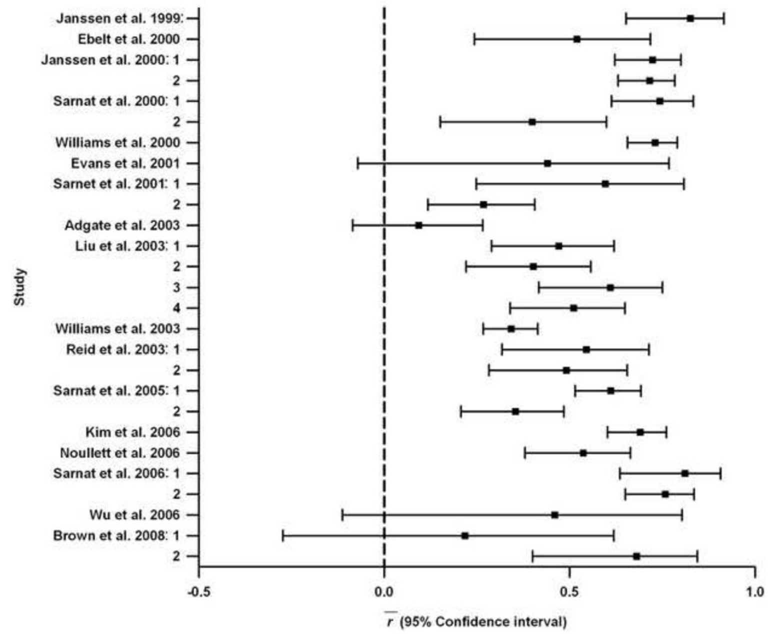

Figure 1.

Twenty-seven estimates of $\bar{r}$ (95% CI) from eighteen studies of the within-participant correlation between ambient and personal $PM_{2.5}$. See Table 1 for descriptions of sub-studies.

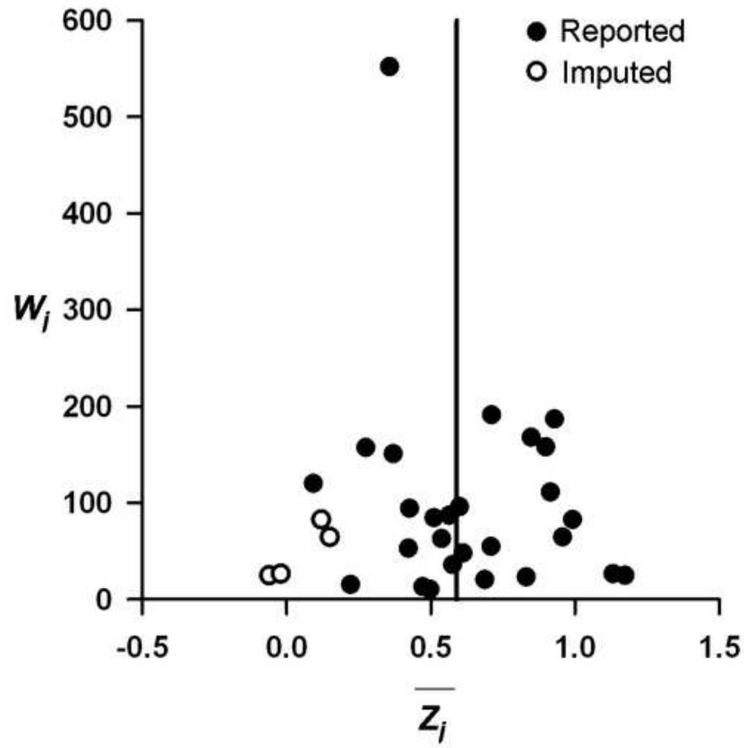

Figure 2.

Funnel plot for 27 reported and four imputed estimates of the within-participant correlation between ambient and personal $PM_{2.5}$.

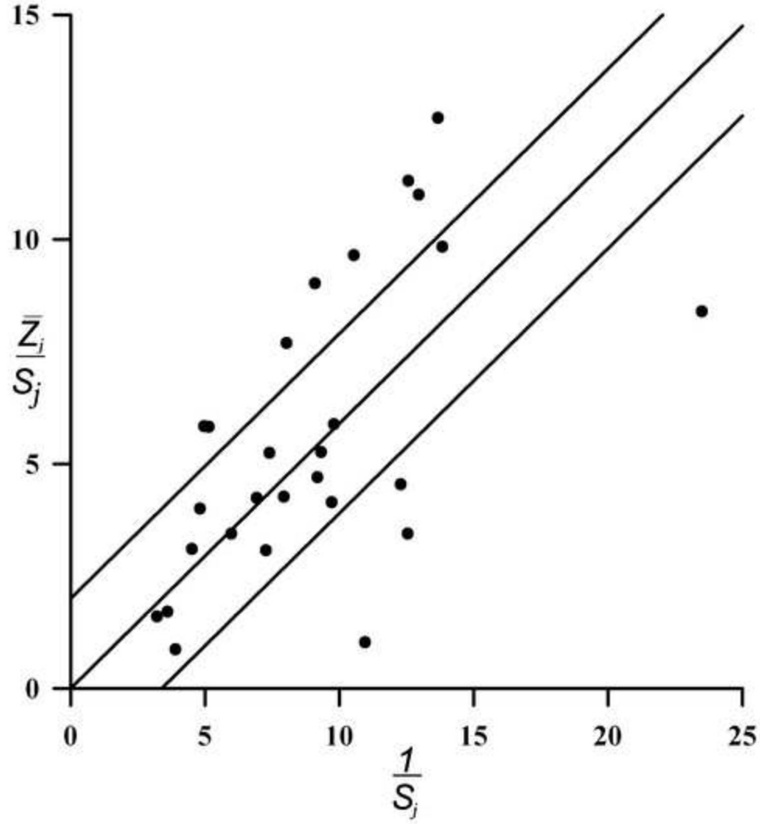

Figure 3.
Galbraith plot with 95% confidence intervals for 27 estimates of the within-participant correlation between ambient and personal $PM_{2.5}$.

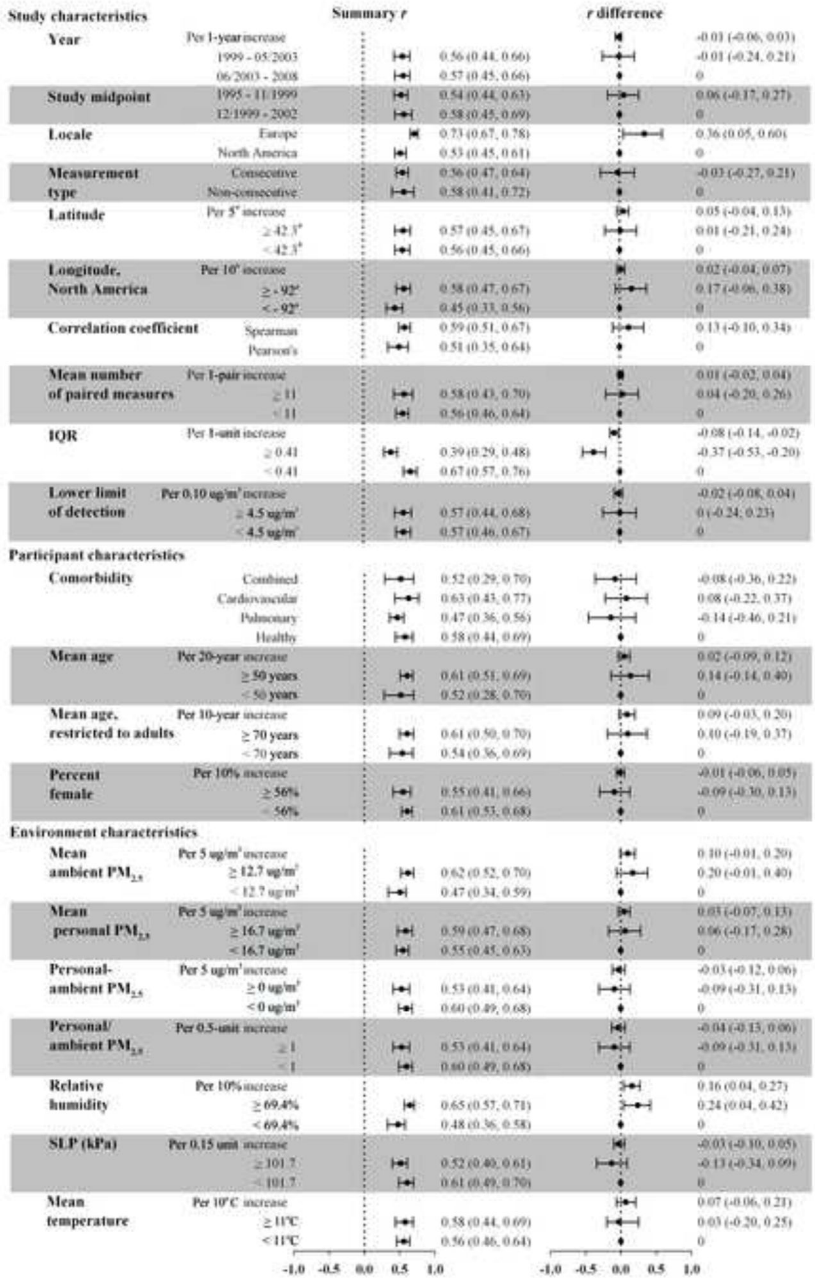

Figure 4.

Summary correlations (95% CI) and correlation differences (95% CI) by study, participant, and environment characteristics for eighteen studies examining the within-participant correlation between ambient and personal $PM_{2.5}$.

TABLE 1

Characteristics of eighteen studies examining the within-participant correlation between ambient and personal $PM_{2.5}$.

		Setting			Study Dates			Ambient & Personal $PM_{2.5}$ Measures		
Study	**Sub-study**	**City**	**State/Province**	**Country**	**Start**	**End**	**Duration (months)**	**Timing**	**No. Pairs**[a]	***r***
Janssen et al. 1999[8]		Wageningen		Netherlands	03/29/1995	06/15/1995	2.5	N	6	P
Ebelt et al. 2000[45]		Vancouver	British Columbia	Canada	04/21/1998	09/25/1998	5.1	N	7	S
Janssen et al. 2000[27]	1	Amsterdam		Netherlands	11/02/1998	06/18/1999	7.4	N	9	S
	2	Helsinki		Finland	11/01/1998	04/30/1999	5.8	N	7	S
Sarnat et al. 2000[28]	1	Baltimore	Maryland	United States	06/29/1998	08/07/1998	1.3	C	9	S
	2				02/02/1999	03/13/1999	1.3	C	9	S
Williams et al. 2000[46]		Towson	Maryland	United States	07/26/1998	08/23/1998	0.9	C	16	P
Rodes et al. 2001[47,48]		Fresno	California	United States	02/01/1999	02/28/1999	0.9	C	6	P
Sarnat et al. 2001[29]	1	Baltimore	Maryland	United States	06/29/1998	08/23/1998	1.8	C	8	S
	2				02/02/1999	03/13/1999	1.3	C	12	
Suh et al. 2003[49]	1	Los Angeles	California	United States	06/12/2000	07/24/2000	1.4	C	NR	NR
	2				02/11/2000	03/22/2000	1.3	C		
Adgate et al. 2003[30]		Minneapolis	Minnesota	United States	04/26/1999	11/21/1999	6.7	C	8	P
Liu et al. 2003[50]	1	Seattle	Washington	United States	10/26/1999	08/10/2000	9.3	C	7	P
	2				10/26/1999	10/26/2000	11.8	C	7	P
	3				02/07/2000	05/24/2001	15.2	C	7	P
	4				11/27/2000	02/24/2001	2.9	C	7	P
Williams et al. 2003[51]		Raleigh	North Carolina	United States	06/09/2000	05/21/2001	11.2	C	20	P
Reid 2003[12]	1	Atlanta	Georgia	United States	09/21/1999	11/23/1999	2.0	C	6	S
	2				04/01/2000	05/13/2000	1.4	C	6	S
Sarnat et al. 2005[41]	1	Boston	Massachusetts	United States	06/13/1999	07/23/1999	1.3	C	12	S
	2				02/01/2000	03/12/2000	1.3	C	12	S
Kim et al. 2006[11]		Toronto	Ontario	Canada	05/02/2000	10/31/2001	17.6	N	9	S
Noullett et al. 2006[52]		Prince George	British Columbia	Canada	02/05/2001	03/16/2001	1.3	N	9	S
Sarnat et al. 2006[42]	1	Steubenville	Ohio	United States	06/04/2000	8/18/2000	2.4	C	17	S
	2				09/24/2000	12/15/2000	2.6	C	20	S

Author Manuscript
Author Manuscript
Author Manuscript

		Setting			Study Dates			Ambient & Personal $PM_{2.5}$ Measures		
Study	**Sub-study**	**City**	**State/Province**	**Country**	**Start**	**End**	**Duration (months)**	**Timing**	**No. Pairs**[a]	***r***
Wu et al. 2006[53]		Pullman	Washington	United States	09/03/2002	11/01/2002	1.9	C	5	P
Brown et al. 2008[40]	1	Boston	Massachusetts	United States	11/15/1999	01/29/2000	2.4	C	6	S
	2				06/06/2000	07/25/2000	1.6	C	6	S
18 studies, 1999 – 2008[b]	**29**	**17**	**10**	**4**	**1995 – 2002**		**2.0**	**79% C**	**8**	**37% P**

[a]Mean number of ambient-personal paired measurements for estimation of within-participant correlations.

[b]Summary statistics reported as counts, range, proportion, or median.

N indicates non-consecutive, C consecutive.

NR, not reported; P, Pearson product-moment correlation coefficient; $PM_{2.5}$, particulate matter < 2.5 μm in diameter (μg/m3); *r*, within-participant ambient-personal $PM_{2.5}$ correlation estimation method; S, Spearman rank correlation coefficient.

TABLE 2

Characteristics of participants in eighteen studies examining the within-participant correlation between ambient and personal $PM_{2.5}$.

			Participant Age (years)				
Study	Sub-study	No.	Mean	Min	Max	% Female	Comorbidity
Janssen et al. 1999[8]		13	10.8	10	12	54	N
Ebelt et al. 2000[45]		16	74	54	86	56	P
Janssen et al. 2000[27]	1	36	72	55	84	35	C
	2	46	68	54	89	49	C
Sarnat et al. 2000[28]	1	14	75	64	NR	60	N
	2	14	75	64	NR	60	N
Williams et al. 2000[46]		19	81	72	93	81	N, C, P
Rodes et al. 2001[47,48]		5	85	55	NR	68	N
Sarnat et al. 2001[29]	1	6[a]	11	9	13	33	N
	2	28[a]	(Children and elderly)			NC	N, P
Suh et al. 2003[49]	1	15	68.1	55	84	87	P
	2	15	70	60	84	93	P
Adgate et al. 2003[30]		28	42	24	64	72	N
Liu et al. 2003[50]	1	34	76.3	66	88	61	N
	2	51	77.3	65	89	55	P
	3	33	76.6	57	86	35	C
	4	21	9	6	13	24	P
Williams et al. 2003[51]		36	70	55	85	74	C
Reid 2003[12]	1	16	64	33	88	33	C, P
	2	21	63	33	84	50	C, P
Sarnat et al. 2005[41]	1	29	(Children and elderly)			73	N
	2	27	(Children and elderly)			83	N
Kim et al. 2006[11]		28	64	49	80	11	C
Noullett et al. 2006[52]		14	11	10	12	53	N
Sarnat et al. 2006[42]	1	10	72.4	NR	NR	80	N
	2	10	69.8	NR	NR	90	N

Study	Sub-study	No.	Participant Age (years) Mean	Min	Max	% Female	Comorbidity
Wu et al. 2006[53]		11	27	18	52	66	P
Brown et al. 2008[40]	1	12	NC	40	NC	20	C, P
	2	11	NC	40	NC	27	C, P
18 studies, 1999 – 2008[b]	**29**	**619**	**70**	**6**	**93**	**60%**	**41% N**

[a] Excludes participants in Sarnat et al, 2000[28]

[b] Summary statistics reported as counts, range, proportion, or median

For comorbidity, N indicates none; P, chronic pulmonary disease; C, chronic cardiovascular disease.

NR indicates not reported; NC, not collected.

TABLE 3

Characteristics of the environment in eighteen studies examining the within-participant correlation between ambient and personal $PM_{2.5}$.

		Ambient $PM_{2.5}$ ($\mu g/m^3$)	Personal $PM_{2.5}$ ($\mu g/m^3$)	*r*		Meteorological data (mean over study period)		
Study,	**Sub-study**	**Mean (SD)**	**Mean (SD)**	$\bar{r}$ *(SD)*	**IQR**	**T (°C)**	**SLP (kPa)**	**RH (%)**
Janssen et al. 1999[8]		17.1 (2.8)	28.3 (11.3)	0.83 (0.20)	0.29	10.6	101.66	76.6
Ebelt et al. 2000[45]		11.4 (4.1)	18.2 (14.6)	0.52 (0.17)	0.70	16.6	101.60	76.6
Janssen et al. 2000[27]	1	20.8 (4.0)	22.2 (25.7)	0.72 (0.09)	0.38	7.8	101.52	84.7
	2	12.7 (2.0)	10.9 (4.4)	0.72 (0.08)	0.26	−1.8	101.10	87.4
Sarnat et al. 2000[28]	1	25.2 (11.5)	22.3 (10.1)	0.74 (0.12)	0.30	24.6	101.56	64.6
	2	20.5 (9.4)	15.0 (14.6)	0.40 (0.14)	0.73	3.1	101.75	59.9
Williams et al. 2000[46]		22.0 (12.9)	13.0 (3.2)	0.73 (0.07)	0.22	24.0	101.85	68.3
Rodes et al. 2001[47,48]	1	22.9 (10.1)	13.1 (5.9)	0.44 (0.28)	0.32	9.6	102.27	75.2
Sarnat et al. 2001[29]	1	24.7 (14.0)	21.1 (8.1)	0.60 (0.22)	0.37	24.4	101.63	66.2
	2	20.1 (9.4)	18.5 (17.8)	0.27 (0.08)	0.41	3.1	101.75	59.9
Suh et al. 2003[49]	1	ND (ND)	25.1 (20.8)	ND (ND)	ND	21.1	101.34	71.3
	2	ND (ND)	19.6 (14.5)	ND (ND)	ND	13.7	101.70	69.7
Adgate et al. 2003[30]		10.1 (6.2)	26.4 (30.2)	0.09 (0.09)	0.57	16.9	101.50	62.7
Liu et al. 2003[50]	1	8.3 (5.7)	9.3 (8.4)	0.47 (0.11)	0.66	9.9	101.78	78.9
	2	8.4 (5.7)	10.5 (7.2)	0.40 (0.10)	0.61	10.8	101.78	77.8
	3	11.9 (5.7)	10.8 (8.4)	0.61 (0.14)	0.60	10.0	101.82	76.0
	4	11.4 (5.7)	13.3 (8.2)	0.51 (0.11)	0.42	6.9	101.90	77.1
Williams et al. 2003[51]		19.2 (8.6)	23.0 (16.1)	0.34 (0.04)	0.29	17.2	101.92	67.4
Reid 2003[12]	1	20.6 (9.7)	16.3 (8.4)	0.54 (0.14)	ND	15.7	102.01	68.3
	2	15.7 (5.4)	15.0 (7.5)	0.49 (0.12)	ND	17.2	101.64	62.0
Sarnat et al. 2005[41]	1	15.5 (12.1)	28.6 (12.2)	0.61 (0.07)	0.37	22.8	101.58	62.3
	2	11.7 (6.8)	16.7 (9.8)	0.35 (0.08)	0.49	2.6	101.68	60.7
Kim et al. 2006[11]		11.0 (8.0)	22.0 (42.0)	0.69 (0.27)	ND	11.0	101.72	73.8
Noullett et al. 2006[52]		18.0 (15.0)	18.0 (13.0)	0.54 (0.10)	0.31	−6.0	102.02	69.4
Sarnat et al. 2006[42]	1	20.1 (9.3)	19.9 (9.4)	0.81 (0.19)	0.35	20.7	101.63	75.0
	2	19.3 (12.2)	20.1 (11.6)	0.76 (0.11)	0.28	7.0	102.12	71.8

		Ambient $PM_{2.5}$ ($\mu g/m^3$)	Personal $PM_{2.5}$ ($\mu g/m^3$)	r		Meteorological data (mean over study period)		
Study,	**Sub-study**	**Mean (SD)**	**Mean (SD)**	$\bar{r}$ *(SD)*	**IQR**	**T (°C)**	**SLP (kPa)**	**RH (%)**
Wu et al. 2006[53]		11.5 (8.0)	13.8 (11.1)	0.46 (0.31)	1.04	9.6	101.88	48.1
Brown et al. 2008[40]	1	9.9 (5.1)	12.0 (6.0)	0.22 (0.26)	0.94	2.0	101.67	59.0
	2	11.8 (5.5)	10.0 (6.2)	0.68 (0.21)	0.36	20.4	101.43	70.3
18 studies, 1999 – 2008[a]	**29**	**15.7 (8.0)**	**18.2 (10.1)**	**0.54 (0.12)**	**0.38**	**10.8**	**101.7**	**69.7**

[a]Summary statistics reported as counts or median.

IQR indicates interquartile range of r between participants within studies; r, within-participant ambient $PM_{2.5}$-personal $PM_{2.5}$ correlation coefficient; RH, relative humidity; SD, standard deviation; SLP, sea level pressure; T, temperature; ND, no data (Data requested, but not provided as of 06/11/09).