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## Estimating error in using ambient PM<sub>2.5</sub> concentrations as proxies for personal exposures

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### Abstract

**Background**—Several methods have been used to account for measurement error inherent in using ambient concentration of particulate matter  $< 2.5 \mu\text{m}^3$  (PM<sub>2.5</sub>) as a proxy for personal exposure. Such methods usually rely on the estimated correlation between ambient and personal PM<sub>2.5</sub> 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<sub>2.5</sub>.

**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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> as a proxy for personal exposure.

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.<sup>1-3</sup> Investigators from the National Morbidity and Mortality and Air Pollution Study,<sup>4</sup> 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<sub>10</sub> 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.<sup>5</sup> Also, cross-sectional PM correlations may be weaker than longitudinal, within-person PM correlations, due to inter-individual variation in behaviors influencing exposure.<sup>6-8</sup>

There has not been a systematic and quantitative review of studies of the ambient-personal PM<sub>2.5</sub> 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<sub>2.5</sub> concentration as proxies for personal PM exposure. To address this gap, we systematically and quantitatively reviewed the literature estimating within-participant, ambient-personal PM<sub>2.5</sub> correlations and determined the extent and sources of measurement error inherent in using ambient PM<sub>2.5</sub> as a surrogate for personal exposure. These results will facilitate quantification of bias resulting from the use of ambient PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub>, measurement of personal PM<sub>2.5</sub>, and estimation of the within-participant, ambient-

personal PM<sub>2.5</sub> 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<sub>2.5</sub> detection, number (minimum, mean) of paired PM<sub>2.5</sub> 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<sub>2.5</sub> concentrations (ambient, personal); the within-participant, ambient-personal PM<sub>2.5</sub> 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 GONet 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/climate/research.html>).

**Statistical analysis**

Uniform measures of association for the *j*<sup>th</sup> study were estimated from the personal-ambient PM<sub>2.5</sub> correlations measured within each of the *i*<sup>th</sup> participants. We converted each within-participant correlation coefficient (*r<sub>i</sub>*) to its variance-stabilizing, Fisher’s z-transform

$$(Z_{r_i}) = \frac{1}{2} \log_e \left( \frac{1+r_i}{1-r_i} \right) \tag{9}$$

Estimates of the within-participant variance (*v<sub>i</sub>*) =  $\frac{1}{n_i-3}$  and

between-participant variance ( $\tau_j^2$ ) =  $\frac{Q_j - (k_j - 1)}{c}$  for the *j*<sup>th</sup> study were estimated from the number of paired personal-ambient PM<sub>2.5</sub> measurements for each participant (*n<sub>i</sub>*), the number of participants per study (*k<sub>j</sub>*), the weighted sum of squared errors

$$(Q_j) = \sum_{i=1}^k (n_i - 3) (Z_{r_i} - \bar{Z}_{r_i})^2, \text{ and a constant } (c) = \sum_{i=1}^k (n_i - 3) - \frac{\sum_{i=1}^k (n_i - 3)^2}{\sum_{i=1}^k (n_i - 3)}. \text{ The transformed}$$

effect size for the *j*<sup>th</sup> study is given by  $\bar{Z}_j = \frac{\sum_{i=1}^k w_i Z_{r_i}}{\sum_{i=1}^k w_i}$  with weights (*w<sub>i</sub>*) =  $\left( \frac{1}{n_i - 3} + \tau_j^2 \right)^{-1}$ ,

standard errors  $(S_j) = \sqrt{\frac{1}{\sum_{i=1}^k w_i}}$  and study-specific weights  $W_j = \left( \frac{1}{S_j} \right)^2$ .<sup>10</sup> Negative  $\tau^2$  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<sup>11,12</sup> 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,<sup>13,14</sup> and a non-parametric “trim and fill” method that imputes hypothetically missing results due to publication bias.<sup>15</sup> 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 ( $P_{\text{Begg}}$ ;  $P_{\text{Egger}}$ ) give evidence of asymmetry.

Inter-study heterogeneity was evaluated using a plot<sup>16</sup> of  $\frac{\bar{Z}_j}{S_j}$  versus  $\frac{1}{S_j}$  and Cochran’s Q test.<sup>17</sup> The plot and test are related, in that the position of the  $j^{\text{th}}$  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  $P_{\text{Cochran}} > 0.1$ .

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.<sup>18</sup> 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<sub>2.5</sub> health effects: latitude, longitude, presence of comorbidities, mean age, percent female, mean ambient PM<sub>2.5</sub>, 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<sub>2.5</sub> data over consecutive days. During data collection, the studies recorded an average of eight (range 5 to 20) ambient and personal PM<sub>2.5</sub> 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<sub>2.5</sub> concentrations (range 8.3 to 25.2 ug/m<sup>3</sup>) were lower than personal PM<sub>2.5</sub> concentrations (range 9.3 to 28.6 ug/m<sup>3</sup>) overall, with a median personal-ambient PM<sub>2.5</sub> 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  $r_i$  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  $\bar{Z}_i$ , which suggests little evidence of asymmetry. This result is consistent with  $P_{\text{Begg}} = 0.9$  and  $P_{\text{Egger}} = 0.2$ , 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  $P_{\text{Cochran}} < 0.001$ .

The interquartile range (IQR) of  $r_i$  (range dichotomized as  $\geq 0.41$  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  $\text{PM}_{2.5}$  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  $\text{PM}_{2.5}$  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,<sup>19</sup> where they are exposed to numerous sources of  $\text{PM}_{2.5}$ , with physical and chemical properties and toxicities that often differ from those of ambient  $\text{PM}_{2.5}$ .<sup>20,21</sup> Thus, estimates of personal  $\text{PM}_{2.5}$  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.<sup>22–26</sup> Nonetheless, certain studies are often cited to justify using ambient  $\text{PM}_{2.5}$  concentrations as proxies for total personal  $\text{PM}_{2.5}$  exposures.<sup>8,27–29</sup> These studies report strong within-participant ambient-personal  $\text{PM}_{2.5}$  correlations. Other studies, which report ambient-personal  $\text{PM}_{2.5}$  correlations as low as 0.10<sup>30</sup> are rarely cited.

Motivated by this apparent pattern of citations, we reviewed studies of the within-participant correlation between ambient and personal  $\text{PM}_{2.5}$ , 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  $\text{PM}_{2.5}$  as a proxy for personal  $\text{PM}_{2.5}$  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 starting-

date limitations. Indeed, this systematic review had all the features of a meta-analysis deemed necessary to ensure its sensitivity.<sup>31–33</sup>

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<sub>2.5</sub> concentrations<sup>34</sup> or closer proximities to regulatory monitors. Furthermore, the direct associations of ambient PM<sub>2.5</sub> concentrations and relative humidity with  $\bar{r}$  suggest an increased contribution of ambient PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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).<sup>6–8</sup> A series of studies conducted in the Netherlands also found that ambient-personal PM correlations were stronger when analyses were conducted longitudinally.<sup>35</sup> Because studies of within-versus between-participant correlations address systematically different questions—the recognition of which precludes simultaneous evaluation<sup>36</sup>—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.<sup>37</sup> One method to assess the validity of our conclusions and eliminate the potential for ecologic bias<sup>38</sup> 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.<sup>39</sup> 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<sub>2.5</sub> although several European countries also regulate PM<sub>10</sub>. It remains unclear whether findings for PM<sub>2.5</sub> extend to PM<sub>10</sub>. 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.<sup>40–42</sup> Nonetheless, the results presented here have potentially important implications for studies examining the health effects of PM<sub>2.5</sub> 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,<sup>3,6–8,43</sup> Crooks et al<sup>44</sup> 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<sub>2.5</sub> 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<sub>2.5</sub> as a proxy for personal exposure. The wide range in estimated correlations between personal and ambient PM<sub>2.5</sub>, 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<sub>2.5</sub> as a proxy for personal exposure.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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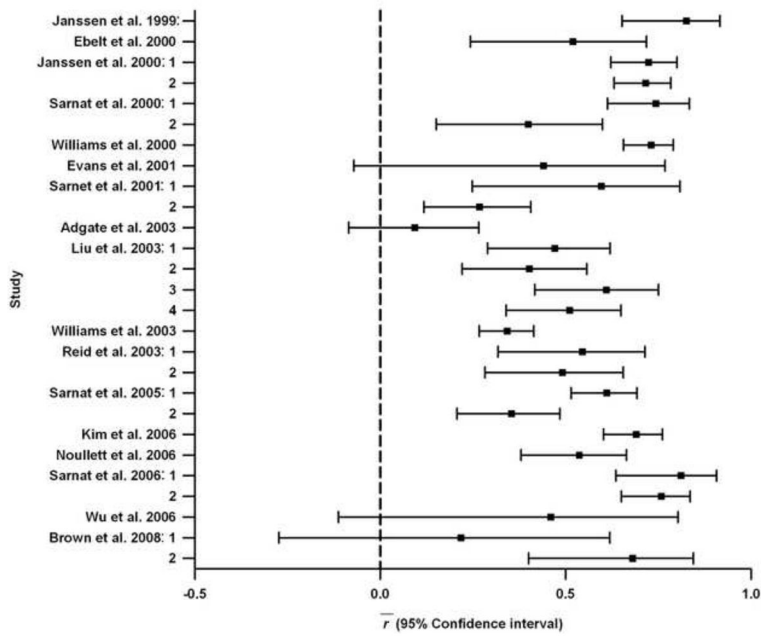
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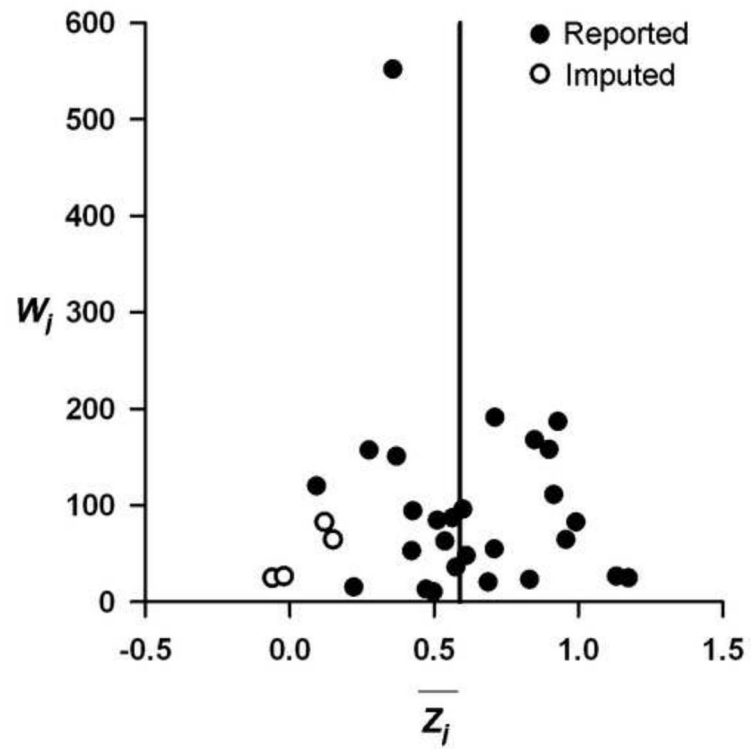


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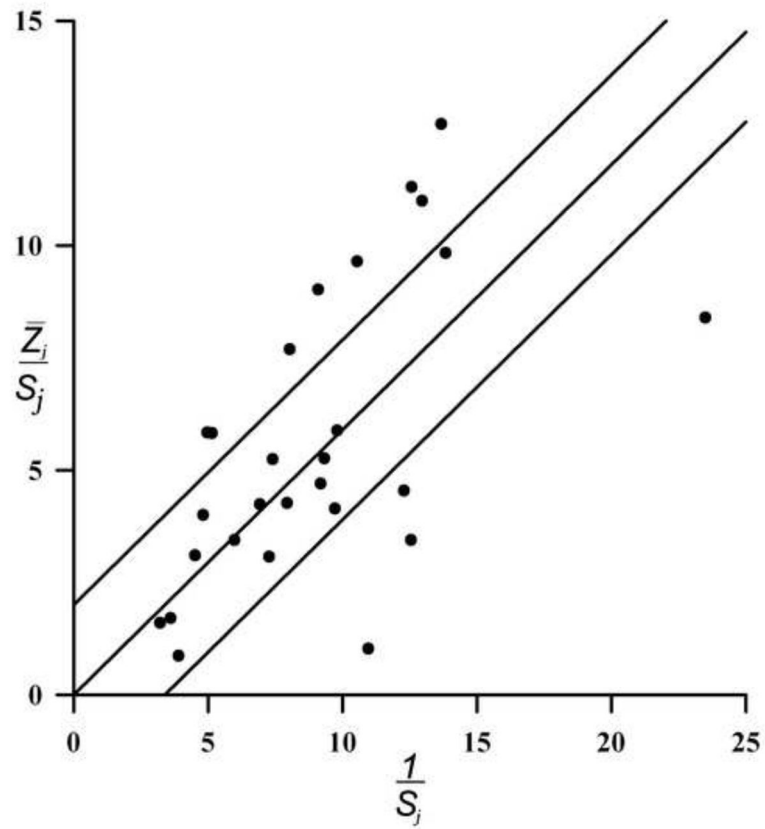
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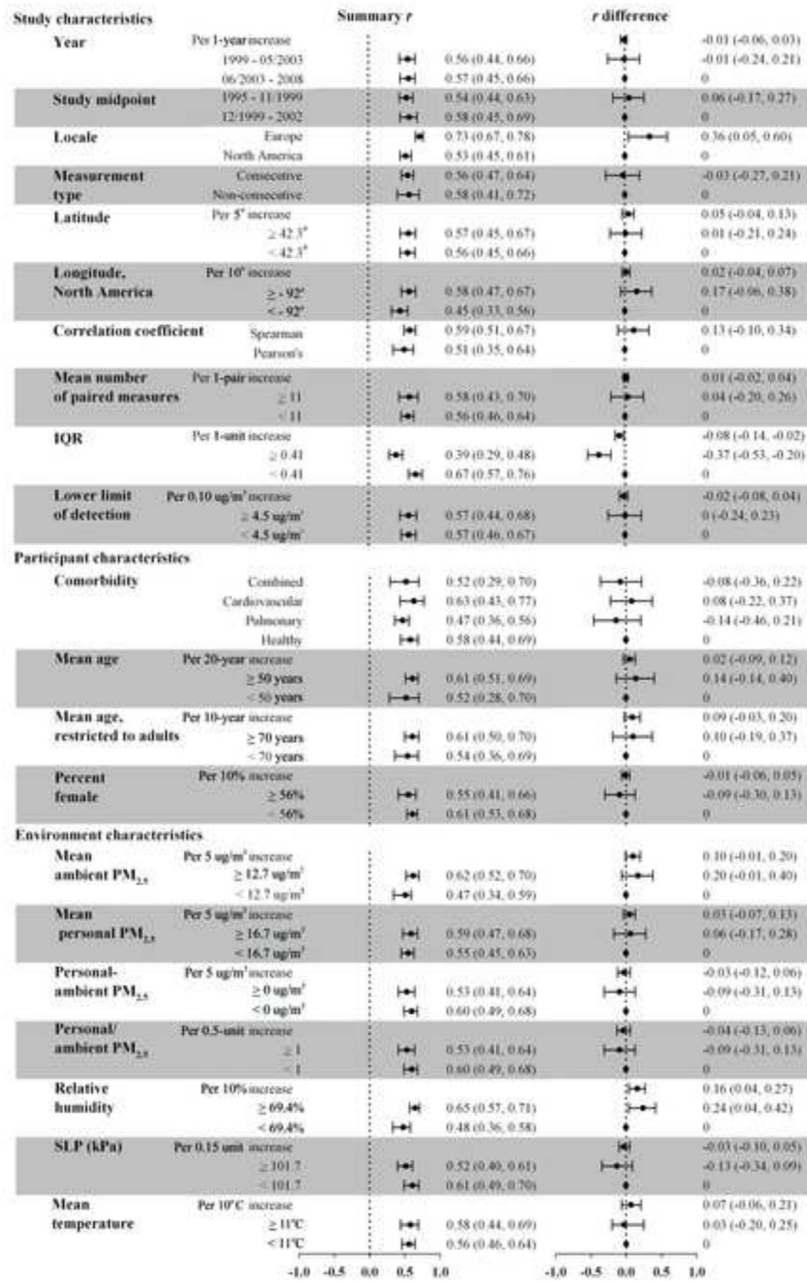
**Figure 1.** Twenty-seven estimates of  $\bar{r}$  (95% CI) from eighteen studies of the within-participant correlation between ambient and personal  $PM_{2.5}$ . See Table 1 for descriptions of sub-studies.



**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<sub>2.5</sub>.



TABLE 1

Characteristics of eighteen studies examining the within-participant correlation between ambient and personal PM<sub>2.5</sub>.

Study	Sub-study	Setting			Study Dates			Ambient & Personal PM <sub>2.5</sub> Measures		
		City	State/Province	Country	Start	End	Duration (months)	Timing	No. Pairs <sup>d</sup>	r
Janssen et al. 1999 <sup>8</sup>		Wageningen		Netherlands	03/29/1995	06/15/1995	2.5	N	6	P
Ebelt et al. 2000 <sup>45</sup>		Vancouver	British Columbia	Canada	04/21/1998	09/25/1998	5.1	N	7	S
Janssen et al. 2000 <sup>27</sup>	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 <sup>28</sup>	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 <sup>46</sup>		Towson	Maryland	United States	07/26/1998	08/23/1998	0.9	C	16	P
Rodes et al. 2001 <sup>47,48</sup>		Fresno	California	United States	02/01/1999	02/28/1999	0.9	C	6	P
Sarnat et al. 2001 <sup>29</sup>	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 <sup>49</sup>	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 <sup>30</sup>		Minneapolis	Minnesota	United States	04/26/1999	11/21/1999	6.7	C	8	P
Liu et al. 2003 <sup>50</sup>	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 <sup>51</sup>		Raleigh	North Carolina	United States	06/09/2000	05/21/2001	11.2	C	20	P
Reid 2003 <sup>12</sup>	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 <sup>41</sup>	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 <sup>11</sup>		Toronto	Ontario	Canada	05/02/2000	10/31/2001	17.6	N	9	S
Noulett et al. 2006 <sup>52</sup>		Prince George	British Columbia	Canada	02/05/2001	03/16/2001	1.3	N	9	S
Sarnat et al. 2006 <sup>42</sup>	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

Study	Setting				Study Dates			Ambient & Personal PM <sub>2.5</sub> Measures		
	Sub-study	City	State/Province	Country	Start	End	Duration (months)	Timing	No. Pairs <sup>d</sup>	r
Wu et al. 2006 <sup>53</sup>		Pullman	Washington	United States	09/03/2002	11/01/2002	1.9	C	5	P
Brown et al. 2008 <sup>40</sup>	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
<b>18 studies, 1999 – 2008<sup>b</sup></b>	<b>29</b>	<b>17</b>	<b>10</b>	<b>4</b>	<b>1995 – 2002</b>		<b>2.0</b>	<b>79% C</b>	<b>8</b>	<b>37% P</b>

<sup>a</sup> Mean number of ambient-personal paired measurements for estimation of within-participant correlations.

<sup>b</sup> 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<sub>2.5</sub>, particulate matter < 2.5 μm in diameter (μg/m<sup>3</sup>); r, within-participant ambient-personal PM<sub>2.5</sub> correlation estimation method; S, Spearman rank correlation coefficient.

Characteristics of participants in eighteen studies examining the within-participant correlation between ambient and personal PM<sub>2.5</sub>.

**TABLE 2**

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

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

<sup>a</sup>Excludes participants in Sarnat et al. 2000<sup>28</sup>

<sup>b</sup>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<sub>2.5</sub>.

Study,	Sub-study	Ambient PM <sub>2.5</sub> (µg/m <sup>3</sup> )		Personal PM <sub>2.5</sub> (µg/m <sup>3</sup> )		r		Meteorological data (mean over study period)			
		Mean (SD)	Mean (SD)	Mean (SD)	F (SD)	IQR	T (°C)	SLP (kPa)	RH (%)		
Janssen et al. 1999 <sup>8</sup>		17.1 (2.8)	28.3 (11.3)	0.83 (0.20)	0.29	10.6	101.66	76.6			
Ebelt et al. 2000 <sup>45</sup>		11.4 (4.1)	18.2 (14.6)	0.52 (0.17)	0.70	16.6	101.60	76.6			
Janssen et al. 2000 <sup>27</sup>	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 <sup>38</sup>	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 <sup>46</sup>		22.0 (12.9)	13.0 (3.2)	0.73 (0.07)	0.22	24.0	101.85	68.3			
Rodes et al. 2001 <sup>47,48</sup>	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 <sup>29</sup>	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 <sup>49</sup>	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 <sup>30</sup>		10.1 (6.2)	26.4 (30.2)	0.09 (0.09)	0.57	16.9	101.50	62.7			
Liu et al. 2003 <sup>50</sup>	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 <sup>51</sup>		19.2 (8.6)	23.0 (16.1)	0.34 (0.04)	0.29	17.2	101.92	67.4			
Reid 2003 <sup>12</sup>	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 <sup>41</sup>	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 <sup>11</sup>		11.0 (8.0)	22.0 (42.0)	0.69 (0.27)	ND	11.0	101.72	73.8			
Noulet et al. 2006 <sup>52</sup>		18.0 (15.0)	18.0 (13.0)	0.54 (0.10)	0.31	-6.0	102.02	69.4			
Sarnat et al. 2006 <sup>42</sup>	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			

Study,	Sub-study	Ambient PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )		Personal PM <sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ )		$r$	Meteorological data (mean over study period)			
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)		IQR	T ( $^{\circ}\text{C}$ )	SLP (kPa)	RH (%)
Wu et al. 2006 <sup>53</sup>		11.5 (8.0)	13.8 (11.1)	0.46 (0.31)	1.04	9.6	101.88	48.1		
Brown et al. 2008 <sup>40</sup>	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		
<b>18 studies, 1999 – 2008<sup>a</sup></b>	<b>29</b>	<b>15.7 (8.0)</b>	<b>18.2 (10.1)</b>	<b>0.54 (0.12)</b>	<b>0.38</b>	<b>10.8</b>	<b>101.7</b>	<b>69.7</b>		

<sup>a</sup> Summary statistics reported as counts or median.

IQR indicates interquartile range of  $r$  between participants within studies;  $r$ , within-participant ambient PM<sub>2.5</sub>-personal PM<sub>2.5</sub> 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).