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APPROACH TO ESTIMATING PARTICIPANT POLLUTANT EXPOSURES IN THE MULTI-ETHNIC STUDY OF ATHEROSCLEROSIS AND AIR POLLUTION (MESA AIR)

Martin A. Cohen[1,*], **Sara D. Adar**[1], **Ryan W. Allen**[1,2], **Edward Avol**[3], **Cynthia L. Curl**[1], **Timothy Gould**[4], **David Hardie**[1], **Anne Ho**[1], **Patrick Kinney**[5], **Timothy V. Larson**[4], **Paul Sampson**[6], **Lianne Sheppard**[7], **Karen D. Stukovsky**[7], **Susan S. Swan**[1,8], **L-J Sally Liu**[1,9], and **Joel D. Kaufman**[1]

[1]Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, WA, USA

[3]Department of Preventive Medicine, University of Southern California, Los Angeles, CA, USA

[4]Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA

[5]Department of Environmental Health Sciences, Columbia University, New York, NY, USA

[6]Department of Statistics, University of Washington, Seattle, WA, USA

[7]Department of Biostatistics, University of Washington, Seattle, WA, USA

Abstract

Most published epidemiology studies of long-term air pollution health effects have relied on central site monitoring to investigate regional-scale differences in exposure. Few cohort studies have had sufficient data to characterize localized variations in pollution, despite the fact that large gradients can exist over small spatial scales. Similarly, previous data have generally been limited to measurements of particle mass or several of the criteria gases. The Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air) is an innovative investigation undertaken to link subclinical and clinical cardiovascular health effects with individual-level estimates of personal exposure to ambient-origin pollution. This project improves on prior work by implementing an extensive exposure assessment program to characterize long-term average concentrations of ambient-generated $PM_{2.5}$, specific $PM_{2.5}$ chemical components, and co-pollutants, with particular emphasis on capturing concentration gradients within cities.

This paper describes exposure assessment in MESA Air, including questionnaires, community sampling, home monitoring, and personal sampling. Summary statistics describing the performance of the sampling methods are presented along with descriptive statistics of the air pollution concentrations by city.

*Corresponding Author: Martin Cohen, mcohen@u.washington.edu, Phone: 206-616-1905.
[2]Current address: Faculty of Health Sciences, Simon Fraser University, Burnaby, BC, Canada
[8]Current address: MDS Pharma Services, Inc., Bothell, WA, USA
[9]Current address: Institute of Social and Preventive Medicine, University of Basel, Basel, Switzerland

Brief This manuscript describes the exposure assessment methodology used in the MESA Air study of atherosclerosis and air pollution.

Supporting Information is available on-line that presents more details of the measurement methods and quality control/quality assurance procedures and outcomes. This information is available free of charge via the internet at http://pubs.acs.org.

Introduction

Several epidemiologic studies have reported associations between long-term exposure to fine particulate matter ($PM_{2.5}$) and cardiovascular morbidity and mortality [1]. One mechanism through which chronic exposures are hypothesized to affect cardiac health is through acceleration of atherosclerosis. This hypothesis is supported by evidence from animal toxicological investigations [2-4] and cross-sectional epidemiologic studies [5-8]. Since no published studies have yet evaluated air pollution and the progression of atherosclerosis, the Multi-Ethnic Study of Atherosclerosis and Air Pollution (henceforth "MESA Air") was initiated in 2004 to address this question. The primary aims of the ten-year project are to examine the impacts of chronic exposures to $PM_{2.5}$ of ambient-origin on the progression of atherosclerosis and the incidence of cardiovascular disease. Ambient-origin $PM_{2.5}$ is specifically defined in this study as both outdoor $PM_{2.5}$ and the fraction of outdoor $PM_{2.5}$ that has infiltrated into indoor environments. Secondary aims of MESA Air and its ancillary studies are to evaluate associations between specific gases and particulate components and cardiovascular disease.

In order to meet these aims, MESA Air has developed an exposure assessment methodology that will allow for participant-specific estimates of long-term exposure to $PM_{2.5}$ of ambient-origin during the time period of interest. The concept that ambient exposure should be considered in air pollution epidemiology is not new [9], and ambient exposures are known to be highly correlated with ambient concentrations [10] [11]. However, in comparison with ambient concentrations, ambient exposures have shown larger health effect estimates with smaller confidence intervals in a time series study [12].

Previous chronic air pollution studies have predominantly relied on regulatory monitoring data and have assigned one ambient concentration to numerous participants. We designed a monitoring campaign to better capture within-city variations in pollution, allowing for the resolution of concentrations at a relatively small spatial scale (i.e. tens of meters rather than kilometers). Within-city differences are potentially important since recent evidence suggests that local concentration gradients are linked to cardiovascular outcomes [1,13,14].

Another key feature of MESA Air is the inclusion of participant-specific residential infiltration efficiencies and time-location patterns. These data allow us to estimate exposures to ambient-origin air pollution rather than using ambient concentrations as surrogates [11,15]. This is a potentially important refinement from past research, since individuals spend the vast majority of their time indoors [16], ambient $PM_{2.5}$ concentrations are attenuated as they move indoors, and attenuation differs between homes and over time within homes [17-19].

Since it was not feasible to measure exposures for all 6,200 MESA Air participants, a modeling approach was selected to characterize each participant's long-term exposure to ambient-origin air pollution. This paper describes the general exposure assessment approach of MESA Air, with an emphasis on the air pollution measurements collected, chemical analyses employed, and quality assurance/quality control (QA/QC) procedures utilized. More detailed information on the epidemiologic design appears in an accompanying manuscript (Kaufman et al, in preparation). A description of the ambient concentration modeling approach is presented in Szpiro et al. [20].

Study Population and Geographic Areas

MESA Air is an ancillary study to the MESA, previously described by Bild and colleagues [21]. The primary purpose of MESA is to characterize subclinical cardiovascular disease and its associated risk factors among African American, Caucasian, Chinese, and Hispanic persons aged 45-84 yrs and free of clinical cardiovascular disease at study enrollment. Male and female

subjects were recruited into MESA from six U.S. metropolitan areas: Baltimore, MD; Chicago, IL; Winston-Salem, NC; Los Angeles, CA; Manhattan and Bronx, NY; and St. Paul, MN. MESA participants were eligible for inclusion in MESA Air along with new participants recruited from coastal Los Angeles, CA; Riverside, CA; and Rockland County, NY. These additional participants were recruited to enhance exposure gradients among the existing cohort. Further details about subject recruitment and demographics of the MESA Air cohort can be found in Kaufman et al. (in preparation).

General Approach to Exposure Assessment

The MESA Air exposure assessment approach is illustrated in Figure 1. Extensive pollution measurements were made at the homes and in the communities of a subset of participants in each of the study areas. These data, along with local geographic, meteorological, and emission data inform a hierarchical spatiotemporal model that predicts long-term average concentrations outside of each participant's home [20]. Measurements of indoor and outdoor particulate sulfur are integrated with housing characteristics data collected from each participant to predict home-specific infiltration efficiencies (F_{inf}) and personalized estimates of indoor concentrations of ambient-generated $PM_{2.5}$ [22]. The ambient concentration to which individual i within area k during time period v is exposed $\left(E^{A}_{kiv}\right)$, is a function of the fraction of time spent outdoors (f^{o}), the particle infiltration efficiency (F_{inf}), and the ambient concentration $\left(C^{A}_{kiv}\right)$:

$$E^{A}_{kiv} = [\, f^{o} + (1 - f^{o})\, F_{\text{inf}}]\, C^{A}_{kiv}$$

The total personal exposure can be written as:

$$E^{P}_{kiv} = E^{A}_{kiv} + E^{N}_{kiv} = [\, f^{o} + (1 - f^{o})\, F_{\text{inf}}]\, C^{A}_{kiv} + E^{N}_{kiv}$$

where E^{N}, or exposure to non-ambient sources, is the sum of exposure to indoor-generated $PM_{2.5}$ (E^{I}) and exposure to personal activity $PM_{2.5}$. E^{I} is exposure to the fraction of the indoor particles generated indoors, expressed as the difference between total indoor concentration C^{I} and infiltrated concentration:

$$E^{\text{I}} = [\, 1 - f^{o}]\left[C^{\text{I}} - \left(F_{\text{inf}} \times C^{\text{A}}\right)\right]$$

Exposure to personal activity $PM_{2.5}$ is the difference between the measured E^{P} and the sum of calculated E^{A} and E^{I}. [23]

Further detail pertaining to long-term average ambient concentration modeling at the subject's home address $\left(C^{A}_{kiv}\right)$ can be found in Szpiro et al [20]. The data collection methods, measured parameters, analytic methods, and quality control procedures are described below.

Pollutants of Interest

The pollutant of primary interest in MESA Air is $PM_{2.5}$. Due to the influence of traffic-generated pollution on within-city spatial gradients and the potential importance of those gradients on health [24], light absorbing carbon (LAC), total oxides of nitrogen (NO_x), and nitrogen dioxide (NO_2) were also measured. $PM_{2.5}$ composition was determined by analyzing for elemental composition, organic carbon (OC), elemental carbon (EC), and specific organic compounds. Ozone (O_3) and sulfur dioxide (SO_2) were also measured in select situations.

Data Sources and Collection Methods

Community-Based Monitoring

MESA Air Fixed Sites—In order to expand our characterization of temporal variability to more locations, we operated between 1 and 5 fixed monitoring stations in each study area. These "fixed sites" remained at set locations and collected two-week integrated samples of $PM_{2.5}$, LAC, NO_x, NO_2, EC, OC, elemental and organic composition of $PM_{2.5}$, and SO_2 (Table 1) while MESA Air participants were being observed for subclinical and clinical disease. The locations for these sites included libraries, schools, or other buildings that were in participant-dense areas underrepresented by the existing U.S. EPA's regulatory Air Quality System (AQS) network. One monitor was also placed within 100 m of an interstate or state highway in each area to characterize any differences in temporal trends near major roadways, where AQS PM monitors are generally not located. One fixed site per area was also co-located with a local EPA speciation site (except in Rockland, NY and coastal Los Angeles, CA) to calibrate MESA Air measurements with the Federal Reference Method (FRM) measurements.

Community Saturation Monitoring—Approximately 100 simultaneous two-week samples of NO_2, NO_x, and SO_2 (Table 1) were collected in each study area to create a spatially rich dataset that would identify important geographic predictors of within-city concentration variability. Since traffic is a major source of this variability, the saturation samples focused on roadway concentration gradients but also captured other local sources.

Saturation sampling occurred during three sampling periods (December through February; May through August; and in October/November, or March/April) to capture seasonal differences in spatial concentration patterns. All samples were collected using passive Ogawa samplers attached to utility poles approximately 3 m above ground level. Based on our preliminary spatial models and past investigations [25-27], we chose a factorial sampling design to sample near and far from major roadways and in areas of high and low population density. To maximize variability while minimizing technician driving time, we selected a roadway gradient design for most locations with six samples collected along a trajectory perpendicular to a major roadway (i.e., interstate or state highways or major arterials) as defined by the U.S. Census Bureau's Census Feature Class Code (CFCC) A1, A2, or A3. In each direction, one sampler was situated between 0 and 50, 50 and 100, and 100-350 meters, respectively, from the major roadway's edge. Care was taken to avoid intersections with a large fraction of "stop and go" traffic and samplers were deployed both in North-South and in East-West orientations.

To ensure adequate capture of non-roadway conditions, gradient locations were sited in areas of low, medium, and high population density (defined by tertiles of the general population in our region of interest) and in areas of varied land-use. We also collected 10% of all samples at random locations and added new locations during the second and third sampling campaigns, based on important predictors identified during the first round of sampling.

Home and Participant Monitoring

MESA Air Questionnaire—To extrapolate our measured data to every participant, all subjects completed an exposure questionnaire upon study entry. The questionnaire included questions about predictors of F_{inf} including building characteristics, heating and air conditioning, and window opening and sought information about time-location patterns for secondary residences (e.g. winter homes), employment or volunteer positions, time spent indoors and outdoors, and time spent in traffic. All questionnaires and diaries were available to subjects in English, Spanish, and Chinese. Questionnaires are re-administered during follow-up phone calls approximately every nine months if a participant moves or has major life changes

(such as retirement or the death of a spouse). Questionnaires will also be re-administered to all participants during the next follow-up clinical exam, scheduled to begin in April 2010.

Home and Personal Pollution Measurements—Between 18 and 102 homes per area were selected for home outdoor monitoring to add broader spatial coverage to the existing AQS monitoring network, by forcing selections in each of approximately four zones per area. To capture more extreme within-city concentration variations than conventional AQS monitoring, we over-sampled homes both “near” (<50 meters) and “far” (> 300 meters) from major roads.

Outdoor sampling was typically conducted in a participant's backyard, away from all structures. When it was not possible to sample in a backyard, samplers were placed approximately 1 meter out an available window. Outdoor monitoring at participant homes included sampling for $PM_{2.5}$, LAC, NO_x, NO_2, SO_2, EC, OC, and elemental and organic composition of $PM_{2.5}$ (see Table 1). Homes were visited on a rolling basis, typically with up to 5 homes in each area monitored concurrently during any two-week period.

A portion of the homes (18 to 66 per area) selected for outdoor monitoring also received indoor pollution measurements. This sampling allowed us to obtain information to characterize the F_{inf} for homes in each area. Indoor samplers were deployed in the participant's main activity room away from pollutant sources or ventilation systems, and analyzed for similar constituents as outdoor samples. Home-specific ratios of indoor-to-outdoor sulfur concentrations were used to estimate the F_{inf} of $PM_{2.5}$ [11] [22], while O_3 was measured to characterize the F_{inf} of reactive gases. Households with smokers were excluded from this portion of the study because previous studies have found elevated indoor sulfur in homes of smokers [28].

At all homes with indoor measurements, technicians administered an *Infiltration Questionnaire* to the participants. This questionnaire characterized the predictors of F_{inf} during the nominal two-week period when paired indoor-outdoor monitoring occurred. These data inform models of F_{inf} that will be used to predict F_{inf} for all MESA Air homes. Questions were also asked about indoor sources of sulfur.

A subset of indoor-outdoor monitoring participants (4 to 16 in each area) was also selected for personal monitoring. Personal monitoring was conducted concurrent with home sampling to better understand potential sources of measurement error in our study, and to assess modeled estimates of ambient-generated $PM_{2.5}$ and traffic-related gases. Only participants living in non-smoking households participated in personal monitoring. Participants carried active samplers to collect $PM_{2.5}$ mass and elements, and Ogawa samplers to measure NO_2, NOx, and SO_2. By including sulfur measurements, the ratio of personal sulfur exposure to ambient sulfur concentration can be used as an estimate of the ratio of ambient component of personal $PM_{2.5}$ to the ambient $PM_{2.5}$ concentration. This latter ratio is the “attenuation factor” [29], or the “ambient exposure factor”, α [30], and is equal to $f^o+(1-f^o)F_{inf}$, described previously.

Due to the US Department of Homeland Security's higher level of alert, personal sampling among New York City participants who used public transportation was limited to passive measurements.

In addition to the home-based questionnaires, personal monitoring participants completed a *Time-Location Diary* (TLD) to collect information on the impact of activities and microenvironments on personal exposure and to provide additional comparative data. On the TLD, participants recorded their hourly presence in seven microenvironments: home indoor or outdoor, work indoor or outdoor, motor vehicle, or other indoor or outdoor. In addition, participants indicated if they conducted or experienced any of the following: exposure to environmental tobacco smoke (active or passive), cooking, dusting or vacuuming, close

proximity to a fire, proximity to a major road while not in a vehicle or building, heavy traffic while driving, or other sources of smoke.

All home and participant-based sampling was designed to be conducted twice per location/person with repeat samples targeted to capture two of three distinct seasons: summer, winter, or a transitional season (spring or fall).

Measurement Methods

$PM_{2.5}$ mass concentrations were gravimetrically determined from Teflon filters at the UW in a temperature and humidity controlled environment [31] using standard filter weighing procedures [32]. The Teflon filters were also used to determine LAC, a surrogate for EC, via reflectance. The relationship between LAC and EC is developed empirically in each area. Following post-sample gravimetric analysis and reflectometry, the filters from homes selected for indoor-outdoor or personal monitoring were analyzed for 48 elements by X-Ray Fluorescence (XRF). EC and OC were also determined using pre-fired quartz fiber filters.

Ogawa passive samplers were used to measure NO_2, NO_x, SO_2, and O_3 using ion chromatography and ultraviolet spectroscopy. Ambient concentrations of each pollutant were calculated using the equations provided by Ogawa & Co.[33].

A more in-depth description of the measurement methods can be found in the on-line supporting information.

Geographic Data

All participant home locations were geocoded using ArcGIS 9.2 (ESRI Corporation, Redlands, CA) and Dynamap 2000 TeleAtlas (Menlo Park, CA). Only those homes with a minimum match score of 80% were geocoded in an automated fashion. All others were geocoded interactively with a minimum match score of 90 to ensure high accuracy. In addition, at all monitored homes our technicians collected curb-side GPS measurements at the centerline of the property and at selected sampling locations to evaluate accuracy and reproducibility.

Geographic data to be used in our spatio-temporal concentration prediction models originated from a wide variety of sources. For example, block group information and population density data were obtained from the US Bureau of the Census (http://www.census.gov/) while land use was obtained from the United States Geological Survey (http://edc.usgs.gov/geodata/). Pollution emission data were characterized using the Toxic Release Inventory (http://www.epa.gov/tri/) and traffic volumes were characterized by overlaying traffic demand models developed between 2000 and 2006 by regional traffic authorities on the Dynamap 2000 TeleAtlas road network.

Quality Control/Quality Assurance

Both field blanks and co-located duplicate samples were deployed at a rate of 10% at the fixed and home sites for all sampling media. Blanks and duplicates were deployed during community saturation sampling at rates of 10% and 15%, respectively. To reduce participant burden, no duplicate personal $PM_{2.5}$ samples were collected. Duplicate Ogawa samples were collected during personal sampling at a rate of 15%. As a result of artifact issues associated with quartz filter sampling [34], we used both standard blanks (10% of samples) and dynamic blanks (20% of samples); the latter are back up filters placed downstream of the sample filter to collect any off-gassed organic compounds. More details on the program can be found in the on-line supplement.

Preliminary Results

Data Summary and Design Goals

Air pollution monitoring began in July, 2005 and is planned to continue through August, 2009. Sampling goals for the home, personal, and community saturation sampling were met by August, 2008, with 620 unique homes and 793 unique community locations monitored. Of the 620 homes with outdoor air samples, 443 were also sampled for indoor air, and 88 of those homes with paired indoor-outdoor samplers had additional personal monitoring. Fixed sites totaled 27 unique locations. Counts of the sampling locations by area are presented in the on-line supporting information. Overall, we were generally successful in meeting our design goals for siting of our samples with good variation in proximity to roadways, population density, and land use. Details are presented in the on-line supporting information.

Quality assurance demonstrated high data quality with all pre-defined data quality objectives (DQOs) met. Precision, as assessed by the relative percent difference of duplicate samples divided by the square-root of 2, was less than 10% for all pollutants. Comparisons of co-located MESA Air and EPA AQS stations also showed good overall correlation between methods, with R^2 ranging between 0.56 and 0.93, with some scatter explainable by the small number of 24-hr AQS samples included in the 2-week averages. Further detail is presented in the on-line supporting information.

Preliminary Findings

Figure 2 presents preliminary monitoring results for $PM_{2.5}$ from outdoor home samples collected in each of the MESA Air areas. In order to reduce the impact of temporal variations, we have normalized these 2-week concentrations by dividing by the 2-week area-average concentration and multiplying by the long-term average (2005-2008) concentration for that area. Area-wide short- and long-term averages were calculated using AQS data.

These data demonstrate that there is intra- and inter-urban spatial variation in concentrations. Riverside and Los Angeles communities consistently have the highest $PM_{2.5}$ concentrations while concentrations were consistently lowest in Rockland and St-Paul; the range in normalized median concentrations across these communities was approximately 15 $\mu g/m^3$. Within-area variability of $PM_{2.5}$ was generally on the order of 5 and 10 $\mu g/m^3$ ($10\text{-}90^{th}$ percentile differences) with smaller variation documented in Baltimore and Winston-Salem and larger variation found in Riverside and Los Angeles. Szpiro et al. [20] provide more details on the structure of the spatio-temporal variability of the data.

Substantial variation in F_{inf} was also observed. Figure 3 presents preliminary indoor-outdoor particulate sulfur ratios from a subset of homes. These data are presented independent of season due to the limited homes with analyzed speciation data at the time of publication. These ratios range on average from 55% in St Paul, MN to approximately 85% in New York and Los Angeles.

Limitations

Despite its considerable strengths, some limitations of this exposure assessment approach should be noted. First, one emphasis of this project was to characterize residential exposures to ambient-origin pollution. Although information was collected on commuting patterns and work exposures, we do not have information to accurately quantify concentrations in non-residential scenarios. Additionally, MESA Air was not intended to fully characterize indoor sources of exposure. The exposure assessment methodology employed assumes that average non-ambient personal exposure neither varies across communities nor covaries with ambient exposure. However, this assumption is consistent with previous research [29] [35], and we will

be able to explore its validity by comparing questionnaire-derived data on non-ambient pollutant sources across communities.

An additional limitation of this project is that our $PM_{2.5}$ samples may not capture volatile or semi-volatile components; therefore our measured concentrations may in some cases be underestimates [36,37]. This may be especially problematic in and around Los Angeles due to the high concentrations of particulate nitrate [37]. Nevertheless, the FRM also underestimates the concentration of nitrate and other semi-volatile species, so our $PM_{2.5}$ measurements are expected to be comparable to the measured using the FRM [37]. This issue also has implications for our estimation of F_{inf} since the F_{inf} of sulfur accurately represents F_{inf} of non-volatile $PM_{2.5}$ but may overestimate the F_{inf} of total $PM_{2.5}$ in regions with relatively high nitrate concentrations [38].

Discussion

Links between ambient $PM_{2.5}$ and adverse cardiovascular health effects are increasingly well established [1], though epidemiological studies to date have used relatively simple exposure estimation methods. MESA Air was funded by EPA to reduce uncertainty in the relationship between $PM_{2.5}$ and cardiovascular disease in part through improved exposure assessment. Unlike many past chronic epidemiology studies that have assigned one exposure estimate to large groups of participants, MESA Air aims to predict exposure for every study participant using a statistical modeling-based approach. This approach characterizes and incorporates spatial and temporal variations in ambient concentrations, differences in residential F_{inf}, and the general movement of study participants between indoor and outdoor microenvironments. To our knowledge, this is the first epidemiological study of long-term air pollution effects to directly incorporate many of these potentially important sources of exposure heterogeneity into an exposure assessment. Based on past research by Ebelt and colleagues [12], we anticipate that these improvements in our exposure assessment will result in less biased and more precise effect estimates.

In most urban areas, traffic is a major source of within-city variability in air pollution concentrations, and evidence is accumulating that these within-city contrasts may play an important role on cardiovascular mortality and morbidity [13,14,24,39]. Due to a lack of routine pollution monitoring near roads it has become common for chronic health studies to use residential proximity to major roadways as an exposure surrogate. Although this approach is supported by data showing elevated concentrations within approximately 100-300 meters of the roadway's edge [40], this approach is limited by uncertainties in the proximity-exposure relationship (due to topography, wind direction, or other factors) [41]. The extensive data collected in MESA Air should allow us to better characterize small-scale spatial gradients and empirically determine the relationships between traffic-generated air pollutants and geographic predictors in each study area.

Another limitation of previous air pollution epidemiology studies is that they have relied on outdoor monitoring data as a surrogate for personal exposure to ambient pollution. This approach implicitly assumes that the attenuation of ambient concentrations by buildings is the same for all participants. However, previous studies have demonstrated differences in residential F_{inf} between homes (both between and within cities) and over time within homes [18,19,42]. Failure to account for this exposure heterogeneity may lead to uncertainty and/or bias in health effect estimates [42]. The ability of MESA Air to account for these differences in such a large cohort of individuals in multiple locations is another unique feature of this investigation.

In summary, MESA Air aims to characterize important sources of between and within-city heterogeneity in exposure to ambient-generated $PM_{2.5}$ and co-pollutants. MESA Air will calculate for each study participant exposure estimates that will incorporate personalized estimates of ambient concentrations outside their home, individual-level F_{inf} estimates for their homes, and weights for the duration of time spent inside their homes. Together, these efforts should provide more accurate estimates of ambient-source exposure than have previously been available on cohorts of this size, which we expect will improve our ability to assess relationships between chronic air pollution exposure and cardiovascular disease.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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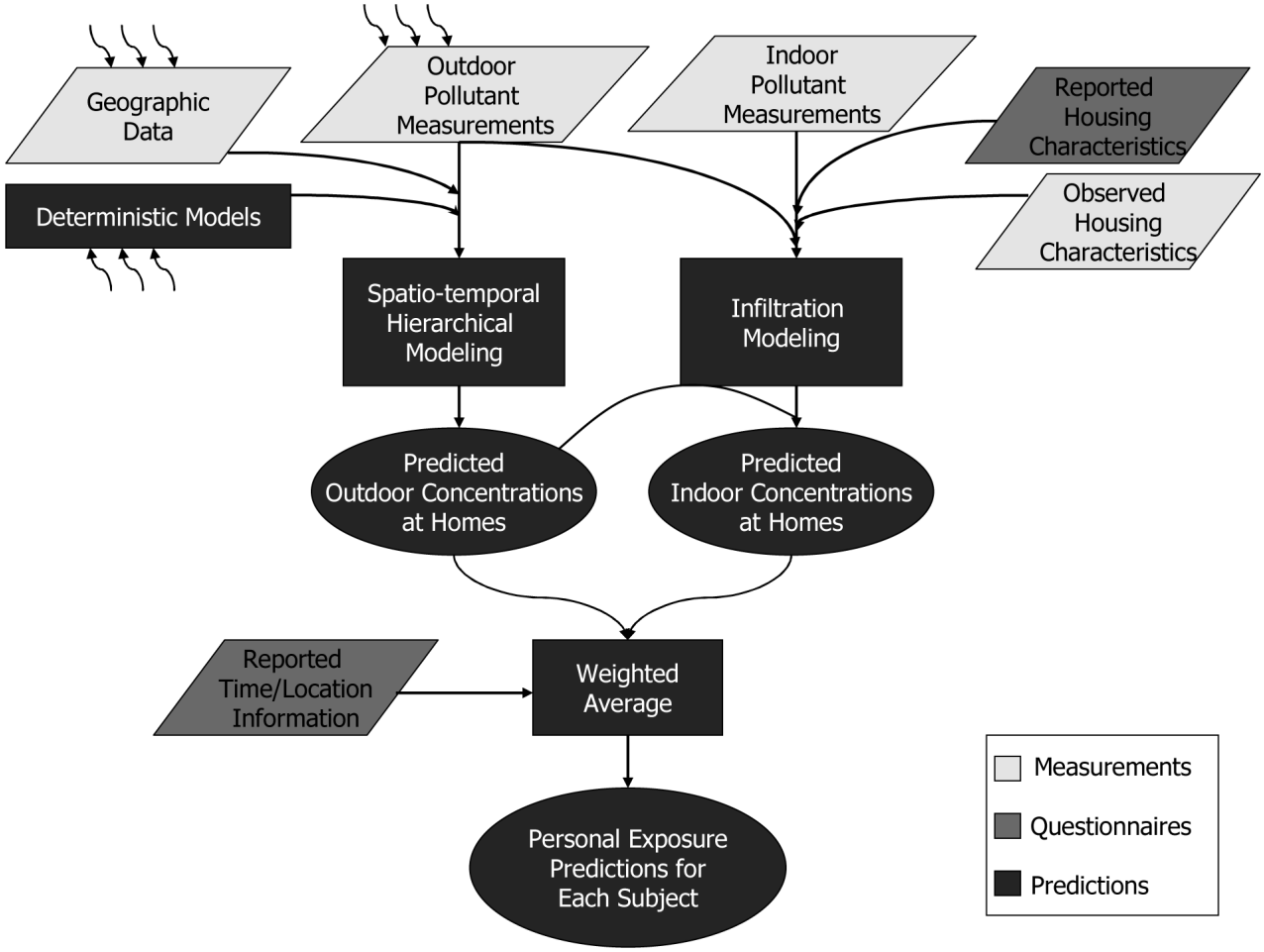

Figure 1.
Conceptual diagram of MESA Air exposure assignment methodology. The wiggly arrows indicate multiple sources of input.

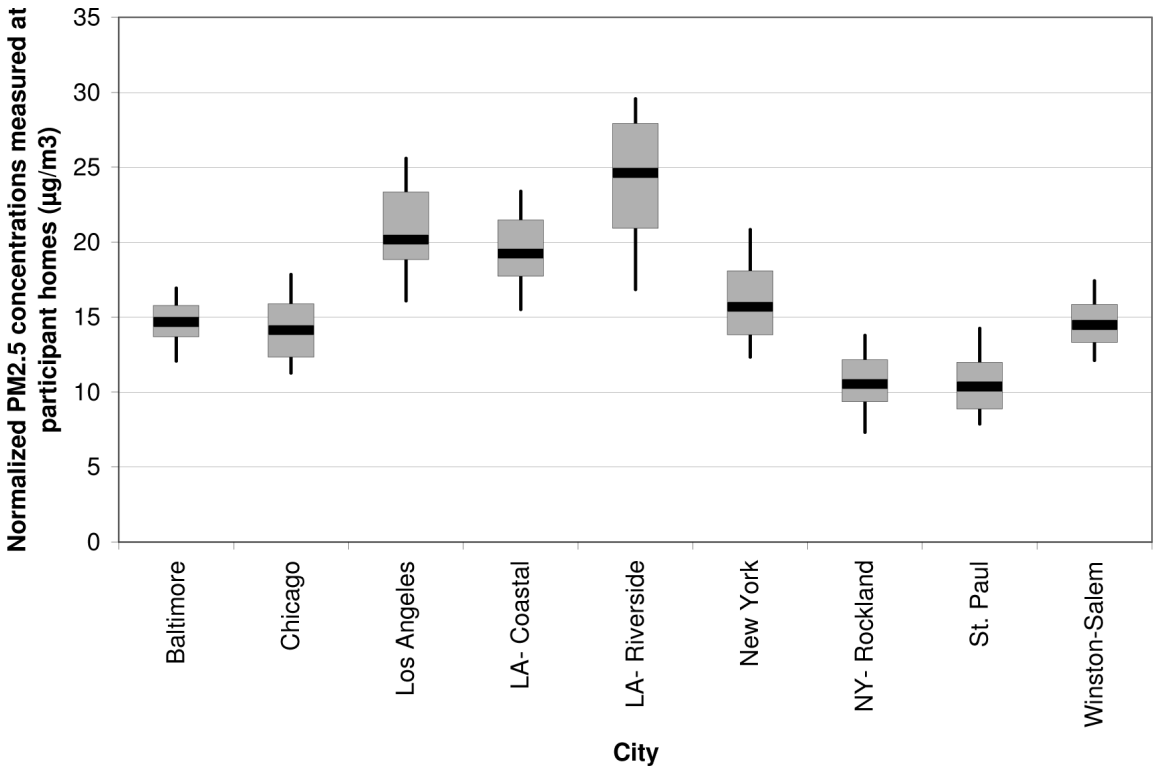

Figure 2.
Normalized outdoor $PM_{2.5}$ ($\mu g/m^3$) concentrations at participants' homes.

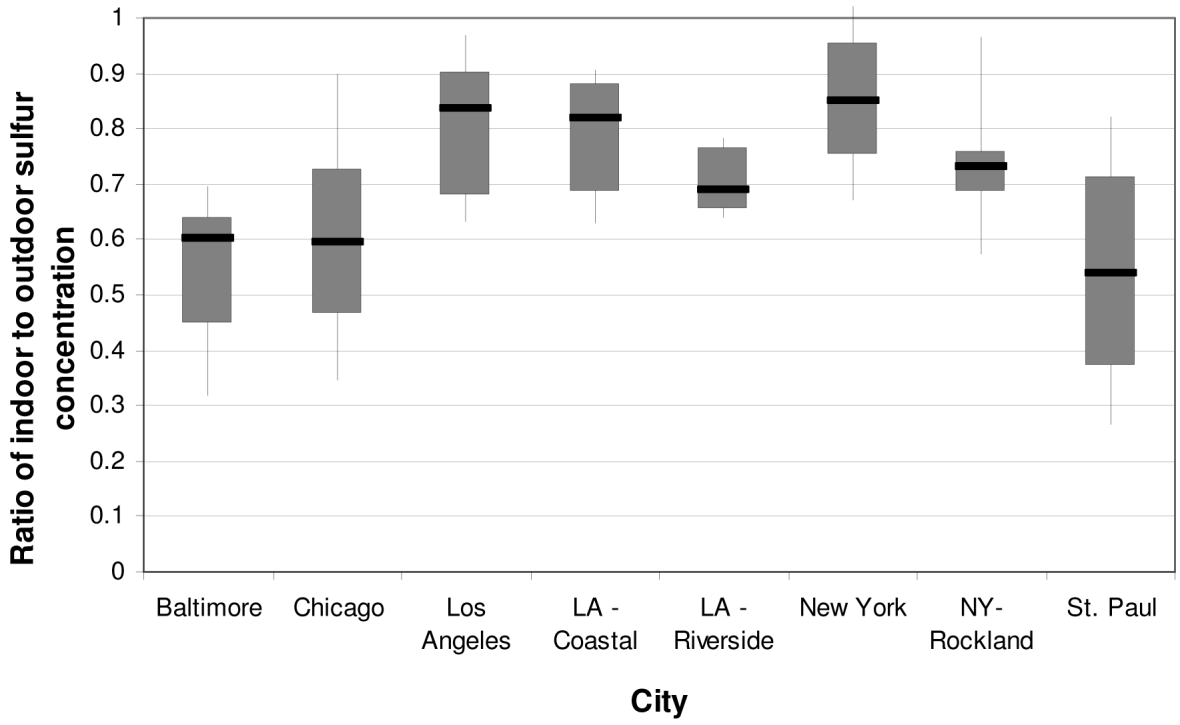

Figure 3.
Indoor to outdoor particulate sulfur concentration ratios by area. Winston-Salem data not presented because samples had yet to be analyzed.

Table 1

Sampling sites and parameters measured

	Fixed	Community Saturation	Home Outdoor	Home Indoor[a]	Personal[b]
Nominal Sample Duration	2 weeks	2 weeks	2 weeks	2 weeks	2-3 days/2 weeks[c]
Number of Sites Per Area	1-5	44-152	18-102	18-66	4-16
Number of Sites Per Area Per 2 Week Session	1-5	0 or 100	3-5	2-3	1-2
Number of Repeat 2 Week Sampling Sessions at Each Sampling Site	Sequential, ~26/yr	3	2	2	2
Questionnaire[d]				Infiltration Questionnaire	Time Location Diary
Pollutant Measurements (Method)					
$PM_{2.5}$[e] (Harvard PEM - Gravimetric)	✓		✓	✓	✓
Light-Absorbing Carbone[e] (Harvard PEM - Reflectometry)	✓		✓	✓	✓
Elementse[e] (X-ray fluorescence)	✓		✓	✓	✓
EC/OC[f] (IMPROVE, Thermal Optical Reflectance)	✓		✓		
Specific Organic Compounds[f] (Gas chromatography mass spectroscopy)	✓		✓		
NO_x (Ogawa - UV Spectrometry)	✓	✓	✓	✓	✓
NO_2 (Ogawa - Ion Chromatography)	✓	✓	✓	✓	✓
SO_2 (Ogawa - Ion Chromatography)	✓	✓	✓	✓	✓
O_3 (Ogawa - Ion Chromatography)			✓	✓	

[a] All home indoor measurements are concurrent with home outdoor measurements.

[b] All personal measurements are concurrent with home outdoor and indoor measurements.

[c] $PM_{2.5}$ is collected with 2 or 3 day consecutive samples which are then composited over the ~2 week period, NO_X/NO_2 samples are nominally 2 weeks.

[d] All participants, including those not selected for home monitoring, complete the full MESA Air questionnaire and the follow-up questionnaire.

[e] Measured on $PM_{2.5}$ Teflon filters.

[f] Measured on $PM_{2.5}$ Quartz fiber filters.