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Estimation of ultrafine particle concentrations at near-highway residences using data from local and central monitors

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Abstract

Ultrafine particles (UFP; aerodynamic diameter < 0.1 micrometers) are a ubiquitous exposure in the urban environment and are elevated near highways. Most epidemiological studies of UFP health effects use central site monitoring data, which may misclassify exposure. Our aims were to: (1) examine the relationship between distant and proximate monitoring sites and their ability to predict hourly UFP concentration measured at residences in an urban community with a major interstate highway and; (2) determine if meteorology and proximity to traffic improve explanatory power. Short-term (1 – 3 weeks) residential monitoring of UFP concentration was conducted at 18 homes. Long-term monitoring was conducted at two near-highway monitoring sites and a central site. We created models of outdoor residential UFP concentration based on concentrations at the near-highway site, at the central site, at both sites together and without fixed sites. UFP concentration at residential sites was more highly correlated with those at a near-highway site than a central site. In regression models of each site alone, a 10% increase in UFP concentration at a near-highway site was associated with a 6% (95% CI: 6%, 7%) increase at residences while a 10% increase in UFP concentration at the central site was associated with a 3% (95% CI: 2%, 3%) increase at residences. A model including both sites showed minimal change in the magnitude of

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the association between the near-highway site and the residences, but the estimated association with UFP concentration at the central site was substantially attenuated. These associations remained after adjustment for other significant predictors of residential UFP concentration, including distance from highway, wind speed, wind direction, highway traffic volume and precipitation. The use of a central site as an estimate of personal exposure for populations near local emissions of traffic-related air pollutants may result in exposure misclassification.

Keywords

Ultrafine particles; highway; community-based participatory research; CBPR; temporal variation; residential exposure

1. INTRODUCTION

Air pollution exposure has been associated with mortality (Dockery et al., 1993; Laden et al., 2000; Pope et al., 2002) and morbidity including lung cancer (Nyberg et al., 2000; Pope et al., 2002), deep vein thrombosis (Baccarelli et al., 2008), atherosclerosis (Kunzli et al., 2005) and childhood asthma symptoms (Delfino et al., 2008; McConnell et al., 2010). Important components of urban air pollution are combustion emissions from motor vehicle exhaust, a complex mixture of particulate matter, carbon monoxide, nitrogen and sulfur oxides, and hydrocarbons (Brugge et al., 2007; Kittelson, 1998; Westerdahl et al., 2005).

In many epidemiological studies a single monitoring site has been used to characterize air pollution exposures for relatively large urban populations (Laden et al., 2006; Pope et al., 2002). A single site may not capture the elevated concentrations of ultrafine particles (UFP; aerodynamic diameter <0.1 micrometer), nitric oxide, nitrogen dioxide (NO_2) and carbon monoxide near highways and busy roadways (Durant et al., 2010; Karner et al., 2010; Zhu et al., 2002a; Zhu et al., 2002b). Other studies have attempted to account for spatial variability in air pollution by including proxy measures such as traffic density and distances to roadways (Baccarelli et al., 2009; Hoffmann et al., 2009; Kunzli et al., 2010; Rioux et al., 2010). Some health studies, in attempts to resolve near-roadway exposure differences, have focused on NO_2 , which has been associated with overall mortality and cardiovascular death (Jerrett et al., 2009; Rosenlund et al., 2009). However, based on toxicological evidence NO_2 may be a surrogate for the causal components of near-roadway air pollution (Araujo et al., 2008; Beckerman et al., 2008; Seaton and Dennekamp, 2003; Tong et al., 2010). UFP are a good candidate for a causal agent for near-highway health effects, because UFP have the ability to travel deep into the lungs and their large surface areas are available for the adsorption of harmful chemicals (Delfino et al., 2005; Knol et al., 2009; Sioutas et al., 2005). In addition to combustion, UFP also result from photochemistry, which has varying potential throughout the year based on atmospheric conditions (Shi et al., 2001).

We are interested in gaining a better understanding of neighborhood levels of UFP near a major highway. The specific goals of this paper are to: (1) examine the relationship between distant and proximate monitoring sites and their ability to predict hourly UFP concentration measured at residences in an urban community with a major interstate highway and local traffic and; (2) determine if proximity to traffic and meteorology improve explanatory power.

This work is part of the Community Assessment of Freeway Exposure and Health (CAFEH) study, a 5-year, cross-sectional, community-based participatory research study of near-highway air pollution and cardiovascular health in the Boston area. The central hypothesis of the CAFEH study is that chronic exposure to UFP is associated with increases in blood

markers of inflammation. The study has enrolled residents from three near-highway neighborhoods in the Boston, Massachusetts (USA), metropolitan area. The highway of interest is Interstate-93 (I-93) an 8-lane highway that carries approximately 150,000 vehicles per day on an elevated roadway through the study area (MPO). All participants completed an in-home questionnaire and a subset completed additional supplemental questionnaires and provided blood markers. The project will develop improved estimates of UFP exposure by combining spatiotemporal models of ambient UFP with data on participant time-activity and housing characteristics. The results of the analysis presented here will be used in future analyses for the CAFEH project to test associations with health measures.

2. METHODS

2.1. Study Area

The monitoring effort described here pertains to the eastern part of Somerville, through which I-93 runs (Figure 1). I-93 is elevated above grade for much of its 4400-m length through Somerville. The residential area east of the highway is characterized by an 18-m high hill. A 3-m noise barrier is located on the east side of the highway for a portion of its length. Although I-93 has the highest traffic volume within the study area there are also contributions from local arterial highways; Massachusetts-28 (MA-28), carrying 50,000 vehicles per day and MA-38 carrying 20,000 vehicles per day; as well as busy roadways such as Broadway, which carries 20,000 vehicles/day (Figure 1). Participants were selected from three recruitment areas based on residential distance to I-93: less than 100 m, 100 – 400 m and greater than 1000 m (urban background).

Monitoring was conducted at three types of monitoring sites: near-highway sites, residential sites and a distant site central to the greater Boston area. Distance from highway was measured from the edge of the nearest lane of travel of I-93, excluding ramps. Distance from other roadways was measured using the same method. Two near-highway sites were established. The first was at the Mystic Activity Center (MAC), a local community center in the Mystic View Housing Development. The MAC site was approximately 43 m west of the I-93 and 18 m west of Mystic Avenue. The monitor was placed on the roof of the MAC, ~9 m above the ground, approximately level with the highway. The second site was at the Blessing of the Bay Boathouse (BBB) located on the Mystic River 75 m east of the highway. The BBB site was located at ground level below the elevated highway. The central site was located at the Harvard School of Public Health (SPH) in Boston, MA on the roof of the Countway Library of Medicine (~20 m). It was 51 m away from Huntington Avenue, the nearest major roadway (approximately 20,000 vehicles/day), ~3 km from the closest portion of I-93 and ~7 km from the near-highway sites and the Somerville study area. Monitoring took place between November 6, 2009 and December 2, 2010 at SPH and MAC; and from December 7, 2009 to April 10, 2010 and August 6, 2010 to December 2, 2010 at BBB. Monitoring at residential sites was prioritized over the BBB site when instruments were limited.

Short-term (1 – 3 weeks) residential monitoring was conducted at the homes of 18 participants recruited from the larger CAFEH study. The time period covered was April 26, 2010 through October 15, 2010, which encompassed spring, summer and fall seasons. The homes represented a convenience sample; however, we made efforts to include a diversity of homes with regard to distance from highway, type (eg. single-family) and monitoring floor. Three homes were located in the urban background west of I-93 within a residential neighborhood of Somerville. The other homes were within the study boundary of 400 m of I-93 with four homes east of I-93. Homes were geocoded to parcel centroids and corrected visually using OrthoPhotos to assign the location to the center of the living space. Two homes were monitored simultaneously when possible. Monitors were placed in the living

room or bedroom of the residence. All participants provided informed consent; the study was approved by the IRB at the Tufts University School of Medicine.

2.2. Monitoring strategy and instrumentation

The near-highway monitors in Somerville were protected from weather in a heated (winter) and ventilated (summer) enclosure. UFP was measured using water-based condensation particle counters (WCPC) (Model 3781, TSI Inc., Shoreview, MN), which measure particles in the 6 to > 3,000 nm size range. UFP comprise approximately 80-90 percent of particle number concentration (PNC) in urban areas and therefore many studies, including this one, use PNC as a surrogate for UFP (Morawska et al., 1998; Zhu et al., 2002a). The MAC site recorded meteorological variables including wind speed, wind direction, temperature and relative humidity using a Vantage Pro2 instrument (Davis Instrument Corp, Hayward, CA). Wind direction data was collected according to 16 cardinal wind directions (N, NNE, NE, etc.). UFP concentrations at the near-highway sites were recorded as one-minute averages and meteorology at the MAC as five-minute averages according to the data-storage capacity of each instrument. At the central site (SPH) continuous hourly measurements of UFP were made using a butanol-based CPC (BCPC) (Model 3022A, TSI Inc., Shoreview, MN), which counts particles in the 7 to > 3,000 nm size range. Residential monitors consisted of a WCPC (Model 3781, TSI Inc., Shoreview, MN), for the measurement of UFP and a HOBO (Onset Computer Corp, Pocasset, MA) for measurement of temperature and humidity. Each residential monitor contained indoor and outdoor sampling lines of similar length (~2 m) made of stainless steel and flexible conductive Tygon® tubing ($\frac{3}{8}$ -inch diameter). The indoor line was located on the top of the box and the outdoor line ran through a specially designed window guard that extended ~0.5 m from the side of the house. A solenoid valve switched the flow of air between the two lines at approximately 15-minute intervals. Only outdoor measurements, approximately 30 minutes of each hour for the residential monitors, are analyzed here. The flow rate was held constant at 0.12 L/min and monitoring instruments were checked for adequate flows and functioning before and after each monitoring session. Instruments were rotated between near-highway and residential sites to avoid any systematic bias between locations. Traffic count data was collected from a MassHighway monitoring station (MA093340) located on I-93 at the southern end of the study area. The station monitored both northbound and southbound lanes and vehicle counts for both directions were combined to obtain a total vehicle count per hour. The data was downloaded from MassHighway using the Traffic.com website (MassHighway, 2010).

Data for the MAC, BBB and residential sites were collected as 1-minute averages, which were checked for errors; data with error flags were removed from the dataset. A small number of readings <500 particles/cm³, a result of malfunctions of the instruments due to low temperatures or high humidity, were also removed from the dataset. Valid data was then aggregated to 1-hour geometric means. Although the WCPCs used in the field and the BCPC used at the SPH have similar lower cut points they use different mediums in order to identify and count particles. Co-location monitoring with both types of instruments was conducted for 10 days at the SPH site. UFP readings for a single WCPC were, on average, 20% lower than the BCPC. However, the Spearman's rank correlation coefficient of hour-averaged UFP concentration between instruments was high ($r \sim 0.95$).

2.3. Analysis

Summary statistics were calculated and Wilcoxon rank-sum tests conducted to compare UFP levels between near-highway (MAC and BBB) and central monitoring sites (SPH). To evaluate the association between monitors and the contribution of other covariates, we fit a mixed effects linear regression model with hourly UFP concentration at residences as the dependent variable, a random intercept for residence, and significant predictors (listed

below) as independent variables. Due to the skewed distribution of UFP, measurements were log-transformed for all models. Autocorrelation between hourly averages was adjusted using an AR(1) correlation structure, which has been used in past studies of particle counts (Houseman et al., 2002; Zwack et al., 2011). Potential predictors of UFP were first evaluated individually and those predictors with p-values < 0.15 were included in the initial multivariate model. The multivariate model was then reduced to only those predictors with p<0.05. The goodness of fit of the model was evaluated using Akaike's Information Criterion (AIC). The form of the model is given below:

$$\log(\text{UFP}_{ij}) = b_i + \beta_0 + \beta_1 \log(\text{UFP}_{\text{fixj}}) + \beta_2 \mathbf{X}_j + \beta_3 \mathbf{Z}_i + \beta_4 \sin_ \text{hour} + \beta_5 \cos_ \text{hour} + \varepsilon_{ij}$$

where $\log(\text{UFP}_{ij})$ is the log-transformed UFP concentration at home i and time j ; b_i is the random intercept for home; β_0 is the overall intercept; $\log(\text{UFP}_{\text{fixj}})$ is the concentration at either near-highway site, central site or combination of sites at time j ; $\mathbf{X}_j$ is a matrix of covariates that vary over time (including wind speed, wind direction, traffic volume, traffic speed, temperature and precipitation); $\mathbf{Z}_i$ is a matrix of covariates that vary by home (including distance to I-93 [<100 m, 100 - 400 m, >1000 m], distance to other roadways, buffers of road length [50m, 100m, 150m, 200m], buffers of average daily traffic [50m, 100m, 150m, 200m], traffic analysis zone, position of monitor relative to highway and monitoring floor); sine and cosine terms of hour of day ($\sin_ \text{hour}$ and $\cos_ \text{hour}$) were used as harmonic regression coefficients to account for diurnal variations; and ε_{ij} is the error term. The harmonic regression coefficient for day of year was not significant in the models likely due to the fact that data was collected in homes only during warmer temperatures. Thus, we did not capture seasonal variation in our dataset.

3. RESULTS

3.1. UFP concentrations at fixed and residential sites

Table 1 presents summary statistics for UFP concentrations measured at the fixed and residential sites. A total of 18 residences were monitored for 7-21 days (median = 14 days [336 hours]). Three of the residences were smoking households, however, we do not believe that this impacted ambient concentrations at these residences. Figure 2 presents the distribution of UFP from fixed sites by month. A right-skewed distribution is evident due to the significant number of high concentrations. The SPH showed a strong seasonal trend with lower concentrations in the warmer months and higher concentrations in the cooler months. Distributions at the MAC and BBB sites were similar and showed little, if any, seasonal variation.

3.2. Correlations between monitoring sites

Table 2 provides Pearson correlations between log-transformed hourly UFP at near-highway, central and residential sites. The correlation between the MAC and BBB was the highest between any two fixed sites ($r = 0.50$). The correlations for hourly UFP for the two highway monitors (MAC and BBB) and the distant central site (SPH) were lower, 0.41 and 0.24, respectively. The correlations remained essentially unchanged when restricting to time periods of concurrent data for all three sites. Correlations between the near-highway sites and residences were 0.45-0.88 for the MAC (on the west side of I-93), and 0.27-0.87 for the BBB (on the east side); correlations between the SPH site and the residential sites were 0.22-0.57. We also evaluated correlations between 24-hour averaged measurements. Overall, correlations between fixed sites using 24-hour data were lower compared to hourly.

3.3. Effects of wind direction and distance

We collected measurements of wind speed and direction at the MAC from December 18, 2009 through December 2, 2010. The predominant wind direction for the whole year was from the northwest, however, the predominant wind directions for winter and summer were from the northwest and southwest, respectively. There was more variation in wind direction during the spring and fall. The percentage of time with calm winds (< 0.5 m/s) was ~11% for the whole year. In the study area, the highway is oriented northwest to southeast; therefore, we created four categories encompassing winds from the west, from the east, from the northwest parallel to the highway and from the southeast parallel to the highway. We examined the effect of wind direction using the near-highway sites grouped into these four categories of wind direction (Figure 3). In general, UFP concentrations tended to be highest with southeast parallel winds. Winds blowing from the direction of the highway (east winds for the MAC and west winds for the BBB) were associated with the next highest UFP concentrations. A similar increase in UFP concentration with southeast winds was also seen in the residential data (data not shown). Wilcoxon rank-sum tests for differences between UFP concentration and wind direction categories were significant.

Figure 4 presents the distribution of UFP at each residence categorized by and distance to highway. UFP concentrations between both <100 m category and 100 – 400 m categories and the urban background were different using Wilcoxon rank-sum tests. Of the three homes with the lowest median concentrations, two (H1, H2) were located in the urban background area at distances of 1483 m and 1424 m from I-93, respectively. The third (H11) home was located 123 m from the highway on the west side. Even considering the non-concurrent data collection there is an indication of a decreasing trend of outdoor UFP as distance from the highway increases.

3.4. Regression modeling results

Data from 16 homes were used in building models of temporal variability of outdoor residential UFP. Two residences (H7, H17) had no or limited data collected concurrently with near-highway fixed sites and were excluded from model-building. A summary of selected covariates evaluated for inclusion in the model is presented in Table 3. Regression model results including concentrations at the MAC, at the SPH, at both sites together and without fixed sites are presented in Table 4. In Model 1 UFP concentrations were 32% (95% CI: -9%, 83%) and 73% (95% CI: 19%, 153%) higher, for residences 100-400 m and <100 m from the highway, respectively, when compared to residences in the urban background. Other significant predictors included wind speed, wind direction, traffic volume, precipitation and hour of the day. While the UFP concentration measured at both the MAC site and SPH site were significantly associated with UFP at residential monitors, the magnitude of the association was higher for the MAC site. In Model 2, a 10% increase in UFP at the SPH site was associated with a 3% (95% CI: 2%, 3%) increase in UFP at residences. Model 3 calculates that a 10% increase at the MAC site was associated with a 6% (95% CI: 6%, 7%) increase in UFP at residences. When both fixed sites were included together in Model 4, the estimate for the association between UFP measured at the MAC site and at residences remained essentially unchanged, while the estimate of the association between the SPH and residences was reduced to 0.4% (95% CI: 0.1%, 0.8%).

We built models incorporating data restricted to times when both near-highway and central sites were running. In these models the two near-highway sites performed equally well and better than the SPH site (data not shown). We also evaluated the effect of wind direction by side of highway using interaction terms. When compared to the southeast direction, northwest winds were associated with a 13% decrease in UFP concentrations and east winds by a 27% decrease for west side homes. For east side homes, west winds were associated

with 84% higher UFP concentrations and northwest winds a 16% increase when compared to southeast winds.

4. DISCUSSION

Significant predictors of outdoor residential UFP in models included UFP at the near-highway and central site, categorical distance to highway, wind speed and direction, highway traffic volume, hourly precipitation and hour of day. Residential UFP concentration was more strongly associated with UFP concentrations measured at a near-highway site than a central site. These results held whether we considered either of the near-highway sites (MAC or BBB), despite the limited concurrent data between the homes and the BBB site. In a model with a near-highway site (MAC) and central site (SPH) most of the variation was explained by the MAC site and only an incremental amount from the SPH. However, any fixed site improved model fit when compared to a model without data from a fixed site. Other local roadways were not significant in multivariate models. Our results suggest that central monitors may not adequately capture the exposures present in communities with significant local emissions of UFP, a finding that is supported by other studies (Krudysz et al., 2009; Moore et al., 2009).

Development of models for describing near-highway residential concentrations is important because there is substantial variation of UFP concentrations within neighborhoods next to highways with the highest concentrations measured near the roadside (Durant et al., 2010; Kittelson et al., 2004; McAuley et al., 2010; Westerdahl et al., 2005). A few studies have used regression models to identify predictors of UFP on the intra-urban scale (Buonocore et al., 2008; Levy et al., 2003; Zwack et al., 2011), and one recent study created a predictive model (Hoek et al., 2011). Of these only one focused on the near-highway (or near-roadway) environment; identifying distance, traffic volume and wind speed as significant predictors (Zwack et al., 2011).

Our observations for the two near-highway sites (MAC and BBB) are consistent with near-highway PNC measurements in previous studies of long-term trends in UFP concentrations (Birmili et al., 2009; Mejia et al., 2007); however, our measurements were on average lower than other near-highway studies that sought to understand UFP gradients during peak exposure periods (Cyrys et al., 2003; Zhu et al., 2002a). Other differences between studies include differences in traffic flow, vehicle-fleet composition (and therefore local emissions), wind conditions and the presence or absence of monitoring during photochemically-active periods.

The SPH site showed a clear annual pattern of higher UFP in the winter and lower UFP in the summer. Hussein (2004) documented a similar trend in annual variation of UFP at monitoring sites in Helsinki as well as close correlations between UFP concentrations and traffic volume. Monthly variations were not as evident at the MAC (nor the BBB site; however, the BBB site did not have a complete annual record). The annual variations in mixing conditions and predominant wind directions (winter NW, summer SW and spring sea breezes), likely have a differential effect on UFP counts between the SPH and MAC sites. Also, the MAC, being close to I-93, is likely more strongly influenced by local wind conditions and less affected by variations in mixing heights compared to SPH.

The highest median UFP concentrations at the MAC and BBB occurred when the wind was from the southeast, suggesting pollutant channeling by the highway. In addition, there may have been contributions from a local highway (MA-28) within the study area and the central business district in the city of Boston, which is ~4 km southeast of the study area. High UFP concentrations at the MAC and BBB sites were also observed when winds were

perpendicular to I-93 – i.e. east and west. This is consistent with other studies that have noted changes in spatial gradients near highways due to wind direction (Hagler et al., 2009; Hitchins et al., 2000; Mejia et al., 2007; Noble et al., 2003; Reponen et al., 2003; Zhu et al., 2006). UFP variation by wind direction category persisted when evaluating data by month for the MAC, but was more variable at the BBB. In the regression models wind direction was a significant predictor of UFP concentration. The significance of interaction terms with an indicator for side of highway revealed that the effect of wind direction differed between east-side and west-side homes. This is consistent with expectations that the highway is the dominant source of UFP emissions in the area. The strength of this impact is evident when considering that only three homes were located east of the highway.

Although this study was not designed to thoroughly investigate the effect of distance on UFP, decreasing UFP concentration with increasing distance from the highway was evident. This trend may not be as pronounced as reported in other studies due to the presence of a complex urban road network and non-concurrent data collection at the residences in our study. Mixing with cleaner air, particle evaporation and particle agglomeration are responsible for the rapid decrease in UFP with distance from roadways (Durant et al., 2010; Hagler et al., 2009; Kittelson, 1998; Zhu et al., 2002a). A meta-analysis characterized a spatial gradient for UFP that extended to 100-300 m (Zhou and Levy, 2007) while a recent review identified the dependency of gradients upon the particular normalization method used and UFP size definition (Karner et al., 2010). Differences in the spatial extent of UFP between studies are due in part to diurnal variation. The impact of UFP emissions extending out to 2000 m from a highway has been documented during pre-sunrise hours (Hu et al., 2009). In addition, given that this is an urban setting, there are physical constraints (including noise barriers and trees) as well as differences in elevation that impact UFP distribution in the study area. The sound barrier, located on the east side of I-93, likely decreased UFP concentrations at homes immediately adjacent to the highway (Baldauf et al., 2008). The homes next to the highway were at ground level, 8-m below the elevation of the highway and noise barrier. Therefore, monitoring on the first floor of these homes may have resulted in lower concentrations than monitoring on upper floors. The presence of trees has also been shown to reduce particle number (Baldauf et al., 2008) and this may have also affected our UFP measurements, especially between April and October when the trees have foliage. Lastly, the placement of the monitor on the side of the home away from the highway may have resulted in reduced particle numbers; however, it was difficult to identify any differences due to monitor placement because of the relatively small number of monitored homes.

Contrary to expectations, we observed higher UFP concentrations on average at the central site when compared to the near-highway sites. The SPH site was further inland than the Somerville sites in a congested urban area alongside a major commuting road and several large medical facilities. We also observed, through side-by-side monitoring, that readings from a WCPC used in Somerville were approximately 20% lower than the BCPC. There are three possible explanations for these results. First, the counting efficiency for the WCPC drops off more rapidly for smaller sized particles than the BCPC. This may result in an undercount of smaller particles, causing the WCPC to record lower concentrations than the BCPC (Mordas et al., 2008; TSI, 1999, 2007). Second, the BCPC runs at a flow rate of ~0.3 L/min while the WCPC runs at a flow rate of ~0.12 L/min. The slower flow of the WCPC allows for more opportunity for losses by diffusion in the sampling lines (Kumar et al., 2008). Third, past tests have shown that water-based CPCs are more sensitive to hydrophilic particles and butanol-based CPCs are more sensitive to hydrophobic particles, which may account for some differences (Biswas et al., 2005; Mordas et al., 2008). These issues are of limited concern for the home-to-highway site comparisons because the monitoring configurations and instruments were similar. In the analyses comparing MAC and BBB sites

to the SPH site, we did not adjust the measurements to compensate for losses because the primary interest was in relative and not absolute levels. The high, and consistent, correlation between the WCPC and BCPC instruments suggests that the results of the mixed effects models are acceptable, despite differences in absolute concentrations.

An important limitation to our study is the lack of concurrent data collection between residential sites, which included monitoring during periods of both high and low photochemical activity as well as varying meteorology. As a result, we were unable to thoroughly examine spatial variation in the study area. A strength of the study was long-term monitoring at both central and near-highway sites. By using hourly-averaged measurements, we were able to examine the relationships between the fixed sites and 18 occupied homes for over 3,000 hours and determine the amount of temporal variation represented by fixed sites. The inclusion of additional data, allowed us to identify other important explanatory variables for this near-highway community.

5. CONCLUSION

Many epidemiological studies assess air pollution exposures using a single or relatively few centrally-located monitors to represent large urban areas. Using UFP concentrations from a site near traffic and from a more distant central site ~7 km away, we demonstrated that the near-highway site better accounted for temporal variation in ambient UFP at participant homes in the community than did the central site. Additional variables (distance to highway, wind speed, wind direction, precipitation, traffic volume and time of day) were also important in explaining variation. Given the small-scale spatial heterogeneity in traffic-related air pollution in urban settings, exposure misclassification may occur when using data from a distant monitoring site to characterize near-roadway exposures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- We evaluated UFP concentration in a near-highway community
- Models of outdoor home UFP were created including fixed sites and other predictors
- A near-highway site explained more variation in home UFP than a central site
- Other predictors: highway distance, wind speed & direction, traffic, precipitation
- Exposure estimated by central site may cause exposure misclassification for near-highway groups

Figure 1.
Somerville study area showing central, near-highway and residential sites.

Figure 2. Boxplots of ambient UFP concentrations measured at two near-highway sites (MAC and BBB) and the central site (SPH) by month (November 2009 – December 2010). The whiskers represent 1.5*IQR.

Figure 3. Boxplots of UFP concentrations measured at two near-highway sites as a function of wind direction.

Figure 4.

Boxplots of outdoor UFP concentrations measured at residential sites. Residences are arranged according to distance to highway and side of highway. The solid line represents Interstate-93 and the dashed lines delineate categories of distance from the highway. The month of monitoring is also noted for each home.

Table 1

Summary statistics of hourly-averaged UFP concentrations for near-highway, central and residential sites.

Site	N (hours)	Dates	5th percentile	25th percentile	Median	75th percentile	95th percentile	99th percentile
SPH	10,104	11/6/09 – 12/2/10	3,731	6,509	13,419	20,260	30,606	39,076
MAC	7,838	11/6/09 – 12/2/10	3,152	6,177	9,993	16,077	33,349	49,846
BBB	4,858	12/7/09 – 4/10/10, 8/6/10 – 12/2/10	2,684	5,894	9,437	14,596	26,360	36,473
Homes (N=18)	4,674	4/26/10 – 10/15/10	2,022	3,884	5,924	9,328	22,510	37,047

Abbreviations: UFP, ultrafine particles; SPH, Harvard School of Public Health; MAC, Mystic Activity Center; BBB, Blessing of the Bay Boathouse.

Table 2

Pearson correlations of log(UFP) concentrations between sites.

Monitoring site	SPH	MAC	BBB
1 -hour averaged			
SPH			
MAC	0.41		
BBB	0.24	0.50	
Residences *	0.45	0.73	0.72
Median (range)	(0.22 – 0.57)	(0.45 – 0.88)	(0.27 – 0.87)
24-hour averaged			
SPH			
MAC	0.24		
BBB	0.07	0.29	
Residences *	0.59	0.75	0.76
Median (range)	(–0.73 – 0.81)	(–0.34 – 0.98)	(–0.08 – 0.96)

* Two homes were missing concurrent data with both near highway fixed monitors and were excluded from this analysis; an additional six did not have concurrent data with the BBB site and were excluded from BBB summary statistics. Abbreviations: log(UFP), log of ultrafine particle concentration; SPH, Harvard School of Public Health; MAC, Mystic Activity Center; BBB, Blessing of the Bay Boathouse.

Table 3

Summary statistics for covariates evaluated in mixed effects regression models of outdoor residential UFP concentration.

Covariate	Mean $\pm$ SD	Median	Range
Residential covariates (N=16) [*]			
Side of highway	13 homes west of highway	3 homes east of highway	
Residential distance from highway (m)	367 $\pm$ 466	152	33 – 1,483
Hourly covariates (up to N=4,029)			
Traffic Volume (vehicles/hour)	6,428 $\pm$ 3,169	7,832	205 – 11,477
Traffic speed (mph)	56.6 $\pm$ 7.8	59.9	17.6 – 65.4
Temperature (°C)	21.4 $\pm$ 6.1	21.9	1.9 – 36.4
Wind speed (m/s)	2.2 $\pm$ 1.3	2.1	0 – 8.4
Wind direction [†]			
East	0.21 $\pm$ 0.36	-	-
West	0.36 $\pm$ 0.43	-	-
Northwest	0.30 $\pm$ 0.39	-	-
Southeast	0.12 $\pm$ 0.30	-	-
Precipitation (inches/hour)	0.01 $\pm$ 0.04	0	0 – 0.72

Abbreviations: UFP, ultrafine particles; SD, standard deviation; mph, miles per hour.

^{*} Two homes were missing concurrent data with the near highway fixed monitors and thus were excluded from this analysis.

[†] The proportion of 5-minute intervals during which the wind was from the given direction.

Table 4

Multivariate mixed effects regression models of outdoor residential UFP concentration [†]

Covariate	Model 1 No fixed sites		Model 2 SPH site		Model 3 MAC site		Model 4 SPH and MAC sites	
	% change	95% CI	% change	95% CI	% change	95% CI	% change	95% CI
log(UFP _{SPH}) [*]	-	-	3	2, 3	-	-	0.4	0.1, 0.8
log(UFP _{MAC}) [*]	-	-	-	-	6	6, 7	6	6, 7
Distance to highway								
>1000 m (ref)	-	-	-	-	-	-	-	-
100-400 m	21	5, 55	37	3, 82	32	-6, 83	34	-0.7, 81
< 100 m	56	18, 105	78	29, 147	73	19, 53	77	25, 149
Wind speed (m/s)	-18	-20, -17	-16	-18, -15	-6	-7, -4	-6	-7, -4
Wind direction								
Southeast (ref)	-	-	-	-	-	-	-	-
West	-35	-39, -31	-27	-31, -22	7	0.8, 14	8	1, 14
Northwest	-47	-50, -43	-42	-45, -38	-6	-12, -0.4	-6	-12, -0.4
East	-47	-50, -44	-45	-48, -41	-27	-31, -23	-27	-31, -23
Traffic volume (veh/hour)								
<5340 (ref)	-	-	-	-	-	-	-	-
5340-8630	43	35, 51	32	24, 39	13	8, 19	12	7, 18
> 8630	33	24, 43	23	14, 32	7	0.3, 14	6	-0.5, 13
Precipitation (yes/no)	-12	-17, -7	-8	-13, -3	-9	-13, -4	-8	-12, -4
Hour (sine)	-21	-23, -18	-19	-21, -17	-14	-16, -12	-14	-16, -12
Hour (cosine)	-19	-23, -16	-14	-18, -11	-8	-12, -5	-8	-11, -4
AIC	4912		4743		3883		3886	

Abbreviations: UFP, ultrafine particles; log(UFP_{SPH}), log(UFP) at the Harvard School of Public Health monitoring site; log(UFP_{MAC}), log(UFP) at the Mystic Activity Center monitoring site; AIC, Akaike Information Criterion; ref, reference category.

^{*} Represents the percent increase in residential outdoor UFP for a 10% increase in fixed site UFP.

[†]Includes data from 16 homes and 3,297 hour measurements.