Spatial variability of particulates in homes: Implications for infant exposure

Jane Jones a,⁎, Stephen Stick a,b, Peter Dingle c, Peter Franklin a

a School of Paediatrics and Child Health, University of Western Australia, GPO Box D184, Perth, Western Australia, 6840, Australia
b Department of Respiratory Medicine, Princess Margaret Hospital for Children, GPO Box D184, Perth, Western Australia, 6840, Australia
c School of Environmental and Biological Sciences, Murdoch University, Perth, Australia

Received 25 October 2006; received in revised form 5 January 2007; accepted 5 January 2007
Available online 20 February 2007

Abstract

Personal monitoring of particulate matter (PM) exposure in infants is difficult. Indirect, microenvironment modelling methods are more practical. Infants spend most of their time indoors at home and the aim of this study was to investigate spatial variations in PM concentrations within homes. Three size fractions of PM – particles with an aerodynamic diameter of less than 10 μm (PM10), less than 2.5 μm (PM2.5) and total suspended particulates (TSP) – were monitored in the homes of 77 infants (0–2 years) using a multi-stage virtual impactor. In all homes PM was monitored simultaneously in the main living room at heights of 1.4 m and 0.2 m from the floor. In 26 of these homes monitoring was also conducted simultaneously in the infant’s bedroom. Further, PM10 was measured simultaneously in the living room, bedroom and child’s cot in 14 homes using a real-time photometer. All homes in the study were non-smoking households. On average, there were no significant differences between concentrations of any of the different PM size fractions measured at the two heights (living room) and between living room and bedroom concentrations. However, there were only moderate correlations in concentrations between the different microenvironments and in some homes there was considerable variation between sampling sites. From the real-time measurements there seemed to be good agreement between concentrations measured in different rooms and in the cot and short-term peak concentrations at one sampling site were often mirrored at other sites. These results suggest that, although large variations in PM concentrations between rooms within homes can occur, a single monitoring station can provide a reasonable estimate of indoor concentrations.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Particulate matter; Homes; Young children; Variability

1. Introduction

Adverse health effects of particulate (PM) air pollution have been described (Pope and Dockery, 2006). Particulate pollution is most often associated with increased cardio-respiratory morbidity and mortality (Pope and Dockery, 2006) but, for infants, it has also been implicated in sudden infant death syndrome (SIDS) (Lipfert et al., 2000; Kaiser et al., 2004). Most health studies have used outdoor PM concentrations as an indicator of exposure, even for SIDS (Tong and Colditz, 2004). However, in industrialised countries, people spend the majority of their time indoors (Wiley et al., 1991) and for infants, most of the time is spent in the home (Oie et al., 1993; Farrow et al., 1997). Although indoor PM concentrations are strongly influenced by outdoor concentrations (BeruBe et al.,
2004) the outdoor contribution to indoor PM can fluctuate widely (Kopperud et al., 2004) and indoor particle concentrations are unlikely to be represented by central fixed monitoring sites (Morawska et al., 2003). Despite this there have been very few studies on the relationship between domestic indoor PM concentrations and health of residents (Koenig et al., 2005).

Direct personal exposure monitoring is the most accurate method for measuring individual pollution exposure concentrations (Leaderer et al., 1993), however, direct personal monitoring techniques can be expensive, intrusive and impractical to use (Boudet et al., 2001). For example, personal monitors for PM may be particularly impractical for infants or young children due to the requirement of attached pumps. A more practical method for estimating exposure of infants and young children to PM may be to use microenvironmental modelling methods, which requires an understanding of pollution levels in environments where young children will spend the majority of their time.

To date only a few studies have investigated room-to-room variation in PM concentrations within homes (Ju and Spengler, 1981; Clayton et al., 1991; Wigzell et al., 2000; BeruBe et al., 2004). Further, there have been no studies investigating PM concentrations in important microenvironments for young children. Very young children spend a lot their time in their bedroom and cot (Oie et al., 1993; Anders et al., 1995). Furthermore, the breathing zone of these children is closer to the floor where pollutants, such as respirable particles, may accumulate (Bearer, 1995). The aim of this study was to investigate spatial – vertical and room-to-room – variations in PM concentrations within homes with an emphasis on important microenvironments for young children. We hypothesised that PM concentrations would be increased closer to the floor compared to the adult breathing height. We also hypothesised that PM levels would be higher in the cot as it may act as a confined space with different air movement and ventilation patterns to the rest of the home (Corbyn, 1993).

2. Methods

2.1. Subjects and protocol

Particulate matter (PM) was measured in the homes of 91 young children (0–2 years) for one 24-hour period only. All were suburban homes situated within the metropolitan region of Perth, Western Australia and were typical of the housing stock for this city. All were non-smoking households. Selected house characteristics are presented in Table 1. In 77 homes, three size fractions of PM – particles with an aerodynamic diameter of less than 10 μm (PM$_{10}$), less than 2.5 μm (PM$_{2.5}$) and total suspended particulates (TSP) – were monitored simultaneously in the main living room at heights of 1.4 m and 0.2 m from the floor using a multi-stage virtual impactor (RespiCon™ Model 8522, TSI, St. Paul, MN). In 26 of these homes monitoring was also conducted simultaneously in the child’s bedroom. To investigate the relationship in real-time changes in PM$_{10}$ concentrations between microenvironments within homes 24-hour real-time approximations of PM$_{10}$ concentrations were determined in a separate group of 14 homes using a photometer (TSI Model 8520 DustTrak™ aerosol monitor, TSI incorporated, St. Paul, MN, USA). Measurements were collected simultaneously in the living room, bedroom and cot. Residents undertook normal daily activities throughout all monitoring periods.

2.2. Particulate monitoring — gravimetric technique

Three size fractions of PM – PM$_{10}$, PM$_{2.5}$ and TSP – were monitored with the RespiCon. The RespiCon was attached to a low volume air pump (Aircheck™ Model 224-PCXR8, SKC, Eighty Four, PA) and air enters the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Selected physical characteristics of homes</th>
</tr>
</thead>
<tbody>
<tr>
<td>House age (years)</td>
<td>Mean (SD) 37.5 (27.2)</td>
</tr>
<tr>
<td>Range</td>
<td>0.5–102</td>
</tr>
<tr>
<td>House type (%)</td>
<td>Separate house 90.8</td>
</tr>
<tr>
<td>Semi-detached</td>
<td>5</td>
</tr>
<tr>
<td>Flat/apartment</td>
<td>4.2</td>
</tr>
<tr>
<td>Building material (%)</td>
<td>Brick 84</td>
</tr>
<tr>
<td>Wood</td>
<td>14</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
</tr>
<tr>
<td>Storeys (%)</td>
<td>Single 93.4</td>
</tr>
<tr>
<td>Two or more</td>
<td>6.6</td>
</tr>
<tr>
<td>Attached garage (%)</td>
<td>Yes 39.5</td>
</tr>
<tr>
<td>No</td>
<td>60.5</td>
</tr>
<tr>
<td>Main heating fuel (%)</td>
<td>Electric 28.3</td>
</tr>
<tr>
<td>Gas (unflued)</td>
<td>41.7</td>
</tr>
<tr>
<td>Gas (flued)</td>
<td>16.7</td>
</tr>
<tr>
<td>Wood</td>
<td>13.3</td>
</tr>
<tr>
<td>Air conditioning (%)</td>
<td>Yes 63</td>
</tr>
<tr>
<td>No</td>
<td>37</td>
</tr>
</tbody>
</table>

All households were non-smoking.
sampler at 3.11 L/min. Pumps were calibrated before and after each monitoring period. Particles were collected on borosilicate glass fibre with Teflon backing (Pallflex Emfab™ TX40H120, Pall, Ann Arbor, MI). The filters were weighed pre and post sampling in a humidity controlled weighing room (RH 50%). The filters were weighed on a 6-point balance (4503 MICRO, Sartorius Ltd, Epsom, UK), which was calibrated weekly. This balance was enclosed in a perplex box which contained silicate gel under a wire rack. The filters were placed on the airing racks within the desiccator for a 24-h conditioning period pre weighing before and after sampling.

The particle mass concentration of each size fraction was calculated according to the following equations:

\[
C_{2.5} = \frac{m_1 \times 10^6}{Q_1 \times t}
\]

\[
C_{10} = \frac{(m_1 + m_2) \times 10^6}{(Q_1 + Q_2) \times t}
\]

\[
C_{TI} = \frac{[(m_1 + m_2) + (1.5 \times m_3)] \times 10^6}{(Q_1 + Q_2 + Q_3) \times t}
\]

Where

- \(C_{2.5}\) is the concentration of the 2.5 μm size fraction (μg/m³)
- \(m_1, m_2, m_3\) difference in mass of stage 1, 2 and 3 filters before and after sampling (mg)
- \(Q_1\) is the first stage sampling flow rate of 2.667 L/min
- \(t\) is the sample duration (min)
- \(C_{10}\) is the concentration of the 10 μm size fraction (μg/m³)
- \(Q_2\) is the second stage sampling flow rate of 0.333 L/min
- \(C_{TI}\) is the concentration of the total inhalable size fraction (μg/m³)

There were no significant differences between the two heights for the different size fractions but correlations between heights were only moderate.

The RespiCon was initially designed as a personal aerosol sampler (Koch et al., 1999) but has been validated as an area sampler (Li et al., 2000). The precision of the RespiCon used in this study was investigated by co-locating three of them in different indoor environments for 24 h on 5 separate periods. The Co-efficient of Variation (CoV) ranged from 4.5 to 43% across the three size ranges (PM₁₀, PM₂.₅, and T). There was no systematic difference between the different monitors. The variation between our samplers is similar to the variation reported by Tatum et al. (2002) (CoV – ranged from 7 to 70%). The highest degree of variation is found for the smallest size fraction (PM₂.₅), which most likely relates to particle loss due to deposition onto the inner surfaces of the sampler (Li et al., 2000).

2.3. Particulate monitoring — photometer

Real-time approximation of PM₁₀ was measured using the DustTrak aerosol monitor. The DustTrak was programmed with a sample interval of 60 s and was fitted with a PM₁₀ inlet. Two monitors were placed in the child’s bedroom. The intake tube of one of the monitors was attached to the inside of the child’s cot near their breathing zone. Graphical printouts and statistical information was analysed using TRACK-PRO™ data analysis software.

The precision of the DustTrak monitors used in this study was determined by co-locating three of them in one house over a 7-day period. All instruments were highly correlated (\(R^2 = 0.96–0.99\)). The CoV for PM₁₀ ranged from 19 to 62.9% (average 42.8%), however, there was a systematic difference between the pumps,
with each instrument demonstrating a consistent higher or lower reading. The lowest and highest reading instruments were calibrated against the middle reading instrument and the final results were adjusted accordingly. The average CoV for the instruments following adjustment was 9.1%.

2.4. Statistical analyses

Particulate concentrations from the gravimetric sampling were log transformed to achieve a near normal distribution. Comparisons of PM concentrations, individually for each size fraction, at the two different heights and between rooms (using the 1.4-m living room concentration) were done using paired t-tests and Pearson’s correlation. Mean 24-hour concentrations from the DustTrak were normally distributed so comparisons, using one way analysis of variance (ANOVA), between rooms were made with the raw data in the different rooms were done using non-parametric statistics. Finally, real-time trends of PM concentrations in the different microenvironments were compared by overlaying graphs from simultaneous measurements. All analyses were done using SPSS version 9 (SPSS, Chicago, IL). Results are expressed as geometric mean for the RespiCon data and arithmetic mean for DustTrak data.

3. Results

3.1. Height differences

Geometric mean (95% confidence interval) of PM concentrations for each size fraction measured at the two different heights in the main living room using the RespiCon are presented in Table 2. There were no significant differences between concentrations of any of the different size fractions measured at the two heights. However correlations between the same size fractions measured at the two heights were only moderate, ranging from 0.39 for PM$_{2.5}$ to 0.59 for TSP (Table 2). In some cases there were differences of up to 7 times in PM concentrations measured at the two heights (Fig. 1). The direction of the differences was evenly distributed between the two heights.

3.2. Room differences (gravimetric analyses)

There were also no significant differences between the living room and the bedroom for any of the measured PM concentrations, however, correlations between rooms were also only moderate (Table 3).

3.3. Room differences (real-time analyses)

There was no significant difference between PM$_{10}$ in the living room, bedroom and cot using the DustTrak time measurements. The mean (95% confidence interval) for PM$_{10}$ was 33.5 μg/m$^3$ (22.7–44.4 μg/m$^3$),

![Fig. 2. Comparison of PM$_{10}$ between the living room, bedroom and cot in one house over a 24-h time period.](image-url)
et al., 1998a,b). These studies were done in occupational settings and investigated if PM concentrations were increased in the cot when it was occupied. There was a good correlation between bedroom and cot concentrations for PM$_{10}$ ($r=0.89$). We also investigated if PM concentrations were increased in the cot when it was occupied compared to when it was vacant, however, there was no difference between the two time periods ($p=0.64$). Finally, in most cases, the change in PM concentrations at one site was reflected by changes at the other two sites. A typical profile is illustrated in Fig. 2.

4. Discussion

In this study we found that, on average, there were no significant differences in PM concentrations measured at different heights within a room as well as between rooms in homes. However, there was considerable spatial (vertical and room-to-room) variation in concentrations within individual homes. Good inter-room mixing of PM within homes has been demonstrated previously (Ju and Spengler, 1981; Clayton et al., 1991; Wigzell et al., 2000; BeruBe et al., 2004) and Clayton et al. (1991) concluded that, although a single site may not be representative of the entire house, there was little benefit for large studies, in monitoring in several sites. In general our results are in agreement with these conclusions.

The monitoring sites in this study were chosen to investigate important microenvironments for young children. Young children spend most of their time indoors at home (Oie et al., 1993; Farrow et al., 1997). At least half of the day will be spent in the cot (Oie et al., 1993; Anders et al., 1995), and about 25% of time is spent in the living room (Oie et al., 1993). The time activity patterns of infants involved in our study reflect previous research (Oie et al., 1993), however, we also observed that for much of the time (>50%) infants are awake they are near the ground (unpublished data). Therefore, pollution concentrations in the cot and close to the ground are likely to be critical for infant exposure.

Most air pollution monitoring indoors is conducted at an adult breathing height ($\geq 1.4 \text{ m from the ground}$) and therefore may not reflect exposure concentrations relevant for young children (Bearer, 1995). A vertical distribution gradient for PM has previously been observed indoors, albeit non-residential environments (Micallef et al., 1998a,b). In these studies larger particles (PM$_{10}$ and greater) were higher at levels between 1.3 m and 1.8 m (adult breathing height) above the ground than 0.35 m (breathing height for a young child). There was little variation in the smaller particle sizes (Micallef et al., 1998a,b). These studies were done in occupational environments, which were characterised by long periods of low human activity interspersed with short periods of high activity. The largest vertical variations occurred during the periods of increased human activity with very little variation observed when activity was minimal, e.g. at night (Micallef et al., 1998a,b). We felt that in homes with young children there would be more consistent low-grade activity that may increase PM concentrations closer to the ground. However, we did not, on average, find any significant difference between two heights in the living room for any of the PM size fractions although we did often observe large variations. These were not consistent, i.e. they occurred equally at the high and low monitoring site. The reasons for the variation in PM concentrations at different heights in the current study are unknown but may be due to local disturbances near the monitoring equipment. Future work should involve real-time monitoring to investigate when differences may have occurred and activities that contribute to these variations.

The cot is a potentially important environment for exposure of young children to pollutants and allergens. Young children spend a large amount of time in the cot while sleeping (BeruBe et al., 2004) and bacteria (Sherburn and Jenkins, 2005). These agents can be aerosolised simply by the movement of the child’s head (Sherburn and Jenkins, 2005). Therefore, monitoring close to the infant’s breathing zone during sleep may be important for determining exposure to PM. We found no difference in PM$_{10}$ concentrations measured in or out of the cot and no difference in concentrations when the cot was occupied or empty. Further, from the real-time monitoring, we did not observe significant short-term peaks in PM$_{10}$ concentrations when the cot was occupied or empty. The largest vertical variations occurred when the child was in the cot. Indeed, the peak concentrations in the cot were mostly influenced by peaks from other sites. Most cots are designed to allow unrestricted airflow and, for PM$_{10}$, bedroom concentrations seem to be sufficient for determining potential exposure during sleep.

There have only been a few studies that have investigated room-to-room variation in PM concentrations within homes (Ju and Spengler, 1981; Clayton et al., 1991; Wigzell et al., 2000; BeruBe et al., 2004). Although only a small number of homes were monitored for each of these studies they mostly observed very little difference between rooms and correlations of PM concentrations between rooms were generally high (>$0.8$) (Clayton et al., 1991; Wigzell et al., 2000; BeruBe et al., 2004). The number of homes measured in this study was much greater than these earlier studies.
and, although, on average, there was little difference in PM concentrations between rooms the correlation between rooms was only moderate (about 0.6). Some of the variability in this study could be due to the precision of the monitoring equipment (see Methods), however, differences were often much greater than may be expected from equipment measurement error. There are two possible reasons for the differences between the current and earlier studies. Firstly, in some of the earlier studies repeated samples were collected in a small number of homes (Ju and Spengler, 1981; Clayton et al., 1991; BeruBe et al., 2004). Although there can be considerable day to day variability in PM concentration in homes (Ju and Spengler, 1981) the relationship in PM concentrations between rooms within individual homes may remain reasonably consistent. Therefore, the between room correlations will be high. In the current study only one sampling period was undertaken in a large number of homes. Different activities in these homes may impact on inter-room mixing of PM, thereby increasing the within home variability. The other reason may be the choice of homes. In this study we measured homes of families with a young child. Many children in this age group will spend a large proportion of their time, day and night, sleeping. It is possible that in many instances when the child was asleep the door to their bedroom may have been fully or partially closed. Miller and Nazaroff (1997) demonstrated that closing a door between adjoining rooms can reduce the rate of airflow between them from about 60 m$^3$/h to <1 m$^3$/h and considerably reduce the movement of particles from one room to the other. This should be considered when designing sampling strategies for young children.

Interestingly, despite the variations in PM concentrations using time integrated measures, we did observe a high degree of consistency in the pattern of change in PM$_{10}$ concentrations when measured using RTA. This agrees with the findings of Wigzell et al. (2000) who reported similar patterns of change in TSP between the kitchen and living room of 10 homes. Kitchen and living rooms are often open and adjoining, so it would not be unreasonable to expect particulate concentrations to be similar. In our study we compared the living room to the child’s bedroom, which may be separated by a hallway or other rooms. This suggests that events in one room that increase PM will be reflected, to some extent, throughout the home.

For PM, direct monitoring has often depicted higher exposure to pollutants than concentrations monitored from microenvironmental monitors (Clayton et al., 1993). In adults and older children personal exposure levels to PM are about 50% higher than both indoor and outdoor concentrations (Clayton et al., 1993). Unfortunately, it is not currently possible to directly measure personal exposure of young children to PM and therefore it is not known if they will have a similar ‘personal cloud’. However, due to the amount of time infants spend indoors at home it can be assumed that domestic concentrations of PM will be the dominant source of exposure. In the present study there were no significant differences of PM concentrations between different microenvironments within homes when analysed as a group but large variations were noted in individual homes. These results suggest that a single monitoring site within homes can provide a reasonable estimate of indoor PM concentrations. However, the potential for large differences in PM concentrations between sites within individual homes should be considered when estimating exposure from a single monitoring site.

**References**


Corbyn JA. Sudden infant death due to carbon dioxide and other pollutant accumulation at the face of a sleeping baby. Med Hypotheses 1993;41:483–94.


