

Research article

Quantifying potential particulate matter intake dose in a low-income community in South Africa

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Abstract

Understanding how exposure to particulate matter impacts human health is complex. Personal exposure is a function of the pollution concentrations measured at any given place and time. The health impacts of this exposure are, in part, determined by how high pollutant concentrations are and how much pollution can potentially enter the body. This study considered data gathered in the winter of 2013 in a low-income community on the Mpumalanga Highveld, South Africa, which is a geographical area known for its high air pollution levels. Data collected by GPS monitors worn by individuals in the community were used to understand in which microenvironments people spend most of their time. Participants spent time in five main micro-environments: (highest rank first) inside a house, directly outside a house, on a dirt road, on a tar road, and on an open field. Eight days' worth of ambient, indoor and personal particulate matter measurements were paired with individual GPS positioning data for one study participant. We identified pollutant concentrations where the person spent time and how much particulate matter the person potentially inhaled. Highest concentrations were measured inside the dwelling and directly outside the dwelling of the individual. When comparing directly (ranging from 0.02 – 0.76 mg) - and indirectly (0.02 – 0.34 mg) derived time-weighted potential intake doses, directly derived intake doses were higher and more likely to represent how much particulate matter was potentially inhaled by the participant. This study suggests that people living in communities on the Mpumalanga Highveld are exposed to unacceptably high air pollution levels in places in which they spend most of their time. Direct exposure and intake dose assessments are an important element of environmental health studies to supplement data collected by stationary monitors in order to better understand exactly what people are breathing.

Keywords

air pollution exposure, household air pollution, micro-environments

Introduction

The effect of air pollution on human health is dependent on many factors (Wilson et al., 2000). Initial steps towards better understanding how air pollution influences health include 1) identifying how much air pollution an individual comes into contact with at the breathing zone and for how long, 2) determining how much of this air pollution is inhaled, and finally 3) understanding how much pollution is taken up into the body, where the chemical characteristics of the pollutant determine how it can affect organs and bodily systems (Figure 1).

Air pollution exposure

Stationary ambient air quality monitors are often used as a proxy for personal air pollution exposure. Ambient concentrations, however, are not necessarily indicative of the

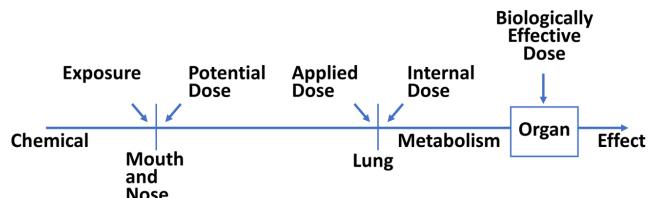


Figure 1: Illustration of Inhalation Route: Exposure and Dose (U.S. EPA 1992)

pollutant concentrations that people are exposed to especially within low-income residential communities where air pollution exposure is highly variable and where people spend their time in different micro-environments (Bruce et al., 2002; Ferro et al., 2004; Diapouli, 2011; Lim et al., 2012). Exposure to air pollution is typically a function of time spent in proximity to pollution

sources in multiple locations (Vette et al., 2001). Even though significant emissions stem from outdoor sources, people spend most of their time in an indoor environment where significant sources also exist (Vette et al., 2001). These sources contribute to the total dose of air pollution inhaled by an individual on a typical day. Consequently, to understand air pollution exposure and how much a person can potentially breathe in, air pollution needs to be measured in every micro-environment in which an individual spends time throughout the day. For this, micro-environment and time-activity pattern identification are essential (Park et al., 2020).

Potential air pollution intake dose

Determining how much air pollution is *potentially* inhaled by an individual to then be taken up by the body requires knowledge of the concentration of the pollutant which the individual is exposed to at the breathing zone, the breathing rate of the individual, as well as the time spent inhaling the air pollution at that concentration.

Breathing rates differ by age and gender, and determine how much and how deeply a specific pollutant is inhaled into the respiratory system (Smith, 1993; Wilson et al., 2000). An individual's physiology, body size and activity level also influence a person's breathing rates (Wilson et al., 2000). Normal breathing rates for adults (men and women combined) range from 12.2 m³/day (for ages 81 years and older) to 16.0 m³/day (for ages 31 to 51 years) (U.S. EPA, 2011).

It is possible to derive direct and indirect exposure to air pollution, as well as direct and indirect potential intake dose estimates. Direct methods consider inhalation-based exposure assessments using personal monitors located in the breathing zone (Abbey et al., 1999; Cong et al., 2021). Indirect methods include questionnaires/time-activity diaries and measurements taken at centrally located, stationary monitoring sites. This estimation considers time spent in specific micro-environments and matches this information with the average particulate matter (PM) concentrations measured in those environments (Jones et al., 2000; Mdluli, 2007). Holistic, total exposure estimates would consider a combination of both direct and indirect measurements with detailed personal activity patterns.

Though ambient and indoor particulate matter data has been collected in low-income communities in South Africa, few studies have considered ambient, indoor, and personal air pollution concentrations simultaneously. To the best of our knowledge, no studies have considered personal exposure to PM concentrations in various micro-environments and presented corresponding potential intake doses. This study aims to fill this research gap.

Methods

Sampling site

The low-income community chosen for this study is situated in



Figure 2: GPS coordinates plotted on an image of the community to identify common micro-environments. Multiple individuals' GPS data are illustrated on this figure to avoid disclosing personal information about the participant in this case study. The different colours represent coordinates of different individuals on different days and have no other meaning.

the Gert Sibande District Municipality in Mpumalanga, South Africa. It is located within the Highveld Priority Area known for poor air quality caused mainly by cumulative emissions stemming from sources such as domestic burning and industrial activities, but also road dust and waste burning (Nkosi et al., 2017).

PM data collection and processing

Ambient PM_{2.5} and PM₁₀ concentrations were measured at a centrally located, stationary site using Horiba BAM and MetOne E-Bam instruments, respectively.

Personal PM₄ concentrations of one adult who gave informed consent were monitored on different days using a TSI SidePak AM510 photometric monitor for a range of one to eight hours per day. This adult also carried a mobile GPS which tracked personal movements. Indoor PM₄ concentrations were measured in the dwelling of the individual using a TSI DustTrak photometric monitor (Models 8520 and 8530). The indoor and personal PM₄ measurements were corrected according to a specific photometric calibration factor obtained for the DustTrak and SidePak instruments (Language et al. 2016).

Measurements were taken between 21 – 28 August 2013. The GPS coordinate readings represented daytime movement patterns ranging from 09:00 to 18:00. No position readings were taken during the night, but it can be assumed that the individual spent less time outside of the dwelling during the evening and spent most of the time indoors at night.

Identification of micro-environments

To track everyday movement patterns, Global Positioning System (GPS) monitors were worn by a sub-sample of 20 consenting community members who were participants in a larger air quality study, and who also wore personal air quality monitors and spent most of their time within the community. Micro-environments were identified by plotting dots of all

recorded GPS readings over the period of the study on a SPOT 6/7 (2015) satellite image using QGIS version 2.14.1 (Figure 2). Areas on the map where the dot-density was highest were identified as places frequently visited whilst wearing the personal monitoring device.

Sampling was conducted as part of a larger sampling campaign in the winter of 2013. This study was conducted under the oversight of the North-West University Health Research Ethics Committee (NWU-00066-13-S3).

Corresponding personal exposure and micro-environments

The personal PM_4 concentrations were paired with GPS tracking data at ten-minute average intervals. Figure 3 illustrates the personal PM_4 concentrations measured in the places in which the individual spent time on 25 August 2013.

Indoor PM_4 measurements for the dwelling in which the individual spent the most time were also considered together with ambient $PM_{2.5}$ concentrations. No detailed behavioural information was considered, and this is recognised as a limitation of the study since exposure is closely associated with behavioural patterns (Terblanche et al. 1992).

Direct and indirect intake doses

Total (integrated) exposure, which considers the period an individual comes into contact with an exposure concentration, is derived by using Equation (1):

$$E = \int_{t_1}^{t_2} C(t) dt \quad (1)$$

Where E is the magnitude of exposure, $C(t)$ is the exposure concentration as a function of time and t is time, $t_2 - t_1$, representing the exposure duration (ED) (U.S. EPA 1992). Once the magnitude of exposure has been determined, it is possible to calculate the *potential* dose, or the amount of a pollutant that could be inhaled (through the mouth or nose), all of which is not absorbed by the body.

Equation 2 shows the *potential* dose for inhalation as the integration of the pollutant intake rate (concentration of the pollutant in the air times the intake rate of the air, C times IR) over time (U.S. EPA 1992):

$$D_{pot} = \int_{t_1}^{t_2} C(t) IR(t) dt \quad (2)$$

D_{pot} is *potential* dose and $IR(t)$ is the inhalation rate of an individual. The quantity $t_2 - t_1$ represents the period over which exposure is examined (U.S. EPA 1992). The above methods describe how the potential intake of exposure concentrations was assessed.

Direct *potential* intake doses were derived using equation 2 by using the direct personal measurements read by the personal monitor. A short-term inhalation rate for an average middle-aged woman at light-intensity activity was used for the purposes

of this exercise ($0.012 \text{ m}^3/\text{min}$) (U.S. EPA, 2011). GPS / Personal PM_4 data did not represent a full day's worth of data, hence a short-term breathing rate was deemed appropriate.

To indirectly derive *potential* intake doses over the same period, instead of personal PM measurements, stationary indoor PM_4 , ambient $PM_{2.5}$ measurements and movement patterns determined by the GPS monitor were used. PM_4 concentrations were directly compared to $PM_{2.5}$ concentrations as these have been found to be comparable in another study, which identified the relationship between PM of different size fractions measured at the same time and place. The median ratio of $PM_{2.5} : PM_4$ was found to be close to one (0.92) (Language 2019) supporting the comparison of the two PM size fractions in this study.

Results

Identified micro-environments

Considering the plotted GPS coordinates in figure 2, a total of five different micro-environments were identified based on GPS monitor data for numerous study participants. Most time was spent (highest rank first) inside a house, directly outside a house, on a dirt road, on a tar road, and in an open field. Most of the personal movements (on average 87%) were concentrated inside- and directly outside of dwellings.

Personal exposure in different micro-environments

The participant wearing the personal PM_4 monitor was exposed to a wide range of PM_4 concentrations in the locations in which the individual spent time on each day between 21 and 28 August. Figure 3 illustrates an example of personal exposure on 25 August 2013 where the individual was exposed to PM_4 concentrations ranging from $36 \mu\text{g}/\text{m}^3$ between 13:00 and 13:10 directly outside a house and $2781 \mu\text{g}/\text{m}^3$ between 18:00 and 18:10 inside a house.

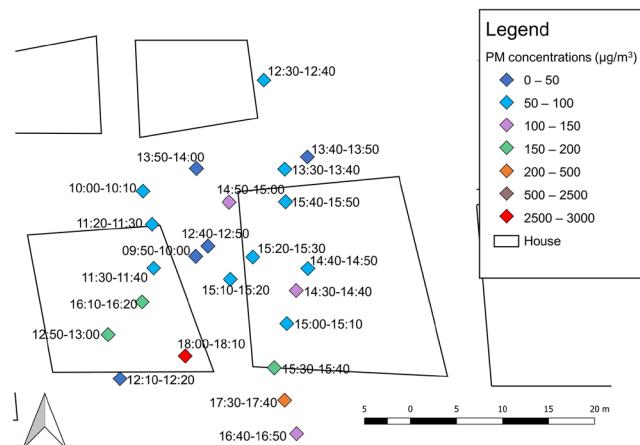


Figure 3: GPS tracks (dots) showing ten-minute average personal PM_4 concentration exposure on 25 August 2013. Micro-environments displayed are "Inside a house" (delineated by an outlined rectangle) and "Directly outside a house" (the space outside the rectangles).

When plotting similar figures for every other day between 21 and 28 August 2013 (the dates on which this specific individual wore the monitors), it was found that personal exposure concentrations ranged from low concentrations to unacceptably high concentrations, and often reached levels into the mg/m³ range. When comparing daily average PM concentrations, personal, indoor and ambient concentrations were highly variable (Table 1).

Table 1: Comparing daily average personal PM measurements with daily average ambient and indoor PM measurements (µg/m³) ± standard deviation

Date	Personal PM ₄	Indoor PM ₄	Ambient PM _{2.5}
21-Aug-13	32 (1.42)	189 (387.55)	35 (6.60)
22-Aug-13	13 (7.58)	259 (1111.50)	37 (19.90)
23-Aug-13	100 (33.82)	207 (381.71)	39 (16.45)
24-Aug-13	100 (30.88)	147 (302.35)	40 (14.05)
25-Aug-13	192 (845.96)	237 (672.13)	42 (13.55)
26-Aug-13	58 (21.27)	87 (51.07)	33 (9.71)
27-Aug-13	71 (36.88)	125 (108.43)	37 (8.61)
28-Aug-13	176 (228.57)	272 (350.77)	61 (29.26)

Table 2: Directly and indirectly derived potential intake doses (mg) between 21 – 28 August 2013 for the number of hours for which personal PM and GPS measurements were available

Direct potential dose for which personal measurements were available		
Date	Dose (mg)	Time (Hours)
21-Aug-13	0.02	1.00
22-Aug-13	0.05	4.83
23-Aug-13	0.52	7.17
24-Aug-13	0.21	3.50
25-Aug-13	0.76	5.83
26-Aug-13	0.19	4.33
27-Aug-13	0.17	2.67
28-Aug-13	0.34	3.50

Indirect time-weighted potential dose for the hours in which ambient, indoor and personal measurements were simultaneously available		
Date	Dose (mg)	Time (Hours)
21-Aug-13	0.02	1.00
22-Aug-13	0.08	4.83
23-Aug-13	0.03	7.17
24-Aug-13	0.14	3.50
25-Aug-13	0.35	5.83
26-Aug-13	0.25	4.33
27-Aug-13	0.14	2.67
28-Aug-13	0.23	3.50

Potential intake doses

Potential PM₄ intake doses ascertained using direct and indirect methods, varied (Table 2). Potential intake dose estimates using the direct potential dose derivation method ranged between 0.02 - 0.76 mg for the time during which GPS measurements were available (i.e. between 09:00 and 17:00). Indirect potential intake doses for the same time ranged between 0.02 - 0.34 mg. Potential intake doses calculated in an indirect manner, using stationary monitoring data, were generally lower compared to potential intake doses calculated from direct personal exposure measurements. On the 23rd of August 2013, for example, the direct potential dose calculated was 0.52 mg over 7 hours, whereas the indirectly derived potential dose for the same period was 0.03 mg (0.49 mg less). In Figure 3, on 25 August 2013, the individual wearing the monitor potentially inhaled a directly derived PM dose of 0.76 mg. When considering the indirectly derived dose for that same day, the individual potentially inhaled a dose of 0.35 mg (0.41 mg of PM less). Highest potential doses mainly corresponded to the days on which readings were available for the longest period of time (Table 2 - final column).

Discussion

Particulate matter exposure and potential intake doses

Air pollution exposure of an individual who resides in a low-income town on the Mpumalanga Highveld, where air pollution is an identified health concern, was investigated (Balmer, 2007; Mdluli, 2007; Garland et al., 2017). Five main micro-environments were identified as places in which time was spent. These were 1) inside a house, 2) directly outside a house, 3) on a dirt road, 4) on a tar road and 5) on an open field. On average, 90% of the time was spent in and around a house. Less time was spent on roads and open fields.

Ambient, indoor and personal PM measurements were found to exceed ambient standards in numerous micro-environments, where PM levels even went into the milligram range.

GPS tracking data and personal PM₄ measurements of a participant were paired at ten-minute average intervals over an eight-day period (between 21 and 28 August 2013). By plotting the matched datasets onto an aerial photograph, location patterns helped understand how much PM₄ the individual was exposed to in each micro-environment where time was spent.

Exposure to highest concentrations could not be pinpointed to the indoor environment only, because high personal PM measurements were also recorded when the individual was in the ambient environment. Nevertheless, the most extreme exposure concentrations were recorded in the indoor environment and directly outside of houses.

Direct and indirect potential intake doses for PM₄ were calculated and compared. A trend of lower potential doses for indirectly derived methods was evident on five of the eight days

studied. On the other three days, the indirectly derived doses were either higher than or equal to the potential dose derived by direct methods. These differences are likely attributable to the fact that stationary monitors used for the indirect methods did not measure the actual concentrations the individual was exposed to at the breathing zone. These monitors measure concentrations in the identified micro-environment in which they were positioned, thereby representing only a proxy for what the individual was potentially exposed to.

The resulting figures are representative of doses of PM potentially inhaled during winter as a result of time spent exposed in the ambient and the indoor environment. Though indirectly-derived potential doses fell below what has been demonstrated to be inhaled in other low-income communities (e.g. when compared to potential inhalation doses in Bangladesh where doses ranged between 4.4 mg and 5.8 mg of $PM_{2.5}$ per day (Chowdhury et al., 2012)), it should be kept in mind that, for smaller PM size fractions there is no threshold below which there is no discernible health effect (Zhao et al., 2020).

The average potential intake dose of $PM_{2.5}$ has been estimated to range between 7.0 – 17.5 mg per cigarette actively smoked (Pope et al., 2009). The results in this study show that the amount of PM potentially inhaled by an individual in their living environment during a few hours are not far from the amount of PM inhaled while actively smoking when extrapolated to an entire day. This exposure could lead to cardiovascular and respiratory health effects without the individual even actively being aware of it (Pope et al., 2009).

It is likely that the directly derived total daily potential intake dose of the individual would be much higher than what has been demonstrated here. This is because peak exposure concentrations during domestic burning times for heating or cooking in the early morning may not have been included, and because the directly derived potential doses have been estimated with an incomplete dataset (only for a few hours a day, for which data were available). As time-activity journals were not kept by the participant of the study, it was not possible to identify the source of the PM to which the participant was exposed at different times. These are clear limitations of the study.

Directly- versus indirectly derived exposure and potential intake dose assessments

An age-old scientific debate between scientists exists, which compares the value of directly- and indirectly derived air quality exposure assessments for air pollution environmental-epidemiologic studies (National Research Council 1997; Wilson 2006; Diapouli et al., 2011). Both methods have advantages and disadvantages depending on the research question. Direct measurements, in this study represented by personal PM_4 measurements and GPS readings, are generally the most accurate estimate of concentrations which people are exposed to at the breathing zone. Indirect measures (stationary air quality

monitors) are less expensive, less time- and resource-intensive, and cover a larger temporal and spatial scale (National Research Council 1997).

In the case of this study, ambient- and indoor PM measurements help better understand indicative personal total exposure rates, if used to derive indirect potential intake doses along with micro-environment data. These measurements help answer the question of whether air quality in the community complies with ambient standards. The more individual-focused elements of this study, like the identification of micro-environments, for instance, help prioritise where specifically to focus action to reduce air pollution. Similarly, by pairing location with personal PM exposure, priority exposures can be identified for risk mitigation and air pollution management strategies.

Gathering more information on the biology of the individual (e.g., weight and breathing rate) as well as understanding the chemical characteristics of the pollutant in question would assist in better understanding how much of the pollutant is eventually taken up into the body and how it impacts on it.

Conclusions

Residents of low-income communities on the Mpumalanga Highveld are chronically exposed to air that is not safe to breathe (Werneck et al., 2015; Language et al., 2016). This study exemplifies that a typical individual living in one of these communities is exposed to high PM_4 concentrations in the spaces in which the most time is spent during a typical day (in winter for this study) and that directly derived potential intake doses, are more likely to represent what an individual breathes in.

This is the first South African study to link PM exposure to micro-environments, to directly- and indirectly-determine this exposure and to then compare potential PM_4 intake doses in these environments, which contributes to our understanding of PM exposure in South African low-income communities.

Direct- and indirect exposure and potential dose intake assessments have been conducted in this study. Micro-environments have also been determined. The next step towards filling South Africa's exposure- and dose-response function gap could be to build upon this study design and to then determine health impacts using daily health diaries and / or medical surveys, coupled with personal measurements and time-activity patterns to support the information collected by more general means, such as ambient air quality monitoring coupled with community surveys. This is a necessary next step in understanding how air pollution affects the people living in communities on the Highveld where air pollution is a serious problem.

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