Assessing socioeconomic bias of exposure to urban air pollution: an autopsy-based study in São Paulo, Brazil

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Summary

Background The characterisation of individual exposure to air pollution in urban scenarios is a challenge in environmental epidemiological studies. We investigated if the city's pollution monitoring stations over or underestimate the exposure of individuals depending on their socioeconomic conditions and daily commuting times.

Methods The amount of black carbon accumulated in the lungs of 604 deceased who underwent autopsy in São Paulo was considered as a proxy for PM_{10}. The concentrations of PM_{10} in the residence of the deceased were estimated by interpolating an ordinary kriging model. These two-exposure metrics allowed us to construct an environmental exposure misclassification index ranging from –1 to 1. The association between the index and daily commuting, socioeconomic context index (GeoSES), and street density as predictors was assessed by means of a multilevel linear regression model.

Findings With a decrease of 0·1 units in GeoSES, the index increases, on average, by 0·028 units and with an increase of 1 h in daily commuting, the index increases, on average, by 0·022 units indicating that individual exposure to air pollution is underestimated in the lower GeoSES and in people with many hours spent in daily commuting.

Interpretation Reduction of health consequences of air pollution demands not only alternative fuel and more efficient mobility strategies, but also should include profound rethink of cities.

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Introduction

Adequate exposure characterisation is a critical aspect in studies aimed to assess the health effects of airborne contaminants. Epidemiological studies generally use environmental data on air pollutant levels at home addresses obtained from fixed monitoring stations to estimate the exposure of individuals. One major limitation of this procedure is that fixed monitors, that in general are sparsely sited and have low spatial resolution,[1,2] cannot directly capture the pollutants concentration over the "activity space" of the urban dwellers that may receive significantly different doses of air pollutants according to their mobility patterns, near-home sources, housing conditions and occupational activities. This can lead to an over- or underestimation of the actual exposure.[3–5] Personal air pollution monitoring devices[3,6] and smartphone-based mobility registries[5,7–9] have been used to better evaluate the individual exposure and

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Research in context

Evidence before this study

The determination of precise exposure to air pollution is a significant challenge in human epidemiological studies particularly in the urban scenario. Urban dwellers may receive different doses of air pollutants based on their occupational activity, mobility patterns, near-home sources and housing conditions. Even studies that employ precise personal monitoring devices may have limitations in the number of individuals evaluated, as well of the time of measurements that usually does not exceed few days. Thus, quantifying long-term individual exposure is still a significant problem, especially in individuals living in the vulnerable areas of the large urban conglomerates.

Added value of this study

To our knowledge the present study was the first of study quantitative estimate the influence of socioeconomic vulnerability on chronic exposure misclassification to airborne pollutants in urban dwellers using a large autopsy data. Our findings add strength to the evidence that underprivileged individuals of a large South American Metropolis have a higher exposure to air pollution. Exposure bias was significantly associated with longer commuting hours, due to socioeconomic spatial segregation within the territory which increases distance from home and jobs.

Implications of all the available evidence

Our findings indicate that exposure misclassification is not a spatially random event but is highly influenced by socioeconomic determinants. Results indicate that the reduction of health consequences of air pollution demands not only alternative fuel and more efficient mobility strategies, but also should include profound reshape of cities.

reduce exposure misclassification. Despite of that, the direct quantification of long-term exposure misclassification deserves further clarification, especially in individuals living in the vulnerable areas of the large urban conglomerates.

Additional challenges in urban air pollution studies refer to the difficulties in disentangling the complex relationship between socioeconomic status and health effects associated to air pollution exposure. Socioeconomic status may interfere with the vulnerability to urban air pollution in different ways. Low-income people generally spend more time exposed in traffic during commuting or live in areas with higher levels of contaminants in the air, thus increasing exposure.[10,11] Furthermore, higher incidence of co-morbidities, nutritional deficiency, less access to information and education as a result of lack of economic resources imposes an increased vulnerability.[12,13] Thus, it is highly probable that both factors – higher dose and greater vulnerability - are interconnected.[14]

Socio-economic vulnerability to air pollution is an important global health problem[15] since higher ambient concentration of air contaminants are observed in countries with lower economic conditions. In addition, probably the interaction between exposure to air pollution and social vulnerability is more prone to occur in cities with marked socioeconomic variation within their boundaries. São Paulo and other large Latin American cities are examples of this situation, but studies on this aspect are somewhat scarce in Latin America. An elegant review paper conducted by Hajat et al.[16] identified no studies conducted in Latin America, probably as consequence of paucity of adequate air pollution measurements in the region. In a recent timely study, Gouveia et al.[17] identified eight articles addressing the role of socio-economic vulnerability with higher exposure level to airborne pollutants, all of them using indirect estimates of exposure such as distance to the monitor, interpolation by "kriging" or near home traffic density. Considering the high level of social and economic contrasts of large Latin America urban centres, the evaluation of the magnitude of socioeconomic influence on air pollution exposure is an important urban health topic to be addressed in this area to propose public policies aimed to reduce the adverse health effects promoted by airborne pollutants.

São Paulo is a 12 million inhabitant city with a circulating fleet about 7·2 million vehicles. Currently, its citizens are exposed to an average annual concentration of 15 $\mu g/m^3$ of $PM_{2.5}$, mostly generated by vehicular emissions.[18,19]

The city combines remarkable socioeconomic inequalities,[20] genetic admixture and high-quality data and could be considered a life laboratory for urban policies aimed to promote urban health, particularly transportation-based policies. From a global perspective, São Paulo is not among the most polluted cities in the world but ranks 5th in the most congested cities,[21] increasing the dose of air pollution that its residents are exposed to. Like the large Latin America cities, São Paulo experienced sharp population growth in the last decades. This context resulted that a significant fraction of its population lives in areas with sanitary and economic vulnerabilities and is submitted to longer commuting hours to access their jobs inside traffic lanes.

In 2019, Takano et al.[22] used pulmonary accumulation of black carbon (anthracosis) in human lungs obtained from a sample of 413 deceased who underwent autopsy in São Paulo as an individual estimator of long-term exposure to airborne particles. Briefly anthracosis – originally described in coal miners – are small areas of pulmonary fibrosis induced by chronic particle inhalation, which are visible in the pulmonary parenchyma and pleura as black spots of black carbon. The authors demonstrated that there is a robust negative association between the black carbon fraction and the socioeconomic index.

Considering the well-known findings that black carbon penetrates and is retained in the lungs, and it has a positive association with the exposure to air pollution[23,24] we moved forward in this topic and quantified the black carbon accumulation in the lungs of additional individuals who underwent autopsy in São Paulo, making it possible to build a high resolution dosimetric study on a citywide scale. To our knowledge, such an approach was not hitherto conducted to such an extent. Moreover, we construct an index that reflects, for each deceased, the difference between the black carbon measured in his lung and the estimated dose at his residence based on the data of fixed air pollution monitoring stations, that is, an index of environmental exposure misclassification. Based on this index we investigated if the city's pollution monitoring stations over or underestimate the exposure of individuals depending on their socioeconomic conditions and daily commuting times. Such result may indicate the need for marked improvements in the methods used to assess personal environmental exposures.

Methods

Determination of spatial variation of aerosol concentrations and emissions based on monitoring and modelling

Air pollution monitoring system

The public environmental agency of São Paulo State (CETESB) has a network with 25 monitoring stations in the metropolitan area of São Paulo (MASP) with the availability of PM_{10} daily concentration data covering 2005 until 2016, the period preceding the autopsies. All the 25 monitoring stations were included in the study. The stations that are in MASP, but outside the municipality of São Paulo were considered in order to obtain a more accurate exposure assessment on the boundary of the city. We joined data from close monitoring stations (Guarulhos station had been relocated twice around less than 1 km far, featuring PM_{10} monitoring data from 2005 to 2009 in the initial location, from 2012 to 2015 in the second location, and from 2016 in the last location; Santo André station had been relocated once around less than 1 km far, featuring PM_{10} monitoring data from 2005 to 2007 in the initial location and from 2009 to 2016 in the last location), discarded information from stations with a small amount of data (Cambuci station featuring PM_{10} monitoring data from 2005 to 2008, and Centro station featuring PM_{10} monitoring data from 2005 to 2009, since both were near Parque Dom Pedro station with data from 2005 to 2016), and calculated in a first step, a monthly average concentration along the 12 years and, in a second step, an average of such monthly averages. This procedure avoids a bias on its seasonal behaviour when the time series present many missing data distributed along the period. The long period of averaging (12 years) was considered because pulmonary anthracosis reflects long-term exposure. PM_{10} data were employed as indicator of exposure to urban particles because there are many air quality stations monitoring this pollutant and because its association with $PM_{2.5}$ in São Paulo ($PM_{2.5}/PM_{10}$ ratio of 0·6).

In parallel, we created a project in a Geographic Information System (ArcMap 10.8.1) to estimate PM_{10} concentrations at the residence of the deceased by interpolating an ordinary kriging model of the concentrations of particles determined by the network with 25 monitoring stations of the MASP. Kriging is a geostatistical method for interpolation based on statistical models that include autocorrelation. Kriging is most appropriate when there is a spatially correlated distance or directional bias in the data. Thus, we performed an autocorrelation analysis before kriging.[25]

Determination of individual variation of inhaled dose of black carbon based on autopsy studies

This part of the study was conducted at the Death Verification Service of São Paulo (DVSSP) from February 2017 to January 2019. In DVSSP, the body is claimed by a next of kin (NOK), who signs a consent form to participate in the study. The deceased must meet the inclusion criteria: i) have died by natural death; ii) age equal to or greater than 18 years; iii) living in São Paulo at the time of death; iv) have a close family member/caregiver to provide reliable and complete information during the interview and v) present no macroscopic alterations of the lungs. Following this procedure and upon acceptance, the NOK was interviewed to provide information about the deceased. A convenience sample of cases satisfying these criteria was included in the study. The questionnaire included questions about age, previous health conditions, residential address, life habits, smoking status, occupation at time of death, time of residence in São Paulo and daily time spent commuting. The daily time spent commuting was evaluated by the question: *How long did the deceased used to take to go from home to work?* When the deceased, depending on his occupational activity, remained exposed to traffic during all his work shift, we adjusted his exposition by adding 8 h to his daily commuting time. The questionnaire also contained questions about smoking habits and a deceased could be classified as non-smoker, current smoker, or former smoker. There was also a specific question about environmental tobacco smoke exposure at home, that is, it was considered that a smoker, or former smoker, could be exposed to an additional burden of tobacco if he lived with a smoker (ETS at home).

Parallel to the clinical assessment, an autopsy in which a macroscopic analysis of all body organs is carried out and permits to collect of lung images, as previously described.[22] In summary, we collected a total of four pictures from the flattened surface of the lungs of each included death (upper and lower lobes of both lungs). The areal fraction (AF) of pleural anthracosis (black carbon spots) was estimated by the point test system using the ImageJ software. For each of the four lobes, points on black patches (BP) and in the clean pleura (CP) were counted. Then, for each lung lobe the AF was determined as: AF = number of BP/(number of BP + number of CP). The black carbon deposition is directly measured on the lung surface and was used to estimate individual lifetime exposure to inhaled particles.

Socio-economic index

Area-based studies show that the socioeconomic conditions of places also affect people's health.[26] Thus, understanding which characteristics of the socioeconomic environment most explain health conditions is a pressing issue. In this study we considered the Socioeconomic Index of Geographic Context for Health and Social Studies (GeoSES).[20] GeoSES synthesizes the most relevant socioeconomic dimensions to contextualize health for research purposes, to evaluate and monitor inequalities, and to develop resource and service allocation strategies: education, income, poverty, wealth, residential segregation, mobility, and material deprivation. For the extraction of this index, the addresses of all the deceased were geocoded and the values of the variables that compose it were obtained from the data of the 2010 Brazilian Demographic Census, the last Census carried out in the country, in the corresponding sample areas. GeoSES varies between –1, that indicates the worst socioeconomic context of the city, and 1, the best context.

Street density

Using ArcMap 10.8.1, with the shapefile of streets, a raster file was generated around each recorded address and the values of street density given by the total number of linear meters of streets divided by the area (m/m^2) in a buffer distance of 100 m were extracted.

Exposure bias and its relationship with socio-economic variables

Environmental exposure misclassification index

Our environmental exposure misclassification index (IEEM) was constructed to reflect the bias introduced in the individual exposure to air pollution when only the concentrations of particles, as determined by the fixed monitoring stations are considered and the daily activities, mobility patterns and residence surroundings characteristics are not considered. With this purpose, for each subject, we first compute the average carbon deposit in the four lobes of the lungs. To obtain the amount of black carbon not explained by personal characteristics, we fit a beta regression model,[27] with logit link function, considering the average black carbon as the response variable and age, residence time in the municipality, smoking habits and environmental tobacco smoke as predictors. The models were fitted via the *betareg* function from the *betareg* library in R. The difference between the observed average black carbon and the predict value by the regression model corresponds to the standardised pulmonary black carbon. The individual values of the standardised pulmonary black carbon, as well as the estimated PM_{10} concentrations at the residences were independently ranked from 1 to N, the number of individuals in the sample. If the official monitoring network estimated PM_{10} concentrations actually reflects individual lifetime exposure to inhalable particles, it is expected that a given individual has similar ranks in the two sets of measurements. Thus, a possible index of environmental exposure misclassification (IEEM) can be defined as:

IEEM= (rank of standardised pulmonary black carbon – rank of estimated PM_{10} concentration)/(N-1) (1)

where (N-1) is a factor scale introduced so that IEEM ranges between –1 and 1. An individual IEEM value equal to 0 indicates absence of exposure misclassification; an IEEM value less than 0, suggests that the PM_{10} monitoring network overestimates the standardised pulmonary black carbon of the individual; if it is larger than 0, there is a suggestion of underestimation. It is important to note that the concentrations of the pollutants black carbon and PM_{10} are comparable, because the black carbon is part of the PM_{10} composition and both in São Paulo are related to traffic emissions according to official inventory from the CETESB and to many studies that have shown the sources of the PM in São Paulo.[18,19]

Association between exposure bias and socio-economic index

Considering that GeoSES was evaluated on the sample areas and not at the individual level, the association between IEEM and daily commuting, socioeconomic index, and street density in a buffer of 100 m around the address of his/her residence as predictors was accessed by means of a two-level linear model with randomly varying intercepts.[28,29] The model was fitted using the restricted maximum likelihood method via the *lmer* function from the *lme4* library in R software. To test the hypothesis that the variance of random effects is equal to zero we applied the likelihood ratio test as described in Stram and Lee.[30] An analysis of the residuals was performed to check whether the assumptions of the model were valid.[31]

Ethics statement

This study was approved by the Research Ethics Committee of University of São Paulo (number 537195). All the participants gave their consent to participate in the survey.

Role of the funding source

The funder of the study played no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The anthracosis was measured in the lungs of 604 individuals whose characteristics are summarized in Table 1. The median of the variable “proportion of lifespan living in São Paulo” is 0.76, that is, at least half of the deceased spent more than 0.76 of their lives in São Paulo. The maximum observed PM_{10} concentration is lower than the maximum value established by the Brazilian Environmental Agency (40 μg/m^3). However, the minimum observed PM_{10} concentration is much higher than the value recommended by WHO[32] air quality guidelines (20 μg/m^3). GeoSES assumes its extreme values, −1 and 1, but more than 50% of the deceased are concentrated in the negative values of the index, that means the worst relative socioeconomic context of the city.

The spatial distribution of the monitoring stations, as well as of the socioeconomic index GeoSES are depicted in Fig. 1a.

The fit of the beta regression model showed that the number of years living in São Paulo and environmental tobacco smoke do not have significant additional contribution to age and smoke to explain the amount of black carbon in the lung ($p = 0.70$ and $p > 0.99$, respectively). These variables were dropped from the model, one by one. The standardised pulmonary black carbon was then computed, and the histogram depicted in Fig. 2 represents approximately its distribution. Their values ranged from −0.259 to 0.463 (mean = 0.000, standard deviation = 0.127). Individual with negative values of this variable have smaller amount of black carbon in their lungs than what is expected for individuals with the same age and smoke status. Positive values correspond to the inverse situation. Fig. 1b represents its spatial distribution, as well as the monitoring network in the city and neighbouring municipalities. It can be seen in this figure that the highest positive values of the standardised pulmonary black carbon were observed in the peripheral region of the city.

The observed values of the index of environmental exposure misclassification (IEEM) ranged from −0.94 to 0.88, mean equal to 0.00 (standard deviation = 0.42) and its distribution is represented in Fig. 3.

The scatterplots of the standardised pulmonary black carbon and GeoSES and of the IEEM and GeoSES are depicted in Figs. 4 and 5, respectively. A decreasing trend can be observed in both graphs. In fact, the Pearson’s correlation coefficient between the standardised black carbon and GeoSES is $r = -0.127$) ($p = 0.0017$) and between IEEM and GeoSES is $r = 0.261$ ($p < 0.0001$).

Table 2 summarises the fixed effects estimates obtained in the fitting of the multilevel regression model considering the IEEM as response variable. GeoSES and daily commuting have significant contribution to explain the IEEM. For individuals with the same daily commuting and the same street density around their residences, those with lower GeoSES tend to have a higher IEEM value. This means that the amounts of carbon in their lungs are greater than the expected when considering the estimated PM_{10} concentrations obtained from the monitoring network for the regions close to their home. The index also tends to increase with the increase in daily commuting hours, keeping the other predictors constant. The street density does not have significant contribution to explain the index. The estimate of the variance of the random effects is 0.071, that is significant ($p < 0.0001$). The residual analysis did not indicate gross deviations from the model assumptions.

Variable	Mean	StDev	Minimum	Median	Maximum	IQR	N	%
Age (years)	68.6	15.1	19	69	110	23		
Sex (Male)							319	52.8
GeoSES	−0.24	0.36	−1	−0.31	1	0.48		
Years living in São Paulo	49.3	20.7	0.08	50	103	22.8		
Proportion of lifespan living in São Paulo	0.73	0.28	0.001	0.76	1	0.41		
Daily commuting (hours)	1.8	2.6	0	1	12	2		
Smoker or former smoker							312	51.6
ETS at home							197	32.6
Black carbon fraction	0.20	0.14	0.001	0.181	0.696	0.193		
Street density (m/m^2)	0.02	0.01	0.00	0.02	0.04	0.01		
PM_{10} (μg/m^3)	34.4	0.91	30.5	34.5	39.2	1.1		

StDev: standard deviation; IQR: interquartile range; GeoSES: socioeconomic index; ETS: environmental tobacco smoke exposure; Street density: street density in a buffer of 100 m around home.

Table 1: **Descriptive summary of the variables evaluated in the 604 deceased who underwent autopsy and environmental factors.**

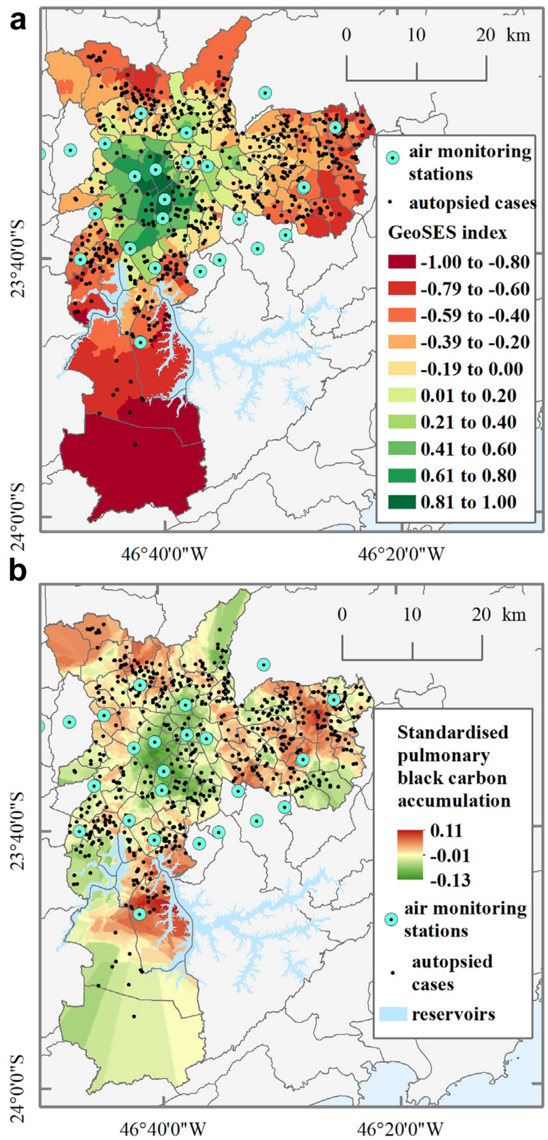

Fig. 1: a) Spatial distribution of the GeoSES index in São Paulo; b) Spatial distribution of the standardised pulmonary black carbon in São Paulo city and the 25 monitoring stations in the metropolitan area of São Paulo (MASP).

Discussion

In our study, we assessed lifetime exposure to ambient particles by determining the amount of accumulation of black carbon in the pleural tissue of deceased individuals living in São Paulo. Data obtained for each individual was plotted in the site of their residence. We observed that the higher levels of accumulation were observed in individuals residing in the most peripheral areas after adjustment for age, residence time in the city and smoking. When these data are plotted on maps, we observed a clear overlap of higher particulate air pollution burden of exposure and lower socioeconomic context, using the GeoSES index. Our findings corroborated with previous studies[15] and indicate that those living in the areas of São Paulo with lower socioeconomic levels are exposed to higher concentration of airborne particulate pollutants. The comparison between the measures of pleural black carbon accumulation and the long-term estimate particle at local of residence (based on São Paulo's fixed air pollution monitoring stations) disclosed a non-random misclassification. Briefly, individuals living in the more economically deprived areas of the city have a greater accumulation than that would be expected by the conventional air pollution fixed stations and vice versa. These findings support the concept that daily commuting and socioeconomic factors are important sources of exposure misclassification. Indeed, the previous literature using personal monitors confirm that the levels of air pollution inside traffic corridors are substantially higher than citywide average.[7,33] Thus, our results which were based in pleural black carbon accumulation – a long term process – are in agreement with those based on personal monitors, providing further evidence to the concept that time spent in traffic is an important determinant of air pollution exposure in the urban scenario.

Different studies highlighted that there is a large degree of variability between exposure assessed by ambient PM concentration and personal exposure, indicating that ambient concentrations measured by fixed monitoring station data near residence is not a good surrogate. In this context Gouveia et al.[17] pointed out for the necessity for studies with a better exposure assessment to quantify the exposure bias in Latin America. Boomhower et al.[34] conducted a meta-analysis to determine source of bias in epidemiological studies related to short term exposure assessment to $PM_{2.5}$, and they found that there is a potential exposure misclassification when ambient measurements of $PM_{2.5}$ are used as a surrogate estimate for individual exposure. Moreover, they point out that there is a large heterogeneity in concentrations between individual ambient $PM_{2.5}$ exposures, indicating the importance of considering variables that modify exposures such as tobacco use, season, occupational activity, daily mobility, and others. A recent meta-analysis conducted by Chen et al.[8] examined personal-ambient variability in black-carbon concentrations e demonstrated moderate correlations between ambient and personal exposures.

Unfortunately, we do not have data to explore if street density has an interaction with poor housing. It is plausible the precarious constructions as those that exist in urban slums are, theoretically more permeable to outdoor air toxicants.[35] A recent study conducted by Lu[36] also found that exposure assessed by residential levels underestimated by 13% (range 5–22%) the real exposure. He found that exposure estimation misclassification is strongly influenced by particle concentrations

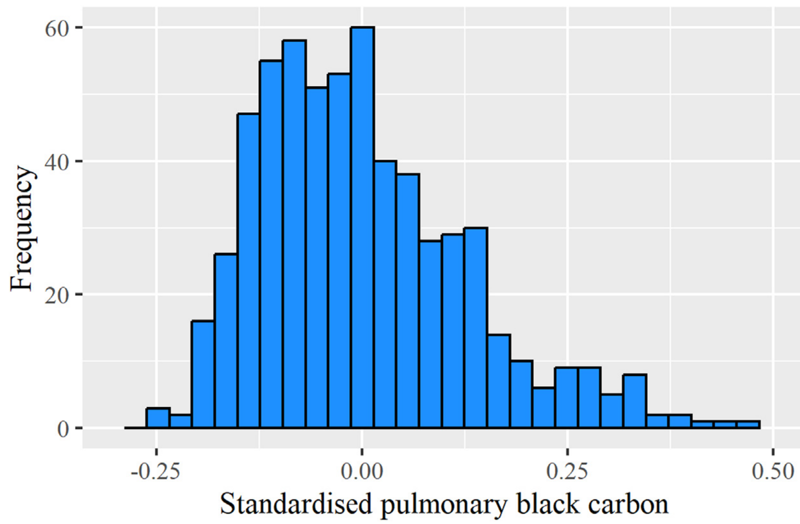

Fig. 2: Histogram of the standardised pulmonary black carbon.

and time spent at residence and workplace, and mobility.

Using personal monitors to determine individual exposure to air pollutants, Manojkumar et al.[37] showed that the period of the day, location in the city, and way of commuting, time spent in traffic influence exposure dose to air pollutants. The importance of mobility activities as modulator of air pollution load was previously demonstrated in an autopsy study with 413 deceased conducted in São Paulo,[22] showing that the amount of black carbon retained in pulmonary tissue is significantly modified by routine commuting profile. In fact, poverty and longer commuting hours are highly correlated,[38] due the spatial disconnection between the low-income areas with high job opportunities from sites with more affordable housing.

Our study has limitations that need to be clearly exposed. First, we used the network of air pollution monitoring that exists in São Paulo, which has a lower spatial density of stations in the less privileged parts of the city. Such situation may implicate that the precision of the estimates based on fixed stations does not have the same spatial precision. We did not have ways of avoiding this question which is structural of São Paulo and mirrors as well all the general uneven distribution of several urban equipment – health, housing, education – presented by the Municipality. We also did not have information on the type of solid fuels indoors. Although

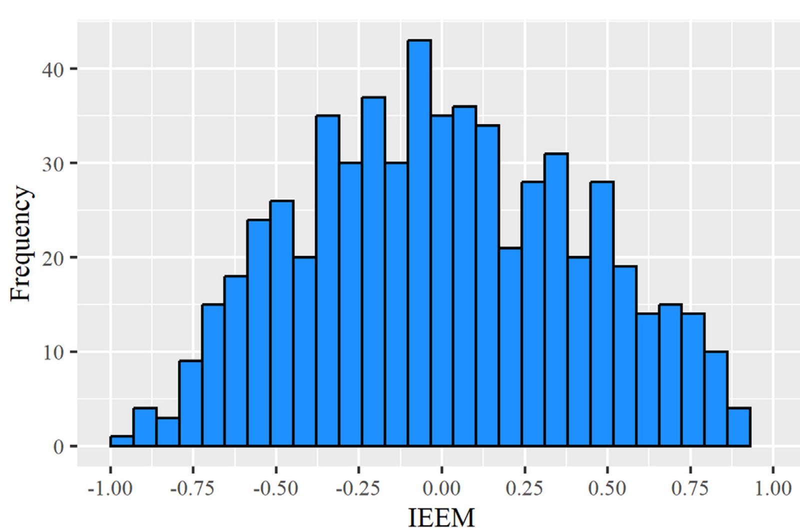

Fig. 3: Histogram of the index of environmental exposure misclassification (IEEM).

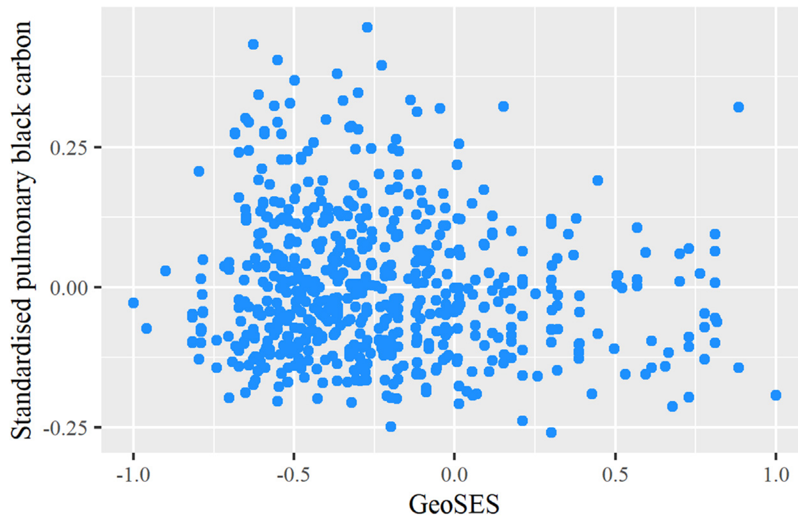

Fig. 4: Scatterplot of the standardised pulmonary black carbon and the socioeconomic index (GeoSES).

it is expected that woodstoves may be more frequently used in poorer areas, this probably did not interfere significantly with our findings, since its use in the urban areas is not frequent in Brazil.[39] However, it was empirically observed that during COVID-19 pandemic, due to its economic consequences, the use of solid fuel has apparently increased, but no data are still available for São Paulo and, moreover, the period considered in this study is prior to that of the pandemic. We must stress that we did not measure the complex mixture of urban pollution in the lungs of our patients, but only black carbon, which represents a fraction of the fine mode urban particulates. Thus, our results did not capture other compounds such as organics particles and gaseous pollutants. Moreover, the interpolation method used to estimate the PM_{10} concentrations at deceased's residences from the fixed monitoring stations did not consider factors that affect the concentrations of PM_{10}, such as wind speed/direction and topographic conditions. We must stress also that the GeoSES is not an individual index, but an area-based measurement of social conditions. Finally, it was not possible to validate the misclassification environmental exposure index because we are not aware of other ways to assess individual long-term exposure to atmospheric particles.

The underestimation of the exposure to air pollution in the socioeconomically vulnerable population is a situation that may also occur in other South American urban conglomerates. Previous studies of our group also reported that poverty is significantly associated with

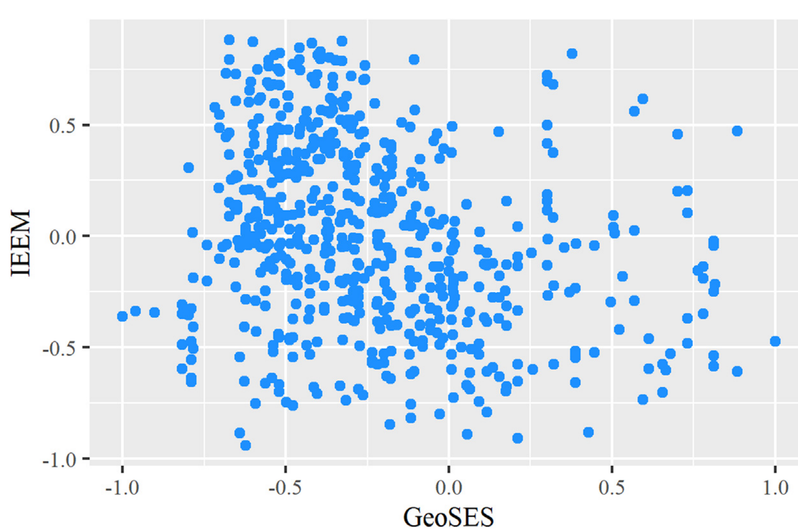

Fig. 5: Scatterplot of the index of environmental exposure misclassification (IEEM) and the socioeconomic index (GeoSES).

Term	Coefficient	Standard error	t-value	P-value
Intercept	−0.171	0.048	−3.591	0.00036
GeoSES	−0.277	0.053	−5.244	<0.0001
Daily commuting (hours)	0.022	0.005	4.205	<0.0001
Street density (m/m^2)	3.374	2.193	1.539	0.12

GeoSES: socioeconomic index; Street density: street density in a buffer of 100 m around home.

Table 2: **Fixed effects estimates obtained in the fitting of the multilevel regression model with IEEM as response variable and daily commuting, GeoSES, and street density as predictors.**

higher mortality rate due to chronic diseases.[20,40] The solutions for solving health consequences of the complex association between higher pollution exposure and higher health frailty are not easily obtained and demand integrated policies combining better access to health, improvement of housing conditions, more efficient mobility modes and more even jobs distribution in the urban territory.

Contributors
PHNS conceived the idea of the paper; JMS, CDSA, PAA, MMV, PHNS and LVB wrote the preliminary version; LVB created the maps and extracted the spatial variables; JMS, CDSA, FMMR performed the statistical analysis; MFA and PAA were responsible by the environmental monitoring data; MMV coordinated the anthracosis measurements; CDSA coordinated the application of the questionnaire; PAA took care of the data management; DW, AMV and GFG collaborated in obtaining the anthracosis measures. All authors contributed to shaping and finalizing the manuscript. All authors approved the manuscript submission.

Data sharing statement
The autopsy data used in this study are available from the São Paulo Death Verification Service (DVSSP). However, restrictions apply to the availability of these data, which were used with permission for the present study. Requests for the use of data must be made to the authors Ligia V Barrozo (lija@usp.br) or Carmen DS Andre (carmensaldiva@gmail.com) who will request permission to use the data.

Editor note
The Lancet Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

Declaration of interests
We declare no competing interests.

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References
1 Apte JS, Messier KP, Gani S, et al. High-resolution air pollution mapping with google street view cars: exploiting big data. *Environ Sci Technol*. 2017;51:6999–7008.
2 Jerrett M, Gale S, Kontgis C. Spatial modeling in environmental and public health research. *Int J Environ Res Publ Health*. 2010;7:1302–1329.
3 Santos UP, Garcia MLSB, Braga ALF, et al. Association between traffic air pollution and reduced forced vital capacity: a study using personal monitors for outdoor workers. Mutlu GM, editor *PLoS One*. 2016;11:e0163225.
4 Hoek G, Ranzi A, Alimehmeti I, et al. A review of exposure assessment methods for epidemiological studies of health effects related to industrially contaminated sites. *Epidemiol Prev*. 2018;42:21–36.
5 Nyhan MM, Kloog I, Britter R, Ratti C, Koutrakis P. Quantifying population exposure to air pollution using individual mobility patterns inferred from mobile phone data. *J Expo Sci Environ Epidemiol*. 2019;29:238–247.
6 Evangelopoulos D, Chatzidiakou L, Walton H, et al. Personal exposure to air pollution and respiratory health of COPD patients in London. *Eur Respir J*. 2021;58:2003432.
7 Yu YT, Xiang S, Li R, et al. Characterizing spatial variations of city-wide elevated PM10 and PM2.5 concentrations using taxi-based mobile monitoring. *Sci Total Environ*. 2022;829:154478.
8 Chen J, Jahn HJ, Sun HZ, et al. Validity of using ambient concentrations as surrogate exposures at the individual level for fine particle and black carbon: a systematic review and meta-analysis. *Environ Pollut*. 2022;312:120030.
9 Tayarani M, Rowangould G. Estimating exposure to fine particulate matter emissions from vehicle traffic: exposure misclassification and daily activity patterns in a large, sprawling region. *Environ Res*. 2020;182:108999.
10 Bautista-Hernández DA. Commuting inequality, role of urban structure, and identification of disadvantaged groups in the Mexico City metropolitan area. *J Transp Land Use*. 2020;13:159–183.
11 Lim S, Bassey E, Bos B, et al. Comparing human exposure to fine particulate matter in low and high-income countries: a systematic review of studies measuring personal PM2.5 exposure. *Sci Total Environ*. 2022;833:155207.
12 Payne-Sturges D, Gee GC, Crowder K, et al. Workshop Summary: connecting social and environmental factors to measure and track environmental health disparities. *Environ Res*. 2006;102:146–153.
13 Hajat A, MacLehose RF, Rosofsky A, Walker KD, Clougherty JE. Confounding by socioeconomic status in epidemiological studies of air pollution and health: challenges and opportunities. *Environ Health Perspect*. 2021;129:065001.
14 Brulle RJ, Pellow DN. Environmental justice: human health and environmental inequalities. *Annu Rev Public Health*. 2006;27:103–124.
15 Clougherty JE, Humphrey JL, Kinnee EJ, Remigio R, Sheffield PE. What is “socioeconomic position (SEP),” and How might it modify air pollution-health associations? Cohering findings, identifying challenges, and disentangling effects of SEP and race in US city settings. *Curr Environ Heal Rep*. 2022;9:355–365.
16 Hajat A, Hsia C, O’Neill MS. Socioeconomic disparities and air pollution exposure: a global review. *Curr Environ Heal Rep*. 2015;2:440–450.
17 Gouveia N, Slovic AD, Kanai CM, Soriano L. Air pollution and environmental justice in Latin America: where are we and How can we move forward? *Curr Environ Heal Rep*. 2022;9:152–164.
18 de Fathima M, de Miranda RM, Fornaro A, et al. Vehicle emissions and PM2.5 mass concentrations in six Brazilian cities. *Air Qual Atmos Heal*. 2012;5:79–88.
19 Nogueira T, Kamigauti LY, Pereira GM, et al. Evolution of vehicle emission factors in a megacity affected by extensive biofuel use: results of tunnel measurements in São Paulo, Brazil. *Environ Sci Technol*. 2021;55:6677–6687.
20 Barrozo LV, Fornaciali M, André CDS, et al. GeoSES: a socioeconomic index for health and social research in Brazil. *PLoS One*. 2020;15:e0232074.
21 INRIX. Global traffic scorecard 2019. https://inrix.com/scorecard; 2019 [Accessed].
22 Takano APC, Justo LT, dos Santos NV, et al. Pleural anthracosis as an indicator of lifetime exposure to urban air pollution: an autopsy-based study in Sao Paulo. *Environ Res*. 2019;173:23–32.
23 Zeidberg LD, Prindle RA. The Nashville air pollution study. II. Pulmonary anthracosis as an index of air pollution. *Am J Public Heal Nations Heal*. 1963;53:185–199.
24 Brauer M, Avila-Casado C, Fortoul TI, Vedal S, Stevens B, Churg A. Air pollution and retained particles in the lung. *Environ Health Perspect*. 2001;109:1039–1043.
25 Auchincloss AH, Diez Roux AV, Brown DG, Raghunathan TE, Erdmann CA. Filling the gaps: spatial interpolation of residential

survey data in the estimation of neighborhood characteristics. *Epidemiology*. 2007;18:469–478.
26 Diez Roux AV. Mair C. Neighborhoods and health. *Ann N Y Acad Sci*. 2010;1186:125–145.
27 Cribari-Neto F, Zeileis A. Beta regression in R. *J Stat Softw*. 2010;34. http://www.jstatsoft.org/v34/i02/.
28 Pinheiro JC, Bates DM. *Mixed-effects models in S and S-Plus*. 3rd ed. New York: Springer; 2000.
29 Raudenbush SW, Bryk AS. Hierarchical linear models*: applications and data analysis methods*. 2nd ed. Sage Publications, Inc.; 2002.
30 Stram DO, Lee JW. Variance components testing in the longitudinal mixed effects model. *Biometrics*. 1994;50:1171–1177.
31 Singer JM, Rocha FMM, Nobre JS. Graphical tools for detecting departures from linear mixed model assumptions and some remedial measures. *Int Stat Rev*. 2017;85:290–324.
32 Team World Health Organization H and EO. *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: global update 2005, summary of risk assessment*. Geneva PP - Geneva: World Health Organization; 2005. https://apps.who.int/iris/handle/10665/69477.
33 Steinle S, Reis S, Sabel CE, et al. Personal exposure monitoring of PM2.5 in indoor and outdoor microenvironments. *Sci Total Environ*. 2015;508:383–394.
34 Boomhower SR, Long CM, Li W, Manidis TD, Bhatia A, Goodman JE. A review and analysis of personal and ambient PM2.5 measurements: implications for epidemiology studies. *Environ Res*. 2022;204:112019.
35 Braubach M, Savelsberg J, World Health Organization. *Social inequalities and their influence on housing risk factors and health: a data report based on the WHO LARES database/by Matthias Braubach and Jonas Salvesberg*. Copenhagen: WHO Regional Office for Europe; 2009:18.
36 Lu Y. Beyond air pollution at home: assessment of personal exposure to PM2.5 using activity-based travel demand model and low-cost air sensor network data. *Environ Res*. 2021;201:111549. Available from: https://www.sciencedirect.com/science/article/pii/S0013935121008434.
37 Manojkumar N, Monishraj M, Srimuruganandam B. Commuter exposure concentrations and inhalation doses in traffic and residential routes of Vellore city, India. *Atmos Pollut Res*. 2021;12:219–230.
38 Macedo M, Lotero L, Cardillo A, Menezes R, Barbosa H. Differences in the spatial landscape of urban mobility: gender and socioeconomic perspectives. *PLoS One*. 2022;17:e0260874.
39 Gioda A, Tonietto GB, de Leon AP. Exposição ao uso da lenha para cocção no Brasil e sua relação com os agravos à saúde da população. *Cien Saude Colet*. 2019;24:3079–3088.
40 Xu R, Zhao Q, Coelho MSZS, et al. Socioeconomic inequality in vulnerability to all-cause and cause-specific hospitalisation associated with temperature variability: a time-series study in 1814 Brazilian cities. *Lancet Planet Heal*. 2020;4:e566–e576.