Atmospheric Environment 127 (2016) 100–106

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Indoor-to-outdoor particle concentration ratio model for human exposure analysis

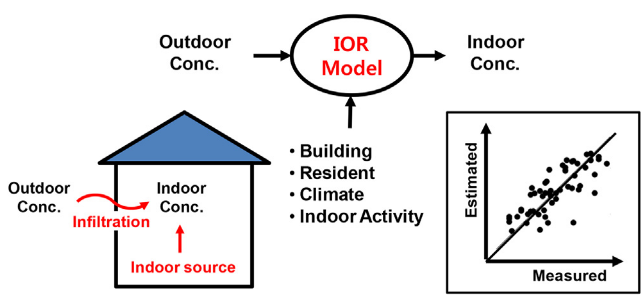
Jae Young Lee, Sung Hee Ryu, Gwangjae Lee, Gwi-Nam Bae*

Center for Environment, Health and Welfare Research, Korea Institute of Science and Technology (KIST), Seoul, South Korea

HIGHLIGHTS

- Concentrations of particulate matter were measured in 16 homes in Seoul, South Korea.
- A model for the indoor-to-outdoor particle concentration ratio (IOR) was developed.
- Multi-step multivariate linear regression analysis was performed to develop the model.
- Temperature and floor level were found to be powerful predictors of the IOR.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form
14 November 2015
Accepted 7 December 2015
Available online 12 December 2015

Keywords:
Particulate matter
Indoor-to-outdoor ratio
Infiltration
Modeling
Regression analysis
Exposure analysis

ABSTRACT

This study presents an indoor-to-outdoor particle concentration ratio (IOR) model for improved estimates of indoor exposure levels. This model is useful in epidemiological studies with large population, because sampling indoor pollutants in all participants' house is often necessary but impractical. As a part of a study examining the association between air pollutants and atopic dermatitis in children, 16 parents agreed to measure the indoor and outdoor PM_{10} and $PM_{2.5}$ concentrations at their homes for 48 h. Correlation analysis and multi-step multivariate linear regression analysis was performed to develop the IOR model. Temperature and floor level were found to be powerful predictors of the IOR. Despite the simplicity of the model, it demonstrated high accuracy in terms of the root mean square error (RMSE). Especially for long-term IOR estimations, the RMSE was as low as 0.064 and 0.063 for PM_{10} and $PM_{2.5}$, respectively. When using a prediction model in an epidemiological study, understanding the consequence of the modeling error and justifying the use of the model is very important. In the last section, this paper discussed the impact of the modeling error and developed a novel methodology to justify the use of the model.

1. Introduction

In epidemiological studies, the level of the indoor air pollutants is the principal parameter for the assessment of the exposure to and the health effects of these pollutants, because people generally spend more than 85% of their time indoors (Klepeis et al., 2001; Wiley et al., 1991). However, because of the limited access to indoor environments in large population studies, outdoor air pollutant concentrations have often been used for the assessment of exposure, based on the assumption that the outdoor concentrations are the same as those indoors (Hwang and Lee, 2010;

* Corresponding author. Center for Environment, Health, and Welfare Research, Korea Institute of Science and Technology, 5, Hwarang-ro 14-gil, Seongbuk-gu, Seoul, 02792, South Korea.
E-mail address: gnbae@kist.re.kr (G.-N. Bae).

http://dx.doi.org/10.1016/j.atmosenv.2015.12.020
1352-2310/

Jalaludin et al., 2004; Jansen et al., 2003; McConnell et al., 1999; Pénard-Morand et al., 2010; Pope, 2000; Zanobetti et al., 2011). These previous studies have shown associations between the outdoor particulate matter (PM) concentrations and the adverse health effects, such as respiratory problems, cardiovascular disease, and atopic dermatitis. However, these associations could be underestimated because of the variations in the infiltration efficiency (F_{inf}) and the indoor sources within each microenvironment.

In an effort to deal with the uncertainty related to personal exposure to indoor air pollutants, some studies have developed infiltration prediction models to estimate the level of the indoor air pollutants. Various factors relating to the building, residents, climate, and the indoor activities have been studied as predictor candidates. Allen et al. (2003) reported that the season and the use of air cleaners were the major parameters affecting the predictions of F_{inf} from $PM_{2.5}$ measurements at 44 homes in Seattle, USA. Koenig et al. (2005) measured $PM_{2.5}$ levels at eight homes in Seattle, USA, and developed a prediction model for F_{inf}. The important predictors in their model were the type of residence, type of air cleaner, average outdoor temperature, and the average daily rainfall. In the study by Meng et al. (2009) $PM_{2.5}$ measurements at 374 homes in three cities in the USA were used to develop their prediction model. They found that air conditioner operation, fan operation, air exchange rate, and the outdoor temperature were associated with changes in F_{inf}. Hystad et al. (2009) measured outdoor and indoor $PM_{2.5}$ concentrations at 84 homes in Seattle, USA, and in Victoria, Canada. Based on their correlation analysis with seasonality, meteorology, and housing characteristic factors, a strong association between F_{inf} and the season (non-heating season vs. heating season) was found. Clark et al. (2010) studied F_{inf}, based on the $PM_{2.5}$ measurements of 60 homes in Toronto, Canada. These authors developed multivariate models to predict F_{inf}, based on housing and meteorological variables. In their model, the air exchange rate, age of the home, use of air conditioning for more than 30 days/year, use of forced air heating, and use of a wood-burning fireplace were the major predictors in determining F_{inf}. Allen et al. (2012) measured the indoor and outdoor concentrations of sulfur at 353 homes and developed a model to predict residential F_{inf}. In the effort to generalize their prediction model, their studies focused on six major cities in the USA. Their findings indicated that F_{inf} was greater during the warm season and the frequencies of air conditioning and window opening were the most important predictors during the warm season.

In this study, an indoor-to-outdoor ratio (IOR) model was developed, using multi-step multivariate linear regression analysis, based on $PM_{2.5}$ and PM_{10} measurements at 16 homes in Seoul, South Korea. Unlike previous studies, we decided to model IOR instead of F_{inf} in order to accommodate the indoor pollutant sources in the model. This study is important in three respects. First, it is the first study to develop an IOR model in a city, where high-rise apartments are the prevailing form of residence. As a result, this paper was able to discover and present the relationship between IOR and the floor level, which no previous work had done before. This finding will be interesting to many people living in cities with lots of high-rise residences such as Beijing, Tokyo, Hong Kong, New York and so on. Second, it performed a comprehensive association study of the IOR by considering various predictor candidates (15 candidates in total) in all four major categories, which are environment, building, resident, and indoor activity (see the Methods section for the details). The candidates in these categories have been studied before in part or in full, as reported in the literature (Barn et al., 2008; Chan et al., 2005; Chao and Tung, 2001; Hänninen et al., 2005; Janssen et al., 2002; Meng et al., 2005; Sherman and Dickerhoff, 1998; Thornburg et al., 2001; Wallace and Williams, 2005). Third, it is the first study to provide an in-depth discussion on the model error. It presents how the model error decreased when the model was used for longer-term IOR estimations. In addition, the study discussed how the model error affected the results of an association study and how the model could be validated. This is very important when using a prediction model in an epidemiological study, but no previous work has discussed this before. The model and the discussion presented in this study could be used directly for other Asian cities with similar housing and weather conditions. The methodology for the modeling and analysis to provide better exposure assessments is applicable, regardless of the region or the pollutant.

2. Methods

2.1. Sample selection

The ANGEL study, involving more than 150 children, was devised to investigate the association between air pollutants and atopic dermatitis (Kim et al., 2013; Lee et al., 2014a). It was not practicable to measure the concentrations of the indoor air pollutants within the residences of all the participants; however, 16 parents volunteered to measure the indoor and outdoor air pollutant concentrations at their homes. The 16 residential homes selected as the pollutant sampling sites were all located in Seoul, South Korea.

2.2. Indoor and outdoor PM measurement

To measure indoor PM concentrations in residential homes, a portable aerosol spectrometer (Grimm Technologies 1.109, Germany) was placed on an experimental tray, 1 m above the floor. The experimental tray was positioned between the living room and the kitchen, where people spent most of their time. The portable aerosol spectrometer reported real-time concentrations of PM_{10} and $PM_{2.5}$ at 1-min intervals. The detection limit is less than 0.01 $\mu g/m^3$ and the standard deviations of the measurements are less than 2%. At each home, the outdoor measurements were taken synchronously with the indoor measurements, using the same type of portable aerosol spectrometer. The outputs of these two spectrometers were cross-validated prior to the synchronous measurements. The outdoor measurements were conducted on the balcony if the house type was a high-rise apartment or in the front yard if the house type was a low-rise building. The measurements of PM concentration were conducted over 48 h at each home from November 19, 2013 to December 4, 2014 (except for Home 3, where measurements were performed for only 24 h due to the request of the residents). The details of the measurement dates are summarized in Table S1 in the Supporting Information.

2.3. Data collection

During the measurement period (48 h), the occupants reported the starting and finishing times of indoor activities conducted at the residence in a logging sheet, such as cleaning and cooking, and the opening of windows and doors. In addition, information regarding the housing and residents, such as home type, home age, size, floor level, stove and ventilation types, the number of occupants, the number of smokers, and the presence of pets were reported by the occupants. Meteorological parameters, such as the average temperature, relative humidity, wind speed, and precipitation of Seoul (measured by the sole and official station located in the center of Seoul) during the measurement period were obtained from the Korea Meteorological Administration. Then, these environmental and residential characteristics (15 variables in total) were used as predictor candidates for the correlation and