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Evaluation of PM_{10}, CO_2, airborne bacteria, TVOCs, and formaldehyde in facilities for susceptible populations in South Korea☆

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Poor indoor air quality can have adverse effects on human health, especially in susceptible populations; however, few studies have measured multiple pollutants in facilities for susceptible populations at a national scale in South Korea. Therefore, we measured the concentrations of indoor pollutants (fine particulate matter (PM_{10}), CO_2, airborne bacteria (AB), total volatile organic compounds (TVOCs), and formaldehyde) to determine their possible relation to other indoor environmental factors and characteristics of facilities with susceptible populations, such as hospitals, geriatric hospitals, elderly care facilities, and postnatal care centers throughout South Korea. Indoor pollutants were sampled at 82 indoor facilities, including 62 facilities for susceptible populations. Spearman's correlation, Kruskal–Wallis, and Mann–Whitney analyses were used to examine the relationship among and differences between pollutants at indoor facilities and indoor/outdoor differences in PM_{10} concentration. There were significant correlations between indoor temperature and AB concentration ($r = 0.37$, $p < 0.01$), TVOCs, and formaldehyde ($r = 0.264$, $p < 0.01$). Indoor PM_{10} concentrations were higher than outdoor concentrations at all facilities for susceptible populations ($p < 0.01$). CO_2 might be a good indicator for predicting indoor pollutants when categorized into two levels ($\leq$750 ppm and >750 ppm). The hazard quotient of formaldehyde was higher than the acceptable level of 1 for children under the age of eight in postnatal care centers, indicative of unsafe levels. Therefore, more depth study for exposure characteristics of formaldehyde and indoor air quality (IAQ) in postnatal care facilities as a national scale is needed for finding the children exposure levels.

1. Introduction

Indoor air quality (IAQ) is a multi-disciplinary issue that is determined by the many pathways by which chemical, biological, and physical contaminants eventually become a part of the total indoor air mass (Tham, 2016). Indoor air pollutants regulated in Korea include particulate matter $(PM)_{10}$, CO_2, airborne bacteria (AB), total volatile organic compounds (TVOCs), and formaldehyde, as included in the present study, as well as nitrogen dioxide, radon, asbestos, and ozone (Ministry of Environment, 2015). The World Health Organization (WHO) and others have suggested that the adverse health effects associated with exposure to biological and chemical agents such as AB and TVOCs may include respiratory symptoms, allergies, sensory irritation, and asthma (Madureira et al., 2016; Tham, 2016). In particular, PM_{10} and formaldehyde are classified as carcinogenic agents that can cause lung cancer under chronic exposure (USEPA, 2016; WHO, 2013).

Since May 2004, the Ministry of Environment in South Korea has controlled and maintained the IAQ in indoor facilities, including facilities for susceptible populations, to protect the health of young and elderly populations from the effects of indoor environmental pollutants. In such indoor facilities, it is essential to know the concentrations and distributions of indoor air pollutants to conduct appropriate interventions to protect sensitive populations from exposure to indoor air pollutants (Hwang et al., 2017a). Susceptible

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populations typically include patients, the elderly, and pregnant women as being the most vulnerable to the effects of indoor air pollutant exposure, even at low concentrations, due to their reduced immunological defenses and multiple underlying chronic diseases in the case of older patients (Mendes et al., 2015). Moreover, such people typically spend a larger proportion of their time (19–20 h/day) indoors compared to the general population (WHO, 2003). In addition, children have a greater susceptibility to air pollutants than adults because of the higher amount of air inhaled per unit of body (Mendell and Heath, 2005). Although recent studies have assessed public facilities such as subway stations (Kwon et al., 2015; Martins et al., 2015), office buildings (Kabrein et al., 2017; Quang et al., 2012), houses (Masih et al., 2017; Shao et al., 2013), schools (Madureira et al., 2016; Yang et al., 2015), few studies have evaluated the IAQ of multiple indoor pollutants at the same time in facilities for susceptible populations at a national scale. As such, research on the IAQ of facilities for susceptible populations is as or perhaps more important than that of other public spaces.

We hypothesize that first of all, there are different exposure levels of indoor pollutants such as PM_{10}, CO_2, AB, TVOCs, and formaldehyde between susceptible populations in facilities (hospitals, geriatric hospitals, elderly care facilities, and postnatal care centers) and general populations because these pollutants are influenced by indoor environmental conditions such as temperature, relative humidity (RH), season, and facility type. Second, indoor concentrations of CO_2 will be predictive of IAQ conditions for indoor pollutants. Third, health risk assessment of formaldehyde will different effect even the same amount of concentrations by children and adult female because children are one of the population groups most susceptible to health risks in the sense of small size and weight.

Therefore, the purpose of this study was to measure the concentrations of PM_{10}, CO_2, AB, TVOCs, and formaldehyde in multi-facilities, including facilities for susceptible populations, such as hospitals, geriatric hospitals, elderly care facilities, and postnatal care centers throughout South Korea to evaluate potential indoor environmental factors and characteristics of facilities for susceptible populations that might influence the IAQ of such facilities, including temperature, RH, season, and facility type. CO_2 concentration is a basic parameter used in management of fresh air supply (Šenitková and Bučáková, 2005). Thus, when considering both high concentrations of CO_2 we divided between the locations with CO_2 concentrations ≥750 ppm and <750 ppm based on limits recommended for sensitive groups because this threshold was based on concentrations designated as unhealthy for sensitive individuals (Pickett and Bell, 2011). In addition, we applied a health risk assessment methodology to evaluate the intake and toxicological risk of formaldehyde in children and adults by age.

2. Methods

2.1. Indoor-facility types and characteristics

This study was conducted at 82 indoor-facilities, including four types of facilities for susceptible populations, which included 23 hospitals, and 36 geriatric hospitals and elderly care facilities, and 3 postnatal care centers in South Korea. A survey and checklist were completed for each indoor facility to gather basic information, such as indoor facility type, sampling location, region, and type of ventilation system (Table 1). Fig. 1 summarizes the distribution of the multi-facilities and number of samples in South Korea.

2.2. Sampling and analysis

All indoor pollutants (PM_{10}, CO_2, AB, TVOC, and formaldehyde) were sampled between February 2014 and October 2015, with a total of 281 samples for all five pollutants. We conducted sampling started from 10:00 AM in the morning for five pollutants with the five set of sampling device at the centers of lobbies, hallways, and indoor rooms at the same time in each place with at least more than two samples of each pollution in facilities. Sampling times were 6 h for PM_{10}, 1 h for CO_2, 4 min for AB, at intervals of 30 min during a 60 min period for TVOC and formaldehyde, respectively. During the sampling period, all samples were collected 1–1.5 m above floor level. Table 2 summarizes the devices and conditions used to sample each pollutant.

The PM_{10} sampler (SARA-4100; KEMIK Corp., Korea) assessed PM levels based on the gravimetrical method (NIOSH, 1998). The indoor temperature and RH of the indoor facilities were measured at the same time. AB were sampled using a microbial one-stage Buck Bio-Culture sampler (Model B30120; A.P. Buck Inc., USA) on nutrient media in Petri dishes placed on an impactor. Tryptic soy agar was used as the culture medium for AB, which were incubated at 35 °C for 48 h (ACGIH, 1999). Formaldehyde sampling was conducted with a 2,4-dinitrophenylhydrazine cartridge and a MP-Σ100 pump (SIBATA Scientific Technology Ltd., Japan). The formaldehyde sampler was placed 1 m from the building wall. After sampling, formaldehyde was extracted from the cartridges using 5 mL of acetonitrile. The extract was analyzed with a high-performance liquid chromatography system equipped with a UV-VIS detector. TVOC levels were measured with Tenax-TA tubes using an air sampler (MP-Σ30; SIBATA Scientific Technology Ltd., Japan) at the same sampling point and time as the formaldehyde sampler. TVOC samples were thermally desorbed and TVOCs were quantified via gas chromatography.

2.3. Health risk assessment

We assessed the impact on children and adult female health exposure to formaldehyde via the inhalation pathway (i.e., the primary route of exposure) based on the formaldehyde concentration data. Formaldehyde dose rates were calculated using Eq. (1), which has been validated previously (Castro et al., 2011; Fonseca et al., 2014; Madureira et al., 2016):

$$D = (BR_{WA} / BW) \times C_{WA} \times OF \times N \quad (1)$$

where D represents the age-specific dose rate (mg kg^{-1} day); BR_{WA} is the age-specific weighted average breathing rate (L min^{-1}); BW is the age-specific body weight (kg); C_{WA} is the weighted average formaldehyde level (μg m^{-3}); OF is the occupancy factor (assumed to be 1); and N is the total times per day spent by age-specific individuals (min day^{-1}). The main daily residence times of children and adults were recorded and analyzed. The BR_{WA} is characterized by the intensity of the activity practiced at the time of exposure.

Regarding non-carcinogenic risks, the estimated RfD of formaldehyde was derived from the Office of Environmental Health Hazard Assessment (2014) as a health-based formaldehyde-exposure indicator with a limit of 9 μg m^{-3} day.

$$HQ = D / RfD \quad (2)$$

If HQ > 1, there is a possibility that some non-cancer effects may occur.

2.4. Statistical analysis

Non-parametric analyses were used to test for relationships