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Method Article

Field-based longitudinal study design for measuring the association between indoor air quality and occupant health status in residential buildings

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ABSTRACT

There has been a growing interest in the association between indoor air quality (IAQ) with an increase in the time spent at home. However, there is still a lack of evidence on the impact of IAQ on occupants' health and well-being in the long term. This study aimed to develop a field-based longitudinal study design to evaluate the IAQ level and daily symptoms of adults and children living in different types of buildings over one year. We proposed vital principles to be considered when recruiting the study participants so that potential confounders, such as age, underlying diseases, and the geographic area would be either removed in advance or matched between different building types. We suggested collecting exposure and outcome data in three categories: lifestyle and housing environment, IAQ measurement, and occupants' health. We presented web-based survey tools for collecting housing and health data, and the frequency of data collection varied from weekly to six-month intervals. We developed two different models using a generalized mixed model for modeling the association between housing environment, IAQ, and human health. The current study design could be applied for future studies on the association between built environment and health, regardless of the type of buildings.

- A real-time indoor air quality monitor was used to monitor indoor air parameters every 5 mins over one year.
- A simple web-based survey tool was developed to collect data for occupants' daily symptoms in the long term.
- A binomial generalized linear mixed model and a Poisson generalized linear mixed model was developed to evaluate the association between indoor air parameters, and building types and daily symptoms.

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Method details

We conducted a longitudinal study of panels in two types of buildings (energy-efficient homes and conventional apartments) traced over one year. In the previous study, we aimed to compare indoor air quality between different types of buildings after controlling seasonality and assess whether the built environment was associated with occupants' health [1]. This method could be applied to any buildings (e.g., energy-efficient buildings, green buildings, schools, or workplaces) and used for the association between IAQ-health in a single building or the purpose of comparison buildings.

Recruitment of study participants

The criteria for participating in the study should be carefully determined, considering potential confounders that may affect the IAQ and health. We propose the following principles for recruiting the study participants.

(1) Recruiting families with children (e.g., under 15 years of age) would increase the efficiency of the measurement. For example, rather than recruiting one adult and one child from different households, recruiting households with children under the age of 15 makes it easier to investigate the health impact in different population groups using the same exposure measurement data. Ideally, all members of the family could participate in the study. However, it would be feasible in terms of costs and ease of responding to the survey to have one representative adult and one representative child per family.
(2) The inclusion of vulnerable populations should be considered when investigating the health effects of the population. For example, indoor air quality is associated with an increased risk of people with allergic diseases, the elderly, housewives, and children who spend most of their time at home [2,3]. If the participants have allergic diseases, it is necessary to investigate the history of the doctor's diagnosis of allergic diseases, under what conditions they currently are, and whether they are currently undergoing treatment or not.
(3) Underlying diseases of adult participants should be identified in advance. For example, people with cardiovascular disease, cancer, and diabetes, etc., should be excluded from participating in the study. Since most of the elderly population has at least one of those underlying diseases, however, the age limit of the study participants should be carefully determined.
(4) Families living with pets are recommended to be excluded from participation in the study.
(5) When comparing IAQ and occupants' health in different buildings, it would be better to limit to the same geographic area since indoor air quality is influenced mainly by outdoor air quality [4].

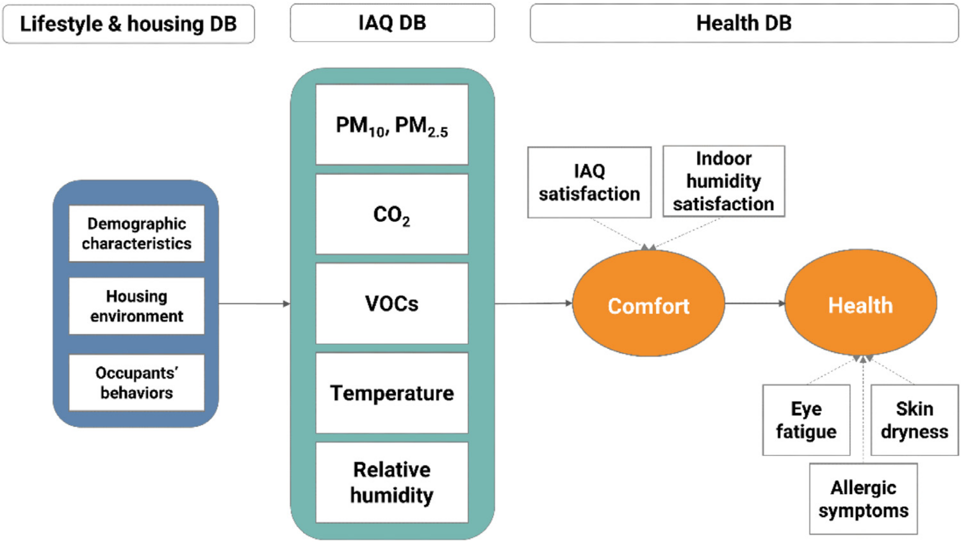

Fig. 1. Conceptual diagram of study design.
PM_{10}, $PM_{2.5}$: particulate matter; CO_2: carbon dioxide; VOCs: volatile organic compounds; IAQ: indoor air quality.

Data collection

Data collection methods are three-folds: occupants' lifestyle and housing, indoor air quality measurement, and occupants' health measurement (Fig. 1). Table 1 summarizes the list of variables, frequency of measurement, and measurement tools for collecting each database.

(1) Lifestyle & housing DB

a. Demographic characteristics
Data on the participants' demographic profiles, such as age, sex, job, household income, the number of family members, and home address, should be collected. Since the demographic characteristics of study participants do not change over time, these can be asked only once at the baseline (the 1st round) survey.

b. Housing environment
The housing environment is divided into three sub-categories: physical environment, indoor air characteristics, and proximity to roads and other sources of air pollution. Physical housing environment includes the year of building construction, residence period, exclusive private area, number of rooms, number of floors, heating system, and heating fuel. Indoor air sources include kitchen fuel, frequency of cooking activities during weekdays or weekends, and the use of insect repellent, air freshener, perfume, or hair spray. Proximity to roads and other sources of air pollution, such as the waste incinerator, plant, and bus terminal, which are likely to affect indoor air quality, should be included.

c. Occupant behaviors
Occupant behaviors include human behaviors that are relevant to improving the indoor air quality, such as the frequency of floor cleaning, use of vacuum cleaner with high-efficiency particulate air filter, frequency and duration of window ventilation, use of air cleaner, humidifier, and air conditioner, and use of kitchen hood while cooking. We propose measuring the occupant behaviors quarterly or at the 6-month interval, as the behaviors may vary by season.

Table 1
Data collection methods.

Database	Category	Sub-categories		Proposed frequency of measurements	Proposed measurement tool
Lifestyle & housing DB	Demographic characteristics	Demographic characteristics (adult)		6-month interval or quarterly	Paper- or web-based questionnaire
		Demographic characteristics (child)			
		Household demographic characteristics			
	Housing environment	Physical environment			
		Indoor air sources			
		Proximity to roads and other sources of air pollution			
	Occupants' behaviors	Behaviors related to IAQ improvement			
		Behaviors related to bad IAQ			
Indoor air quality DB	Indoor air parameters	PM10		24 h 7 days monitoring	Real-time IAQ monitor
		PM2.5			
		CO2			
		VOCs			
		Temperature			
		Relative humidity			
Health DB	Medical history	Medical history (adult)		6-month interval or quarterly	Paper- or web-based questionnaire
		Medical history (child)			
	Daily symptom	Adult	Time spent at home	Once a week	Web-based questionnaire
			Pain and discomfort		
			Allergic symptoms		
			Eye fatigue, skin dryness, headache		
			Cough		
			Satisfaction on sleep quality		
			Satisfaction on indoor air quality and indoor humidity		
		Child	Time spent at home		
			Allergic symptoms		
			Cough		

IAQ: Indoor air quality; VOCs: volatile organic compounds.

(2) Indoor air quality measurement

We propose using a real-time air quality monitoring device (AirGuard K, Kweather, Seoul, Korea), which measures indoor temperature, relative humidity, and indoor air parameters, including particulate matter (PM_{10}, $PM_{2.5}$), carbon dioxide (CO_2), and volatile organic compounds (VOCs) for every 5 min. It is a sensor-based device, with a relatively small size (width 81 mm height 190 mm) and therefore easy to install and manage. For VOCs, a total VOCs concentration was measured using a chemoresistive sensor and quantified as ethanol equivalent. The specifications of the AirGuard K are also shown in the Supplementary Table 1 of the original publication [1]. Using a handy and easy-to-install device is essential, especially when long-term IAQ monitoring is desired. All measurement data are transmitted to the database server so that both researchers and study participants could monitor the IAQ through mobile applications and the website. To standardize measurements, detailed instructions should be provided to participants to install the device in the living room where family members spend the most time, at the height of 1 m or more, and not move it during the study period. It is helpful to provide specific examples of where to avoid when installing the device, such as air conditioners, air purifiers, kitchens, bathrooms, and dressings.

(3) Occupants health measurement

a. Medical history

The medical history of study participants should be reviewed before and during the survey. Ideally, reviewing medical records is the most objective way; however, when access to medical records could not be acquired, study participants may be asked about their experience of doctor's diagnosis of diseases, under what conditions they currently are, and whether they are currently being treated or not.

b. Daily symptom

We developed a web-based questionnaire to ask the participants about their daily presence of relevant symptoms and routine lifestyle. The URL for access to the web survey can be sent via MMS or email on the same day of the week (e.g., every Monday) to collect the daily presence of symptoms in the previous week. Since the survey contains questions about daily symptoms assuming participants stayed home, those who did not stay at home for more than four days of the previous week may decline to respond. Type of symptoms includes allergic symptoms (e.g., allergic rhinitis, atopic dermatitis, and asthma) and other symptoms that could appear after exposure to harmful indoor air pollutants such as eye fatigue, skin dryness, headache, and cough [5,6]. This can be asked either in a binary format (Yes/No) or scoring the severity (0 to 2). The scale should be determined considering the time to complete the questionnaires. Also, we included the overall satisfaction on the indoor air quality, indoor humidity, and sleep quality of the previous week, measured by a 5-point Likert scale (5 – "Very satisfied" to 1 – "Very dissatisfied"). Daily lifestyles include the average hours spent at home and the average hours of sleep per time, which are essential variables to be included in the statistical analysis. Detailed questionnaires are provided in the Supplementary Material.

A web-based questionnaire has advantages over a paper-based questionnaire in terms of coding and managing databases, particularly when the survey questions are relatively simple and repeatedly applied over a long-term period. Also, the response rate can be improved by monitoring the submission status and sending reminders immediately. Monetary incentives could be provided to study participants differently according to their response rate.

Statistical analysis

To investigate the complex interactions between housing environment, IAQ, and human health, we developed two different models rather than include all variables of interest into a single model.

We propose using a binomial GLMM model (Model 1) to examine the effects of IAQ on different symptoms, with each of the symptoms as a dependent variable. The binomial distribution was selected because each of the symptoms was measured by a presence/absence format. Model 1 was fitted with fixed effects of age, sex, each of indoor air parameters (PM_{10}, $PM_{2.5}$, CO_2, VOCs), indoor temperature and relative humidity, day of the week and average hours spent at home, and random effects of each participant and survey week. The results would be presented as a odds ratio (OR) and the percent change in risk, which is calculated using the regression coefficient. Non-linear associations between indoor air parameters and the risk of symptom presence could be visualized using a binomial generalized additive mixed model (GAMM), with the same model structure as Model 1. The values could be interpreted as a percent change in risk by a unit change of indoor air parameters.

When assessing the difference in daily prevalence of symptoms between building types, we propose using a Poisson GLMM model (Model 2). Model 2 included fixed effects of building type, season, day of the week, and history of medical diagnosis of relevant diseases, and a random effect of survey week. The important difference of Model 2 from Model 1 was that a dependent variable was a daily sum of people who reported each of the symptoms, rather than the presence/absence of symptoms per individual, and therefore the total number of survey responses per day per building type was included as an offset. Relative risk (RR) would be calculated, and the value over one would be interpreted as higher prevalence in the building type of interest than the reference group.

We used R (version 4.0.3) for Windows all statistical analyses. R packages called 'lme4′ and 'mgcv' were used for developing GLMM and GAMM model respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2021.101426.

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