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Associations between ventilation and children's asthma and allergy in naturally ventilated Chinese homes

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Abstract

Building ventilation is important for occupants' health. There are few studies of associations between home ventilation and occupant's health in China. During 2013–2016, we measured ventilation in 399 homes in Tianjin and Cangzhou, China, and surveyed the health history of children. Ventilation rates were measured using mass balance of occupant generated CO₂. The associations of home ventilation with children's asthma and allergy were analyzed in different strata of time and space. A low bedroom ventilation at night was significantly associated with an increased proportion of rhinitis among children (rhinitis current, adjusted odds ratio (AOR): 1.59; 95% confidence interval (CI): 1.01–2.49; diagnosed rhinitis, AOR: 3.02 (1.16–7.89)). Our findings suggest a dose-response relationship between ventilation rate at night in children's bedrooms and rhinitis current. The night-time ventilation rate in bedrooms has a greater association with rhinitis than the whole home ventilation rate during daytime.

KEYWORDS

allergy, children, CO₂, home, natural ventilation, rhinitis

1 | INTRODUCTION

Indoor air contains a wide range of pollutants that are often not present in the outdoor air but are emitted by indoor sources. These indoor air pollutants impact occupants' health.^{1–3} To remove or dilute indoor pollutants, ventilation with outdoor air is necessary.^{4–6} Building ventilation has long been recognized for its role in occupant health and comfort. Ventilation standards are usually written in the form of minimum requirements.⁷ The recommended minimum ventilation rate mainly aims to remove odors produced by building occupants, rather than directly addressing occupants' health.⁸ Accordingly, meeting the minimum ventilation rates is not always sufficient to adequately dilute all contaminants except for some bioeffluents. Moreover, in real life, indoor environments differ with respect to pollution loads so that it is difficult to set ventilation rates

that meet ventilation requirements for health in all kinds of indoor environments. However, scientific data can be used to examine whether occupants have more health problems if the outdoor air supply rate is below a certain level.

Scientific literature review concluded that low ventilation rates were associated with increased risk of sick building symptoms among occupants of office buildings⁹ and increased absenteeism and more respiratory symptoms among school students.^{5,10} Considering the evidence that ventilation in office buildings and schools affects health, similar or larger effects of ventilation in residences on health might be expected, because people spend more time at homes than in offices or schools.^{11–13} Moreover, the indoor environments of residences contain specific pollutants different from those in offices and schools, for example, house dust mites (HDM), a well-known risk factor for sensitization and allergic symptoms^{14,15}; tobacco

smoking; and pollutants from cooking. In homes, a study found that wheeze was decreased with the addition of mechanical ventilation.¹⁶ However, the number of studies that investigate potential associations between measurement-based home ventilation rates and health is sparse. All available quantitative studies of ventilation as related to health in homes, to the best of our knowledge, are listed in Table S1. Most of these studies were in Scandinavian countries.¹⁷⁻²³ The results are not fully consistent.⁵ Bornehag et al¹⁷ found that lower ventilation rates were associated with the risk of having asthma and allergic symptoms. Callesen et al¹⁸ found that among children with asthma, ventilation rates were significantly lower for those who were IgE-sensitized. Wang et al¹⁹ found significant association between ventilation rate and current asthma symptoms. Sun et al²⁰ found significant association between ventilation rate and mucosal symptoms. Other studies have not found associations between ventilation rate and health.²¹⁻²⁴ The ventilation modalities in most Chinese residences are infiltration and opening windows, rather than mechanical systems. The ventilation rates in Chinese residences are generally low.^{25,26} Moreover, indoor environmental exposures in China have changed dramatically in the past two decades due to profoundly rapid modernization and urbanization. High indoor pollution combined with low ventilation rates appears to be causing increased prevalences of health problems. It is important to study associations of home ventilation with health in China.

Previous studies have used a wide range of ventilation metrics. For example, ventilation rate can be expressed in volumetric airflow units such as L/s, sometimes normalized by the number of people in the space or the floor area. Ventilation also can be expressed as air change rate which is the volumetric airflow rate at which outdoor air enters the building divided by the building volume, expressed as h⁻¹.²⁷ In residences, ventilation rates have been measured in different locations, such as the whole home and a bedroom,²⁸ during different times, for example night²⁹ and one or more weeks.^{17,22} In previous studies (Table S1), there has been no clear information on which ventilation metrics are the most relevant in terms of associations with health outcomes. An inappropriate metric may cover up the association of ventilation with health. In discussing health-associated building ventilation, it is important to choose the most appropriate ventilation metric.

The aims of the present study are (a) to test the hypothesis that low ventilation rates in Chinese homes are associated with occupants' health; (b) to investigate the most relevant ventilation rate metrics for homes: measurement time, location, and units of ventilation rate.

2 | METHODS

From 2013 to 2016 in Tianjin, China, we performed a study of children's health and home environment as part of the CCHH (China, Children, Homes, Health) study. This study consisted of two phases.

Phase I (May 2013-December 2014) was a cross-sectional questionnaire investigation involving 7865 children (response rate:

Practical Implications

- This study found that low ventilation rate was significantly and positively associated with rhinitis among children. Ventilation rate in the bedroom at night was a strong metric with regard to occupants' health.
- These findings emphasize that in investigations of associations between indoor environmental factors and health, the ventilation rate in bedrooms at night must be considered.
- Our data provide a reference for developing proper ventilation strategy and formulating ventilation regulations for residential buildings.

78%).³⁰ Questionnaires were sent to day-care centers and elementary schools. Parents with children 0-8 years old responded to the questionnaires, giving us self-reported information on children's asthma and allergy. Studies in several countries and areas have used the same questionnaire to investigate children's allergic diseases as related to the home environment.^{17,31-34}

Phase II (September 2013-January 2016) was a nested case-control investigation based on data obtained in Phase I on children's asthma and allergy. The cases were children with asthma and/or allergy, while controls were children without any allergic symptoms. Four hundred and ten (410) children (who did not move from or renovate homes in the last 12 months) in 399 homes were invited to participate. There were 325 apartments, 69 Pingfangs (a one-story house for a single family), and 5 villas. We inspected and made measurements on the indoor environment of these homes. The present paper is based on Phase II measurements.

2.1 | Questionnaires

We have described details of the questionnaire in another paper.³⁰ There are three groups of questions related to children's asthma and allergy:

- Asthma (Wheezing ever: "has your child ever had wheezing or whistling in the chest at any time in the past?" Wheezing current: "in the last 12 months has your child had wheezing or whistling in the chest?" Dry cough current: "in the last 12 months has your child had a dry cough at night for more than two weeks, apart from a cough associated with a cold or chest infection?" Diagnosed asthma: "has your child been diagnosed with asthma by a doctor?").
- Rhinitis (Rhinitis ever: "has your child ever had a problem with sneezing, or a runny, or a blocked nose when he/she did not have a cold or a flu?" Rhinitis current: "in the last 12 months has your child had a problem with sneezing, or a runny, or a blocked nose when he/she did not have a cold or the flu?" Diagnosed rhinitis:

"has your child been diagnosed with hay fever or allergic rhinitis by a doctor?").

- c. Eczema (Eczema ever: "has your child ever had an itchy rash coming and going for at least 6 months?" Eczema current: "in the last 12 months has your child had eczema symptoms at any time?" Diagnosed eczema: "has your child been diagnosed with eczema by a doctor?").

Questions on the home dampness indicators were about visible mold spot, damp spot, inferred invisible damp/mold problems on the ceiling/walls/floor, floor moisture, and flooding.

2.2 | Measurements of ventilation rate

Ventilation rates in the child's bedroom and whole home were measured using occupant produced CO₂ as the tracer gas. The concentrations of CO₂ in the living room, child's bedroom, and other bedrooms were continuously measured over 24 hours at one-minute intervals. Portable CO₂ monitors (AZ[®] 7798) that had an accuracy of 50 ppm ± 5% of reading were used to measure CO₂ concentrations. The CO₂ monitors were calibrated before measurement. We asked a family member to record the height and weight of occupants. We measured the volumes of each room. Ventilation rate was calculated based on analyses of CO₂ produced by occupants.^{26,35} Briefly, based on a mass conservation equation, an individual step increase of CO₂ concentration within time interval $\Delta\tau$ can be formulated as

$$\Delta C = (\Delta\tau/V) \cdot [F \cdot 10^6 - N \cdot V \cdot (C_1 - C_0)] \quad (1)$$

where ΔC is the unit concentration change (ppm), $\Delta\tau$ is the unit time interval (h), V is the volume of the zone (m³), F is the emission rate of CO₂ (m³/h), N is the ventilation rate (h⁻¹), C_1 is initial CO₂ concentration of time interval $\Delta\tau$ (ppm), and C_0 is outdoor CO₂ concentration (ppm).

We assumed an outdoor CO₂ concentration of 400 ppm. The CO₂ concentration at the end of the time interval (C_2) can be computed as a sum of the initial concentration (C_1) and the unit increase of concentration (ΔC). The calculation can be repeated for each successive time interval so that a theoretical exponential curve can be constructed. This theoretical curve is fitted to measured data using least squares. This iterating process gives the best fitting airflow and emission rates for CO₂. The process of error analysis is shown in the Methods S1, "Error analysis of ventilation rate". Ventilation rate measurements had errors of -17% to +26% due to the accuracy of CO₂ monitors and the assumed outdoor CO₂ concentration.

The whole residence was considered as a single zone when the difference between CO₂ concentrations in the living room and bedroom was <10%³⁶ or the CO₂ concentration in the living room and bedroom followed the same trend; that is, the bedroom had the same air change rate as the whole home. Otherwise, the investigated bedroom was considered as a separate zone, which may introduce uncertainty due to neglecting internal zone airflow. However, a previous study demonstrated that this uncertainty was <30%.²⁹

Volume-weighted average CO₂ concentration was used to calculate the ventilation rate of the whole home.

2.3 | Statistical analysis

We analyzed the association of ventilation with asthma and allergy. Several metrics were used to evaluate ventilation rate, with regard to location, time, and units: (a) Ventilation rate with units of h⁻¹ in the bedroom at night (VR-child-night, h⁻¹); (b) ventilation rate with units of L/s per person in the bedroom at night (VR-child-night, L/s per person); (c) ventilation rate with units of h⁻¹ in the home during the night (VR-home-night, h⁻¹); (d) ventilation rate with units of h⁻¹ in the home during daytime (VR-home-day, h⁻¹); (e) average CO₂ concentration in the bedroom during 0:00-7:00 (CO_{2avg}-child-night, ppm); and (f) peak CO₂ concentration in the bedroom during 0:00-7:00 (CO_{2peak}-child-night, ppm).

Logistic regression analyses were used to evaluate the association of children's asthma and allergy with ventilation rates. Potential confounders were determined a priori from literature review.^{26,30,37,38} Odds ratios for children's asthma and allergy were adjusted for the child's age, gender, family allergic history, home dampness, environmental tobacco smoke exposure, outdoor pollution (indicated by PM₁₀ concentrations, as shown in Table S2) and measurement seasons.

Ventilation metrics were examined as both a continuous and a categorical variable. In categorical analyses, median and/or quartile values were used as cut points to determine low versus high ventilation rate. Results were presented as adjusted odds ratios (AOR) supplemented with 95% confidence intervals (CI). We accepted P -value < 0.05 as statistically significant. All statistical analyses were performed with SPSS 20.0 software.

The Research Office at Tianjin University granted ethical approval for this study.

3 | RESULTS

We made measurements in 410 children's homes during the Phase II CCHH study in Tianjin and Cangzhou. Sixty-eight (68) children's homes were measured in spring, 73 in summer, 105 in autumn, and 164 in winter. Missing values due to no occupant in the home during the ventilation measurement period, or the children more than 8 years old, meant that the final analyses were of 374 children. Demographic information for the study population is shown in Table 1.

Table 2 summarizes sample sizes and statistical distribution of the ventilation measurements. For certain homes, information on height/weight of occupants or occupancy level during daytime is missing. The descriptive statistics for ventilation measurements are limited to the number of observations shown in Table 2.

The proportions of asthma and allergy among children in the inspected homes are shown in Table 3 and Table S3. Investigated

TABLE 1 Demographics of the study population in the inspected homes in Tianjin area, China

Characteristics	n (%)
Children	
Age	
<3	56 (15.0)
3-6	244 (65.2)
7-8	74 (19.8)
Gender	
Male	179 (48.5)
Female	190 (51.5)
Family allergic history	
Yes	112 (30.9)
No	250 (69.1)
Environmental factors	
Dampness	
Yes	102 (28.6)
No	255 (71.4)
Environmental tobacco smoke exposure	
Yes	182 (47.9)
No	198 (52.1)

TABLE 3 Proportions of asthma and allergy among children in the inspected homes in Tianjin area, China

	n (%)
Asthma	
Wheeze ever	77 (21.3)
Wheeze current	45 (12.6)
Dry cough current	76 (20.9)
Diagnosed asthma	40 (11.1)
Rhinitis	
Rhinitis ever	212 (58.4)
Rhinitis current	176 (48.5)
Diagnosed rhinitis	65 (18.1)
Eczema	
Eczema ever	211 (57.3)
Eczema current	115 (31.8)
Diagnosed eczema	197 (54.6)

clear dose-response relationships between ventilation rates and children's rhinitis current (Figure 1). Ventilation rate (h^{-1}) analyzed as a continuous variable was strongly and negatively associated with children's rhinitis. The AORs associated with stepwise increments

TABLE 2 Statistical description of ventilation rates and CO_2 concentrations in Tianjin area homes

	Location	Time	Parameter	n	Percentile		
					25th	50th	75th
Ventilation rate	Child's bedroom	Night	VR-child-night, h^{-1}	374	0.21	0.37	0.70
		Night	VR-child-night, L/s per person	374	1.44	3.03	6.46
	Whole home	Night	VR-home-night, h^{-1}	374	0.20	0.32	0.60
		Daytime	VR-home-day, h^{-1}	346	0.42	0.76	1.34
CO_2 concentration	Child's bedroom	Night	$\text{CO}_{2\text{avg}}$ -child-night ^a ppm	374	803	1208	1734
		Night	$\text{CO}_{2\text{peak}}$ -child-night ^a ppm	374	959	1420	2097

^a CO_2 concentration, 0:00 AM-7:00 AM.

children were 0-8 years old. There was no significant difference in asthma and allergy between boys and girls. More asthma and allergy were reported among younger children or children with a family allergic history. Children living in homes with dampness indicators had more asthma and allergy, compared to those living in home with no dampness. The associations between ventilation and children's asthma and allergy were analyzed in logistic regression models, as shown in Table 4. Lower levels of ventilation rate were risk factors for rhinitis. When considering both the number of statistically significant positive associations and magnitudes of odds ratios, higher ventilation rates (h^{-1}) at night in children's bedrooms appeared to be most protective against rhinitis symptoms. Associations of children's asthma and allergy with inter-quartile values of ventilation rate (h^{-1}) in the child's bedroom at night were further analyzed and revealed

of ventilation rate ($\Delta = 0.1 \text{ h}^{-1}$) in the child's bedroom at night were 0.97 (95% CI: 0.94-1.00) for rhinitis ever, 0.97 (95% CI: 0.94-1.00) for rhinitis current, and 0.97 (95% CI: 0.91-1.03) for diagnosed rhinitis.

4 | DISCUSSION

In this paper, we have focused on the association of ventilation with occupants' health, using health data from a questionnaire survey and ventilation data from on-site measurements. The associations of home ventilation with children's asthma and allergy were analyzed in different strata of time (night and day) and place (bedroom and whole home).

Most previous studies of effects of ventilation on asthma and allergy in residences have been in Scandinavian countries.¹⁷⁻²³

TABLE 4 Adjusted odds ratios (95% Confidence Interval) of ventilation rate and CO₂ concentration for children's asthma and allergy in logistic regression models

	Adjusted odds ratios (95% CI) ^a					
	VR-child-night (h ⁻¹) ^b	VR-home-day (h ⁻¹) ^b	VR-home-night (h ⁻¹) ^b	VR-child-night (L/s per person) ^b	CO _{2avg} -child-night ^c	CO _{2peak} -child-night ^c
Wheeze ever ^d	0.62 (0.27, 1.41)	0.54 (0.23, 1.26)	0.53 (0.24, 1.19)	0.80 (0.35, 1.80)	0.39 (0.17, 1.01)	0.72 (0.32, 1.65)
Wheeze current	0.82 (0.40, 1.68)	0.66 (0.30, 1.46)	0.71 (0.35, 1.45)	1.14 (0.55, 2.36)	0.74 (0.36, 1.55)	1.07 (0.51, 2.26)
Dry cough current	1.07 (0.62, 1.85)	0.92 (0.52, 1.62)	1.05 (0.61, 1.81)	1.03 (0.60, 1.79)	0.79 (0.45, 1.38)	0.86 (0.49, 1.51)
Diagnosed asthma ^d	0.54 (0.17, 1.77)	0.76 (0.25, 2.31)	0.48 (0.16, 1.44)	0.69 (0.23, 2.08)	0.63 (0.21, 1.85)	0.87 (0.29, 2.62)
Rhinitis ever ^d	1.43 (0.74, 2.75)	0.66 (0.34, 1.29)	0.88 (0.46, 1.67)	1.09 (0.57, 2.09)	1.22 (0.63, 2.35)	1.69 (0.86, 3.33)
Rhinitis current	1.59 (1.01, 2.49)^e	1.33 (0.83, 2.12)	1.16 (0.74, 1.81)	0.85 (0.54, 1.34)	1.14 (0.72, 1.82)	1.39 (0.87, 2.21)
Diagnosed rhinitis ^d	3.02 (1.16, 7.89)	1.35 (0.56, 3.28)	2.26 (0.92, 5.56)	1.43 (0.59, 3.47)	1.01 (0.42, 2.42)	1.44 (0.58, 3.62)
Eczema ever ^d	0.81 (0.41, 1.62)	1.52 (0.76, 3.06)	0.93 (0.47, 1.81)	1.04 (0.52, 2.04)	0.94 (0.47, 1.87)	0.84 (0.41, 1.69)
Eczema current	0.67 (0.41, 1.11)	1.11 (0.66, 1.85)	0.58 (0.35, 1.01)	0.72 (0.44, 1.19)	0.68 (0.41, 1.14)	0.92 (0.55, 1.53)
Diagnosed eczema ^d	0.89 (0.46, 1.72)	0.91 (0.46, 1.79)	1.04 (0.54, 1.98)	0.73 (0.38, 1.43)	0.78 (0.40, 1.53)	0.66 (0.33, 1.30)

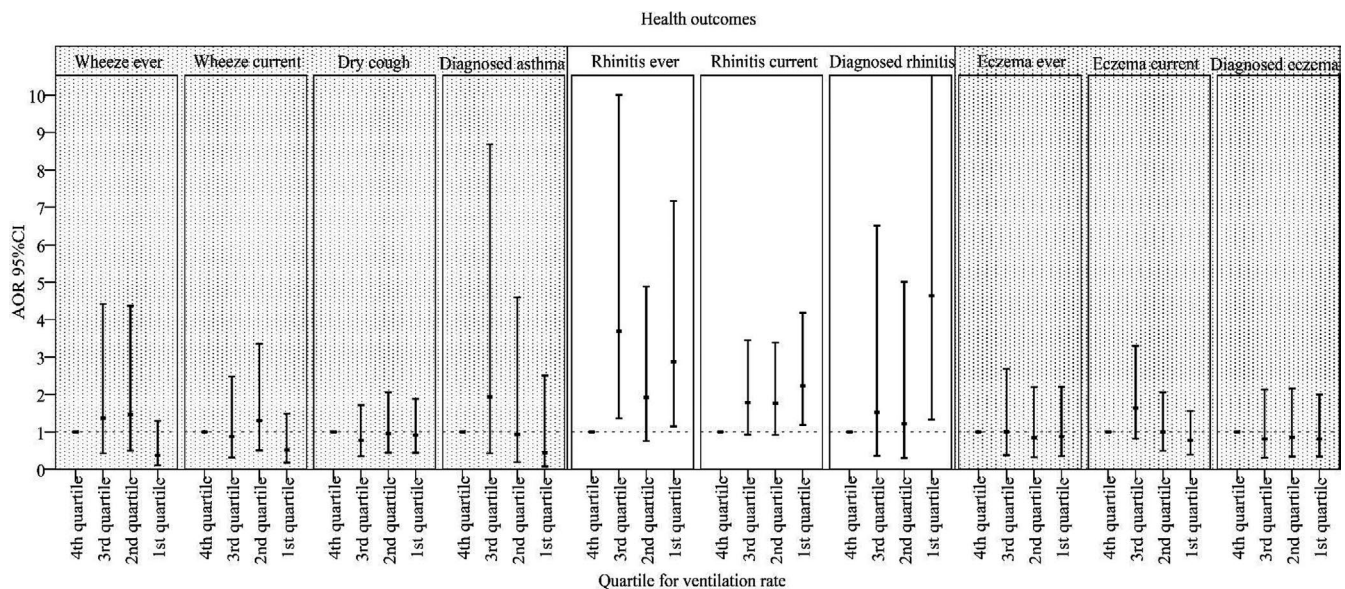
^aAdjusted for gender, age, family allergic history, dampness, environmental tobacco smoke exposure, outdoor PM₁₀, and measurement season.

^bThe data higher than median value (VR-child-night: 0.37 h⁻¹; VR-home-day: 0.76 h⁻¹; VR-home-night: 0.32 h⁻¹; VR-child-night: 3.03 L/s per person) are the reference values.

^cThe data lower than median value (CO_{2avg}-child-night: 1208 ppm; CO_{2peak}-child-night: 1420 ppm) are the reference values.

^dThe data are restricted to the children lived at the present home since birth.

^eValues in bold indicate statistical significance.

**FIGURE 1** Association of ventilation rate (in child's bedroom at night) with children's asthma and allergy (adjusted for gender, age, family allergic history, dampness, environmental tobacco smoke exposure, outdoor PM₁₀, and measurement seasons). The data on wheeze ever, diagnosed asthma, rhinitis ever, diagnosed rhinitis, eczema ever, and diagnosed eczema are restricted to the children lived at the present home since birth

These studies give evidence of health benefits from higher ventilation rates. For example, Bornehag et al¹⁷ found that children with no signs of any allergies were living in homes with a higher ventilation rate compared to allergic children, and that there was a dose-response relationship between ventilation rate and allergic diseases. Hagerhed-Engman et al found that low ventilation rates in combination with residence dampness increased the risk for asthma and allergy. When a ventilation rate < 0.34 h⁻¹ was

combined with dampness indicators, the odds ratios for asthma and allergy were tripled.³⁹ Norbäck et al⁴⁰ observed that CO₂ was significantly higher in the homes of adults who reported nocturnal chest tightness, compared with subjects without this symptom (1020 vs. 850 ppm, $P < .01$). Lajoie et al reported a decrease in wheeze with the addition of mechanical ventilation that increased the geometric mean ventilation rate from 0.17 to 0.34 h⁻¹.²³ Emenius et al²² reported that a proxy for poor ventilation in homes

(absolute indoor air humidity > 5.8 g/kg and windowpane condensation) was related to recurrent wheezing in very young children with an odds ratio of 1.7-2.2. In Phase I of this Tianjin CCHH study, low ventilation as indicated by condensation on windows and use of air conditioning was found to be a risk factor for children's asthma and allergy, while opening windows for ventilation had a protective effect.³⁰ In the present study, we observed a significant association between ventilation rate (<0.37 h⁻¹) and rhinitis symptoms. Increased ventilation rate has been shown to reduce indoor humidity,²² and as a result reducing house dust mite (HDM) numbers and their allergen concentrations,⁴¹ well-known risk factors for sensitization and allergic symptoms.^{14,15} In addition, ventilation has been found to be related to other indoor pollutant exposure, including semi-volatile organic compounds (SVOCs),⁴² which may cause allergic symptoms.^{43,44} Outdoor allergens (such as pollen) cannot explain our results because the high rhinitis incidence month in our study was not during the pollen season (Figure S1). Countries or regions with cold winter climates likely also have low ventilation rates similar to those of Scandinavian countries, but actual measurements of ventilation rates have rarely been performed, so there has been little study of the effect of ventilation rates on health outcomes⁴⁵ (Table S1). Our study and the limited results from previous studies suggest that lower ventilation rates are a risk for rhinitis. To our knowledge, this is the first study that quantifies the association between ventilation in Chinese homes and children's rhinitis problems.

In this study, we found that the bedroom night ventilation rate was more significantly associated with children's rhinitis compared to the ventilation rate measured in daytime or at night for the whole home. The largest proportion of time that most people spend in their homes is in their bedrooms at night for sleeping. Thus, the ventilation rate at night in bedrooms should have the highest priority for monitoring and control. We found that the room-volume-related ventilation rate measure (h⁻¹) was more significantly associated with children's rhinitis compared to the person-related ventilation rate (L/s/person). Ventilation rate expressed as h⁻¹ is based on building material pollutants (emissions from building materials and furniture) being the dominant indoor pollutants, while ventilation rate expressed in units of L/s per person is more descriptive when human bioeffluents are the dominant pollutants. The occupant density in residential settings is usually relatively low so that person- and/or activity-related pollutant sources are less important than building material pollutants.

Ventilation rate associations are stronger than CO₂-related associations. CO₂ in residences is mainly generated by human beings and related to the number of occupants. Therefore, CO₂ concentration may be a proxy more for pollution caused by the human body, rather than pollution from other sources such as building materials and decorative materials.

At present, the regulated ventilation rate is primarily based on indoor air quality surrogates that mostly represent human bioeffluents, such as CO₂ and odors. For example, the ASHRAE standard⁴⁶ sets 21-35 L/s (for home floor area 47-93 m²) as the

required ventilation rate in homes (equivalent to 0.5-0.6 h⁻¹ in a home with a volume of 118-233 m³). Ventilation rates should be more dependent on the health end point of indoor pollution exposure, such as short- and long-term health consequences, than occupants' perception of indoor air quality (IAQ) alone. Thus, a pragmatic approach to setting ventilation requirements would be to observe whether there is an elevated risk for health and comfort complaints when the ventilation rate is at or below a certain level. We have estimated risks, relative to background levels, for various levels of ventilation. The background levels were set based on our previous cross-sectional study, which found that 9.5%, 38.8%, and 29.8% children in Tianjin area had diagnosed rhinitis, rhinitis ever and rhinitis current symptoms, respectively.³⁰ The ventilation rate at night in bedroom among the general Tianjin population was 0.4 h⁻¹.²⁰ Different ventilation levels have been proposed in multi-disciplinary scientific literature reviews and ventilation standards. Seppänen et al⁴⁷ have suggested that SBS symptoms increased with ventilation rates at or below 10 L/s per person (equivalent to 0.8 h⁻¹ in a home with a volume of 180 m³ and 4 persons). Later, Wargocki et al⁹ proposed ventilation rates of 25 L/s per person (equivalent to 2.0 h⁻¹ in a home with a volume of 180 m³ and 4 persons) as necessary to decrease the prevalence of health symptoms. Sundell et al⁵ recommended that the ventilation rate be > 0.5 h⁻¹ to reduce concentrations of house dust mites and the prevalences of asthma and allergy. Carrer et al⁴⁸ suggested that no adverse effects were seen at a ventilation rate of 6-7 L/s per person (equivalent to 0.5 h⁻¹ in a home with a volume of 180 m³ and 4 persons). Our study indicated that each 0.1 h⁻¹ increase in ventilation rate at night was associated with a relative protection of 0.97 for rhinitis current. Assuming this relationship to be causal, we predicted the rhinitis prevalence with various ventilation rates (Figure S3). Minimum ventilation rates as recommended by international standards⁴⁶ or by scientific literature^{5,9,47,48} are highlighted on the prevalence versus ventilation rate curves. For a ventilation rate of 0.5 h⁻¹, the prevalence of rhinitis current would be 28.8%; the prevalence would reduce to 17.4% for a ventilation rate of 2.0 h⁻¹.⁹

Besides indoor air pollution, outdoor air pollution is also associated with children's asthma and allergic disease.⁴⁹ Sun et al⁵⁰ found that in Shanghai the outdoor concentrations of NO₂ and PM₁₀ were associated with general, mucosal and skin symptoms. High outdoor contaminant levels make ventilation rate less beneficial.¹⁰ In Tianjin and Cangzhou, the annual mean concentration of outdoor PM₁₀ was 133 and 138 µg/m³, respectively,^{51,52} higher than the Chinese standard⁵³ of 70 µg/m³. Even so, we found significant associations of low ventilation with children's rhinitis. Stronger associations can be expected in areas with lower outdoor pollution.

4.1 | Strengths and limitations

A strength of our study is the large sample size. Therefore, our finding that two out of ten (2/10) asthma and allergy were significantly

associated with ventilation rate at night ($P < 0.05$) is unlikely due to chance. We controlled for potential confounders correlated with ventilation rate and health outcomes. Therefore, confounding is an unlikely explanation for the findings of our study. Another strength is that we monitored CO₂ concentration in the space adjacent to the bedroom (eg, the living room) simultaneously thus accounting for the internal zone airflow. This has been neglected in previous studies, which regarded the bedroom as a separate zone regardless of the living room CO₂ concentration.^{26,29,54}

The health outcomes in our study were self-reported by home occupants. The questionnaire in our study was developed from the Dampness in Buildings and Health (DBH) study in Sweden,^{4,55} and has been validated and used in many countries and regions. It has been shown that self-reported symptoms are consistent with medical examinations.^{56,57} In our study, CO₂ was measured during a 24-hour period and the ventilation rates were estimated from that one-day period rather than long-term. Still, as an example in Figure S3 shows, variations of CO₂ concentrations (a proxy of ventilation rate) in days-on-roll measurement in separate bedroom and homes were limited due to consistent occupancy levels in homes and unchanged lifestyles of occupants. Therefore, one-day ventilation rates in homes during normal life are representative except during extreme weather conditions. We performed home inspection and ventilation measurements in various seasons. The measurement season was adjusted when we studied the associations between ventilation rate and health outcomes. Therefore, the strong associations of ventilation rate with rhinitis cannot be explained by measurement bias.

This study focuses on health issues as they relate to ventilation of homes, where people spend most of their time. Other environments such as day cares and schools were not considered. Nonetheless, we found ventilation in homes to be associated with children's rhinitis symptoms. If exposure was specified with respect to time spent in homes compared to other places (for example, day cares or schools), associations between home ventilation and health outcomes among occupants may have been even stronger.

5 | CONCLUSION

In Chinese residential buildings, a low ventilation rate at night was associated with children's rhinitis symptoms. The ventilation rate in the bedroom at night may be a substantially important factor among different ventilation indicators for occupants' health. Proper ventilation strategy and efficiency in Chinese homes should be developed to guarantee occupants' health.

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CONFLICT OF INTEREST

The authors declare there is no conflict of interest arising from this work.

AUTHOR CONTRIBUTION

Jing Hou: Data curation (equal); Formal analysis (lead); Investigation (equal); Project administration (lead); Writing-original draft (lead); Writing-review & editing (equal). **Yuexia Sun:** Conceptualization (equal); Data curation (equal); Funding acquisition (lead); Investigation (equal); Methodology (equal); Supervision (lead); Writing-review & editing (equal). **Pan Wang:** Investigation (equal). **Qingnan Zhang:** Investigation (equal). **Xiangrui Kong:** Investigation (equal). **Jan Sundell:** Conceptualization (equal); Methodology (equal).

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Research data are not shared.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Supplementary Materials

Table S1 Studies of the effect of ventilation rate on health in residential buildings.

Study	Location	Number of residences	Method and measurement duration	Measured period	Ventilation (Mean or median) Ventilation rates	Health outcome finding
Ruotsalainen et al. ¹	Finland	242	PFT ^a , 2-week	1988.11-1989.4	0.52 h ⁻¹ (residences, mean) 0.62 h ⁻¹ (apartments with natural ventilation, mean)	Lethargy, weakness and nausea in the naturally ventilated houses were more common than with balanced ventilation. Cough in the balanced ventilated apartments were more common than with natural ventilation.
Øie et al. ² Øie et al. ³	Norway	344	PFT, 14-day	1992.05-1995.05, excluding summer months	0.51 L/s per m ² (apartments with natural ventilation, mean) 0.47 L/s per m ² (single family houses with natural ventilation, mean)	The risk of bronchial obstruction was not directly associated with the ventilation rate in L/s per person and h ⁻¹ in homes. Low ventilation rates strengthen the effects of indoor air pollutants.
Emenius et al. ⁴	Sweden	540	PFT, 4-week	1994-1996, winter	0.68 h ⁻¹ (residences, mean)	Ventilation rate in L/s per person and h ⁻¹ were not directly associated with recurrent wheezing.
Bornehag et al. ⁵ Hägerhed-Engman et al. ⁶	Sweden	390	PFT, 1-week	2001.10- 2002.04	0.36 h ⁻¹ (Single-family houses, mean) 0.48 h ⁻¹ (Multi-family houses, mean) 0.37 h ⁻¹ (Single-family houses with natural ventilation, mean) 0.34 h ⁻¹ (Bedroom of single-family houses with natural ventilation, mean)	Ventilation rates in homes of cases (with allergic symptoms) were lower than in homes of controls (with no symptoms). Dose-response relationships between case (two symptoms of wheeze, rhinitis, eczema) and lower whole home and bedroom ventilation rates.
Kovesi et al. ⁷	Canada	49	PFT	2005.01-2005.03	0.70 h ⁻¹ (mean)	Ventilation rate in L/s per person and h ⁻¹ were not directly associated with lower respiratory tract infection.
Wang et al. ⁸	Sweden	605	PFT, 14-15 days	2007.10-2008.04	0.36 h ⁻¹ (residences, mean)	Ventilation rate was associated with

Bekö et al. ⁹ Callesen et al. ¹⁰	Denmark	500	Mass balance for occupant generated CO ₂ , nighttime	2008.03- 2008.05	0.46 h ⁻¹ (bedrooms, geometric mean)	current asthma symptoms (OR ^b : 0.85 per 0.1 h ⁻¹ , 95% CI 0.73- 0.99).
					0.62 h ⁻¹ (bedrooms, arithmetic mean)	
Sun et al. ¹¹	China	32	Mass balance for occupant generated CO ₂ , nighttime	2016.11-2017.10	0.45 h ⁻¹ (median)	Ventilation rates in the healthy control group were lower than in the homes of children with a clinical diagnosis of asthma, allergic rhinoconjunctivitis, or atopic dermatitis.
						Among children with asthma, significantly lower ventilation rates were measured for those who were IgE- sensitized.
						Lower ventilation rate has OR 1.37(0.56-3.36) for more than one general SBS symptom.
						Lower ventilation rate has OR 2.65(1.16-6.06) for more than one mucosal SBS symptom.
						Lower ventilation rate has OR 1.08(0.49-2.37) for more than one dermal SBS symptom.

^aPassive tracer gas technique (perfluorocarbon tracer).

^bOR: odds ratio.

Table S2 Mean outdoor PM₁₀ concentrations in Tianjin area (i.e., Tianjin metropolis and Cangzhou city) in 2013-2016, ug/m³.

Year	Month	Location	
		Tianjin	Cangzhou
2013	5	142	117
	6	147	113
	7	119	84
	8	120	94
	9	130	83
	10	150	125
	11	159	131
	12	196	162
2014	1	179	194
	2	136	139
	3	173	153
	4	153	130
	5	132	126
	6	93	90
	7	114	120
	8	100	115
	9	84	103
	10	146	170
	11	156	181
	12	154	175
2015	1	161	159
	2	146	145
	3	166	161
	4	108	130
	5	89	117
	6	91	102
	7	87	75
	8	93	77
	9	74	64
	10	96	96
	11	128	126
	12	185	202
2016	1	119	123

Table S3 Distribution of children's asthma and allergic symptoms in the inspected homes in Tianjin area, China, n (%).

	Gender			Age				Family allergic history			Dampness			Environmental tobacco smoke exposure		
	Male	Female	<i>P</i> ^a	0-2	3-6	7-8	<i>P</i>	Yes	No	<i>P</i>	Yes	No	<i>P</i>	Yes	No	<i>P</i>
Wheeze ever ^b	18(22.2)	24(22.6)	0.95	12(29.3)	25(20.7)	5(18.5)	0.46	16(32.0)	24(17.8)	0.04	21(34.4)	18(16.1)	0.01	28(26.2)	12(15.0)	0.07
Wheeze current	25(14.8)	20(10.9)	0.27	13(23.6)	26(11.3)	6(8.2)	0.02 ^c	20(18.5)	23(9.5)	0.02	22(23.2)	21(8.7)	0.00	26(15.6)	17(9.0)	0.06
Dry cough current	37(21.3)	39(21.2)	0.99	12(21.8)	58(24.5)	6(8.5)	0.01	27(24.3)	46(18.9)	0.24	25(25.8)	47(19.3)	0.19	36(21.3)	40(21.1)	0.95
Diagnosed asthma ^b	9(11.4)	12(11.4)	0.99	2(5.1)	14(11.7)	5(18.5)	0.23	10(20.0)	10(7.5)	0.02	14(23.0)	7(6.3)	0.00	15(14.6)	5(6.2)	0.07
Rhinitis ever ^b	45(55.6)	55(52.9)	0.72	25(59.5)	65(54.6)	10(38.5)	0.22	29(56.9)	70(52.6)	0.61	37(60.7)	59(52.2)	0.29	52(49.1)	46(58.2)	0.22
Rhinitis current	85(48.3)	89(48.9)	0.89	30(54.5)	120(51.1)	26(35.6)	0.04	61(56.0)	109(44.5)	0.05	50(51.0)	118(48.2)	0.63	86(50.0)	88(46.8)	0.55
Diagnosed rhinitis ^b	13(16.5)	21(20.6)	0.48	4(9.8)	26(22.4)	4(15.4)	0.18	17(35.4)	16(12.1)	0.00	15(24.6)	19(17.3)	0.25	20(19.6)	12(15.2)	0.44
Eczema ever ^b	40(48.2)	64(61.5)	0.07	26(61.9)	63(52.5)	16(59.3)	0.53	41(80.4)	61(45.2)	0.00	41(67.2)	55(48.7)	0.02	61(58.1)	42(51.2)	0.35
Eczema current	59(34.1)	56(30.4)	0.46	31(56.4)	64(27.4)	20(27.4)	0.00	44(40.4)	69(28.0)	0.02	37(38.1)	69(28.2)	0.07	51(30.5)	61(31.9)	0.78
Diagnosed eczema ^b	40(48.2)	59(58.4)	0.17	24(57.1)	63(53.8)	13(48.1)	0.77	35(70.0)	62(46.6)	0.01	32(53.3)	60(53.6)	0.98	57(54.8)	41(51.3)	0.63

^a*P*-value in Chi-square test^bThe data is restricted to the children lived at the present home since birth.^cValues in bold indicate statistical significance.

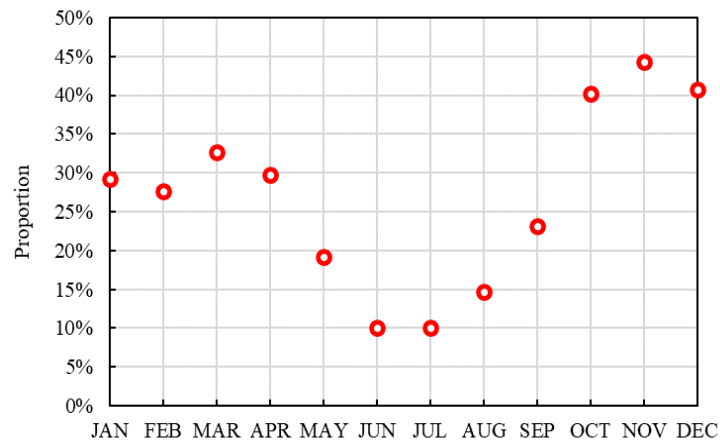


Fig. S1 Incidence rates of rhinitis in each month.

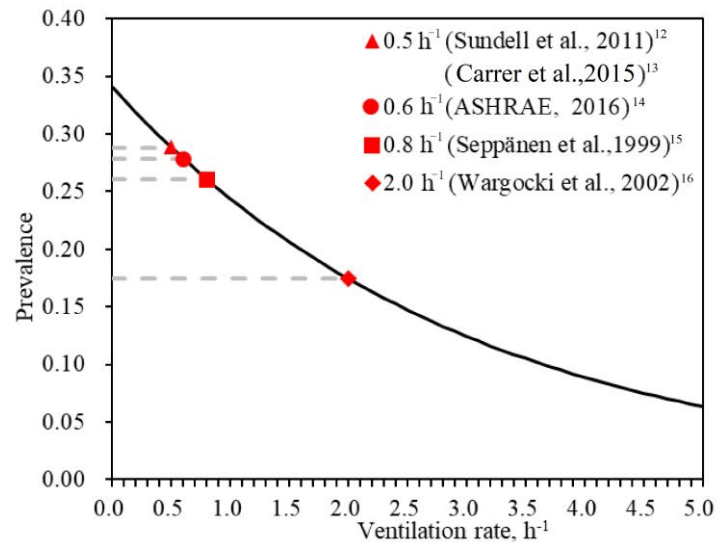
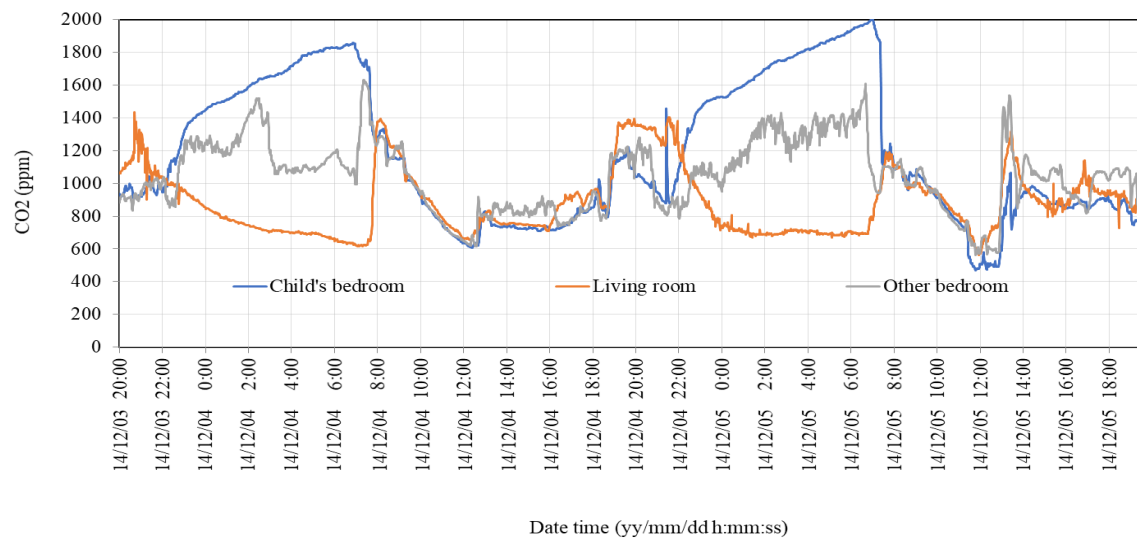
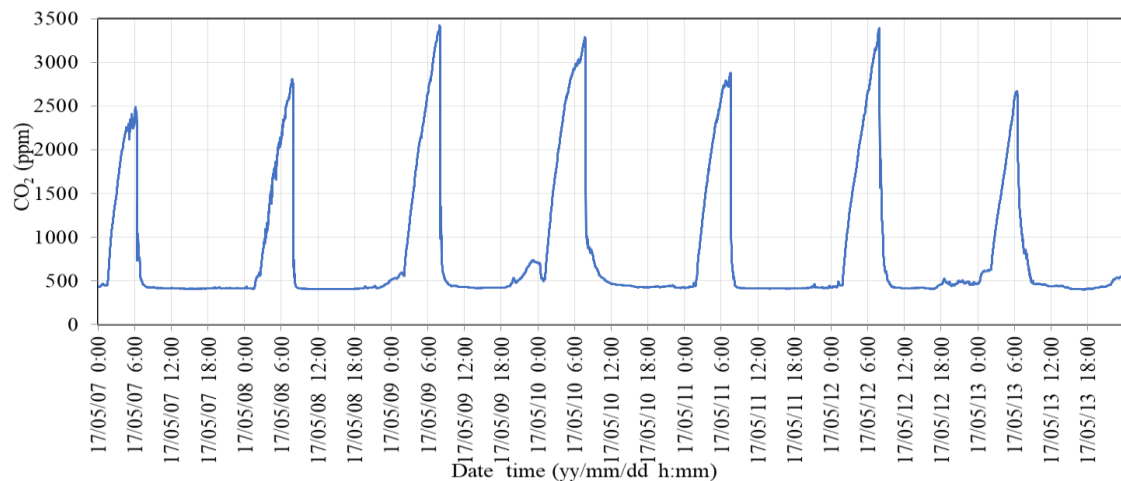


Fig. S2 Prevalence of rhinitis current with various ventilation rates. Symbols represent prevalences associated with minimum/recommended ventilation rates in standards and scientific literature review. (The ventilation rate units from references were converted to ' h^{-1} ' from 'L/s per person' corresponding to a typical room with volume of 180 m^3 and 4 persons.)



a. CO₂ concentration in home during two days



b. CO₂ concentration in bedroom during one week

Fig. S3 Example of CO₂ concentration in home

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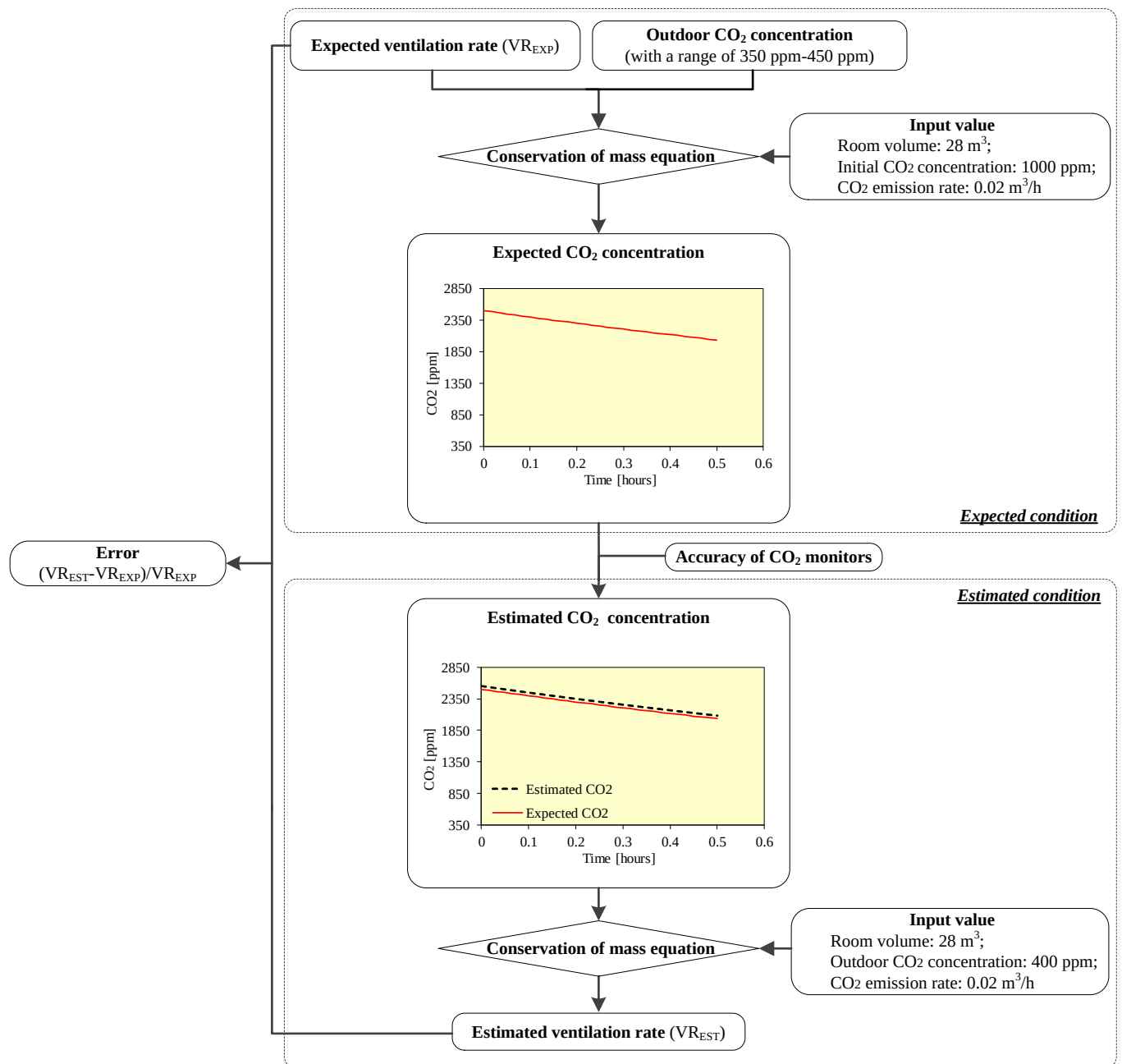
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Supplementary Materials

Error analysis on ventilation rate

In this study, the accuracy of CO₂ monitors and assumption of outdoor concentration (as 400 ppm) may cause errors in ventilation rate. As stated in the manual, CO₂ monitors had an accuracy of 50 ppm, or $\pm 5\%$ of reading. We assumed outdoor CO₂ is 400 ppm, while in reality outdoor CO₂ might vary with a range of 350 ppm to 450 ppm.

Error analysis was performed using a backward inference method, as shown in the follow chart:



The results of error analyses are shown in Fig. S1. Lines indicate the expected ventilation rate, and each point of shadows indicates the estimated ventilation rate.

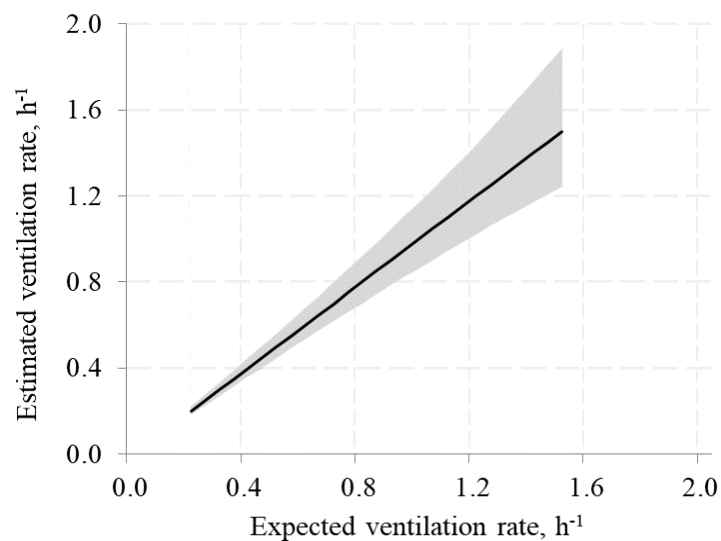


Fig. S1 Error in ventilation rate (Line indicates expected ventilation rate, and each point of shadow indicates estimated ventilation rate. Input value: room volume, 28 m³; initial CO₂ concentration, 1000 ppm; CO₂ emission rate: 0.02 m³/h).