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Indoor air quality impacts of residential mechanical ventilation system retrofits in existing homes in Chicago, IL

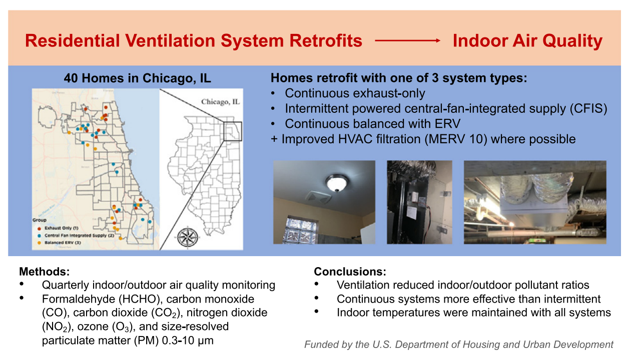
Insung Kang [a], Anna McCreery [b], Parham Azimi [c], Amanda Gramigna [b], Griselda Baca [b], Kari Abromitis [a], Mingyu Wang [a], Yicheng Zeng [a], Rachel Scheu [b], Tim Crowder [b], Anne Evens [b], Brent Stephens [a,*]

[a] *Department of Civil, Architectural, and Environmental Engineering, Illinois Institute of Technology, Chicago, IL, USA*
[b] *Elevate, Chicago, IL, USA*
[c] *Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA*

HIGHLIGHTS

- Measured indoor air quality impacts of residential mechanical ventilation retrofits
- Evaluated continuous exhaust, continuous balanced, and intermittent supply systems
- 2-Year crossover study with quarterly weeklong field visits pre- and post-retrofit
- Ventilation (and filtration) retrofits reduced indoor/outdoor pollutant ratios.
- Continuous ventilation systems were more effective than intermittent.

GRAPHICAL ABSTRACT



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ABSTRACT

Mechanical ventilation systems are used in residences to introduce ventilation air and dilute indoor-generated pollutants. A variety of ventilation system types can be used in home retrofits, influencing indoor air quality (IAQ) in different ways. Here we describe the Breathe Easy Project, a >2-year longitudinal, pseudo-randomized, crossover study designed to assess IAQ and adult asthma outcomes before and after installing residential mechanical ventilation systems in 40 existing homes in Chicago, IL. Each home received one of three types of ventilation systems: continuous exhaust-only, intermittent powered central-fan-integrated-supply (CFIS), or continuous balanced system with an energy recovery ventilator (ERV). Homes with central heating and/or cooling systems also received MERV 10 filter replacements. Approximately weeklong field measurements were conducted at each home on a quarterly basis throughout the study to monitor environmental conditions, ventilation operation, and indoor and outdoor pollutants, including size-resolved particles (0.3–10 μm), ozone (O_3), nitrogen dioxide (NO_2), carbon dioxide (CO_2), carbon monoxide (CO), and indoor formaldehyde (HCHO). Mean reductions in indoor/outdoor (I/O) ratios across all systems after the intervention were approximately 12% ($p = 0.001$), 10% ($p = 0.008$), 42% ($p < 0.001$), 39% ($p = 0.002$), and 33% ($p = 0.007$), for CO_2, NO_2, and estimated PM_1, $PM_{2.5}$, and PM_{10}, respectively. There was a reduction in I/O ratios for all measured constituents with each type of system, on average, but with varying magnitude and levels of statistical significance. The magnitudes of mean differences in I/O pollutant concentrations ratios were generally largest for most pollutants in the homes that received continuous balanced with ERV and smallest in the homes that received intermittent CFIS systems, with apparent benefits to providing ventilation continuously rather than intermittently. All ventilation system types maintained similar indoor temperatures during pre- and post-intervention periods.

* Corresponding author.
E-mail address: brent@iit.edu (B. Stephens).

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1. Introduction

A growing body of research has demonstrated that human exposure to a variety of airborne pollutants is often greater indoors than outdoors (Wallace et al., 1991; Ott and Roberts, 1998; Jones, 1999; Edwards et al., 2001; Weschler, 2006; Logue et al., 2011, 2012), particularly in residences where people spend most of their time (Klepeis et al., 2001). This is because there are many indoor and outdoor sources of airborne pollutants indoors that often lead to indoor pollutant concentrations that are higher than outdoors (Wallace et al., 1985; Sax et al., 2004; Liu et al., 2006; Meng et al., 2005; Adgate et al., 2004a,b). Volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), aldehydes (e.g., formaldehyde), and alcohols are emitted indoors from building materials (Wallace et al., 1987; Wolkoff, 1998; Salthammer et al., 2010), cleaning products (Nazaroff and Weschler, 2004; Singer et al., 2006), and personal care products (Steinemann et al., 2011). Indoor particles, including fine particulate matter ($PM_{2.5}$, or the mass of particles smaller than 2.5 μm), coarse particulate matter ($PM_{2.5-10}$, or the mass of particles between 2.5 and 10 μm), and ultrafine particles (UFPs, or particles smaller than 0.1 μm), are emitted indoors by a variety of sources including combustion (e.g., indoor smoking (Wallace, 1996) and burning incense and candles (Afshari et al., 2005; Ott and Siegmann, 2006)), cooking (Wallace et al., 2004; Wallace, 2006), and resuspension from settled dust (Ferro et al., 2004; Qian and Ferro, 2008). Further, both gases and particles of outdoor origin infiltrate and persist in residences with varying efficiencies (Meng et al., 2005; Wallace, 1996; Sexton et al., 1983; Sirén, 1993; Thatcher and Layton, 1995; Leaderer et al., 1999; Weschler, 2000; Thatcher et al., 2003; Williams et al., 2003; Rim et al., 2010; Stephens and Siegel, 2012; Chen and Zhao, 2011; Stephens et al., 2012). In fact, the majority of human exposure to many outdoor pollutants, including $PM_{2.5}$, PM_{10}, ozone (O_3), nitrogen dioxide (NO_2), and carbon monoxide (CO), often occurs indoors (Weschler, 2006; Meng et al., 2005; Azimi and Stephens, 2020; Chaloulakou et al., 2003; Chen et al., 2012a,b; Dimitroulopoulou et al., 2001; Ji and Zhao, 2015; Stephens, 2015a). Outdoor pollutant entry into homes is influenced by the source of ventilation air, including infiltration through cracks and gaps in building envelopes, delivery through mechanical ventilation systems, or through natural ventilation via open windows (Kearney et al., 2011; MacNeill et al., 2012, 2014; Park et al., 2014a; Rim et al., 2013; Singer et al., 2017). This combination of indoor-generated and outdoor-infiltrated sources yields indoor concentrations of pollutants in many homes that often exceed chronic and/or acute health standards and lead to numerous adverse health effects (Logue et al., 2012; Wallace, 1991; Sax et al., 2006; Hun et al., 2009).

Given the importance of residential indoor air quality (IAQ) and the high prevalence of indoor pollutant sources, dedicated mechanical ventilation systems are increasingly being used to introduce outdoor air to meet ventilation needs and dilute indoor-generated pollutants. Numerous studies have examined the effects of residential mechanical ventilation systems on IAQ, thermal comfort, and/or energy use. For example, Turner et al. examined the potential value of commissioning residential mechanical ventilation systems using a simulation-based approach to assess energy and IAQ impacts (Turner et al., 2013). Walker and Sherman investigated the effects of residential ventilation strategies designed to comply with ASHRAE Standard 62.2 on indoor O_3 levels and predicted that exhaust-only systems would produce lower indoor O_3 concentrations than would occur with balanced ventilation systems operating at the same air change rate (Walker and Sherman, 2013). Park et al. found that residential mechanical ventilation systems reduced the daily average indoor/outdoor (I/O) concentration ratios of submicron and fine particles in fifteen apartments in South Korea by 26% and 65%, respectively (Park et al., 2014b). Francisco et al. observed lower indoor concentrations of VOCs, formaldehyde, and CO_2 in weatherized homes in the U.S. that were retrofitted with exhaust ventilation systems compared to weatherized homes that were not given a mechanical ventilation system, along with some additional improvements in self-reported health outcomes by occupants of those homes (Francisco et al., 2017). Huang et al. recently found that mechanical ventilation systems reduced indoor concentrations of carbon dioxide (CO_2), formaldehyde (HCHO), and total volatile organic compounds (TVOCs) in eight residential buildings in China (Huang et al., 2020).

There is also a growing body of literature on the impacts of residential mechanical ventilation systems on human health. For example, Kovesi et al. found that the installation of residential heat recovery ventilators (HRVs) reduced indoor CO_2 concentrations and relative humidity and led to reductions in reported respiratory symptoms in Inuit children (Kovesi et al., 2009). Wright et al. showed that the installation of balanced residential mechanical ventilation systems with HRV did not lead to a reduction in mite burden in house dust, but did improve peak expiratory flow (PEF) in adults with asthma (Wright et al., 2009). Woodfine et al. provided a tailored package of housing modifications to improve ventilation and improve heating systems in residences in the United Kingdom and found that parent-reported asthma-related quality of life was significantly increased in children with moderate to severe asthma (Woodfine et al., 2011). An economic analysis of these same interventions suggested that although the average cost of the modifications was over $2000 per child, they were considered cost-effective because of the significant improvements to childhood asthma symptoms (Edwards et al., 2011). Lajoie et al. demonstrated that the installation of balanced exhaust and supply ventilation systems with HRVs and energy recovery ventilators (ERVs) significantly reduced indoor concentrations of some pollutants, and also led to slight decreases in some symptoms in asthmatic children (Lajoie et al., 2015).

Despite these demonstrated successes, efforts to improve residential IAQ by installing mechanical ventilation systems are often not considered due to a lack of financial resources of homeowners or landlords to purchase and install the systems, especially in existing homes (Krieger and Higgins, 2002). In addition, there is a wide variety of residential mechanical ventilation system options that builders, contractors, designers, homeowners, and housing agencies can choose from when specifying ventilation system retrofits, including supply-only systems, exhaust-only systems, and balanced systems, each with the potential to operate continuously or intermittently. Recent research suggests that differences in ventilation system design and operation can influence indoor concentrations of indoor-generated pollutants as well as the penetration of outdoor pollutants in different ways, including potentially increasing the penetration of some outdoor pollutants (Zhao et al., 2015; Azimi et al., 2016; Stephens, 2015b; Hun et al., 2013; Yu et al., 2014; Rudd and Bergey, 2014). For example, Rudd and Bergey showed that central-fan-integrated-supply (CFIS) systems with medium-efficiency particle filters installed at the air-handling unit in two test houses yielded lower indoor/outdoor submicrometer particle concentration ratios than when they were operated with a supply-only ERV unit with dedicated ductwork, largely because the ERV unit used a low-efficiency coarse filter at its inlet (Rudd and Bergey, 2014). Indoor/outdoor (I/O) concentration ratios of particles were highest when the same homes were operated with exhaust-only ventilation systems, suggesting high infiltration/penetration rates through the building envelope. VOC concentrations in the same homes were also lowest with the CFIS and supply-only ventilation systems, while VOC concentrations increased in one home with an exhaust-only system. Singer et al. evaluated the impacts of nine different configurations of ventilation and filtration systems on indoor concentrations of particles and O_3 of outdoor origin (no indoor sources) in an unoccupied house in California (Singer et al., 2017). Supply ventilation systems were less effective at reducing indoor particle concentrations of ambient origin than exhaust-only systems unless they were combined with higher efficiency filtration on the intake and return. However, this work was limited to a single unoccupied test home, and differences in envelope airtightness and other factors in other homes could yield different results (Stephens, 2015b). Overall, there is little empirical data on the effects of different types of residential mechanical ventilation systems on IAQ and/or health outcomes in occupied homes.

To fill some of these knowledge gaps, the Breathe Easy Project was designed to evaluate the impacts of three common types of residential mechanical ventilation system retrofits (i.e., continuous exhaust-only, intermittent powered CFIS, and continuous balanced exhaust and supply system with an ERV) on reducing indoor pollutants of both indoor and outdoor origin, maintaining adequate environmental conditions and ventilation rates, and improving adult asthma outcomes in existing homes in Chicago, IL. Here we describe in detail the field measurements that were conducted to characterize indoor and outdoor pollutant concentrations, HVAC system operation, and indoor environmental conditions before and after the ventilation system retrofits were installed in 40 homes participating in the study. This paper does not present results regarding asthma-related health outcomes or energy use.

2. Methodology

The following sections and their associated Supplemental Information (SI) describe the study design; recruitment and selection of participating homes; initial home walkthrough assessments and building performance testing; baseline and end-line surveys of home characteristics and occupant behaviors; instrumentation, calibration, and quarterly field measurements; selection and installation of ventilation system retrofits; and data processing and statistical analysis of IAQ impacts of ventilation system retrofits.

2.1. Study design and recruitment of participating study homes

The Breathe Easy Project utilized a >2-year longitudinal, pseudo-randomized, crossover, parallel-group study design of owner-occupied homes in Chicago, IL between 2017 and 2020. Forty-seven homes were initially targeted for recruitment. Each recruited home had at least one adult resident with self-reported asthma and subsequently received one of three types of ventilation systems halfway through the study: continuous exhaust-only system, intermitted powered CFIS system, or continuous balanced system with an ERV. More than one individual per home was enrolled in homes with multiple adults and/or minors with asthma. Indoor and outdoor air pollutant concentrations, indoor environmental conditions, and HVAC operational characteristics were measured in each home on a quarterly basis during four approximately weeklong periods in the year prior to the installation of mechanical ventilation systems (Summer 2017–Fall 2018), and again during four quarterly weeklong periods in the year after the installation of mechanical ventilation systems (Winter 2019–Winter 2020). The study was approved by the Illinois Institute of Technology's Institutional Review Board (IRB #2017-006). Human consent procedures met governmental guidelines and informed consent was obtained from each participant and/or his or her parent or guardian for minors. The study did not include any attempts to have participants record or alter their behaviors that could influence indoor pollutant concentrations (e.g., no recording or alteration of indoor pollutant emission events, changes in HVAC operation, window opening, etc.). Instead, the study was designed such that in-home monitoring was conducted over all four seasons and at multiple time points both pre- and post-intervention and to capture any changes as they naturally occur in this study population.

Fig. 1 shows a flowchart of the recruitment and field measurement processes of the project. We first identified households with at least one occupant with a self-reported asthma diagnosis in the Spring of 2017, recruited primarily via email contact through the Chicago Bungalow Association. Initially, 117 homes throughout greater Chicagoland expressed interest and made it past a preliminary eligibility screening. Eligibility requirements for participation included: (1) homes must be non-smoking (self-reported); (2) homes must have at least one occupant with asthma (self-reported); (3) homes must be occupant-owned (to decrease the likelihood of attrition and facilitate installation); and (4) participants must agree to participate in 24 retrospective asthma control surveys over a period of two years (i.e., once every month) and allow for 8 week-long IAQ and environmental data collection periods over a period of two years. A total of 47 homes passed eligibility requirements and completed the consent and walk-through assessment process to be recruited into the study in year 1; 44 of those homes remained in the study until after the first year of measurements and before the installation of mechanical ventilation systems. Another three homes dropped between year 1 and 2, and the other home

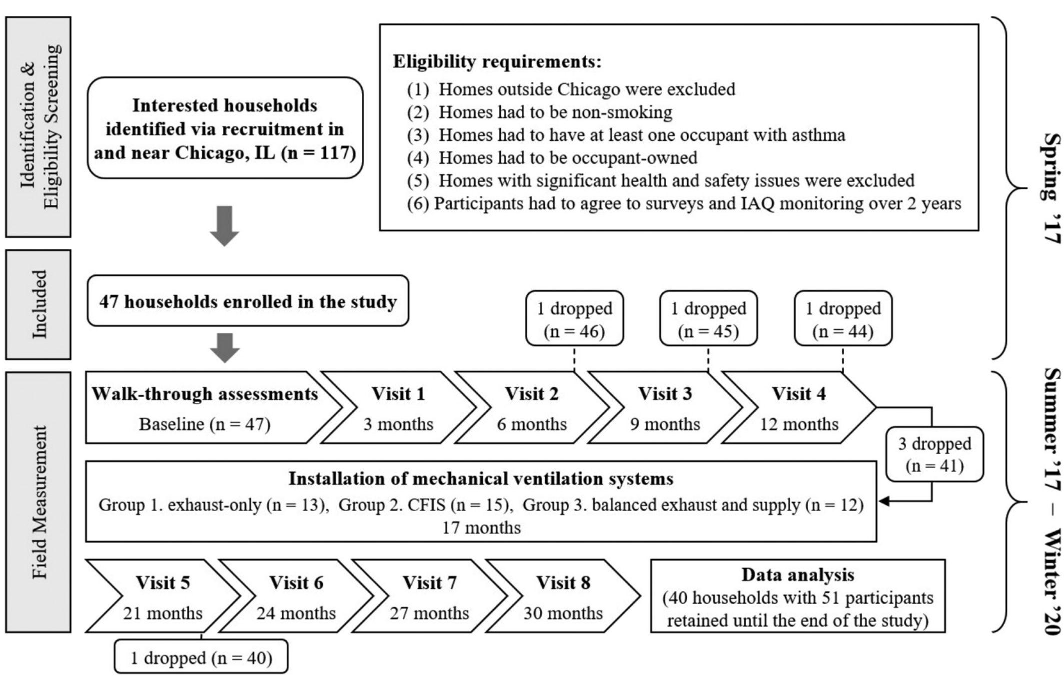

Fig. 1. Flowchart of recruitment and field measurement process of the Breathe Easy Project.

dropped early in year 2. A total of 40 study homes with 51 adult participants (some homes had multiple adult occupants with self-reported asthma) completed participation in the entire study, ultimately receiving a ventilation system, participating in all field visits, and completing baseline, end-line, and monthly questionnaires. This work focuses only on the 40 homes that participated for the entire study duration. These 40 homes are located in 23 community areas across Chicago, IL, as shown in Fig. 2.

2.2. Initial home walkthrough assessments, basic building performance testing, and baseline and end-line surveys

During recruitment, between July 2017 and October 2017, the project team first conducted initial walkthrough assessments in each home to gather basic home information, perform health and safety checks, and conduct basic building performance testing. Additional housing information was also gathered by the research team throughout the project and through occupant questionnaires conducted at the beginning and end of the project period. Through these assessments, we obtained information on home geometry and construction, building envelope (type of walls and roof), insulation (type and approximate R-value), foundation type, kitchen stove type, presence of kitchen exhaust and bathroom exhaust fans (although we did not collect data on recirculating vs. exhaust kitchen range hoods and bathroom fans), heating and/or air-conditioning system type and specifications, domestic hot water system type and specifications, laundry types, and any observed potential health and safety issues such as visible asbestos materials (permissible if they were not damaged), moisture damage, and combustion safety.

The airtightness of the building envelope was assessed using a single-point (50 Pa) fan pressurization test (using an Energy Conservatory Blower Door (ASTM E 779, 2010)) conducted either (i) during these initial visits by the project team, (ii) at the time of ventilation system installation by a local contractor, or (iii) airtightness data were provided from prior tests, as some homes had relatively recently received a blower door test and/or energy efficiency improvements through the Chicago Bungalow Association and its partners. For homes with a central forced-air air handling unit, the project team also measured airflow rates during these initial visits in fan-only and heating or cooling mode (as applicable) using a TrueFlow® Air Handler Flow Plate (The Energy Conservatory, 2006), which consists of a calibrated metering plate, a static pressure probe, tubing, and a DG-700 pressure gauge. The metering plate temporarily replaces the existing filter in the air handling unit during the initial airflow measurement procedure. A static pressure probe tap was left in place to measure the system operating pressure and estimate the air handler flow rate at each subsequent site visit (Stephens et al., 2010a). We also measured the ventilation flow rates of any existing bathroom and kitchen exhaust fans during these initial visits using an Energy Conservatory Exhaust Fan Flow Meter (The Energy Conservatory, 2017) and DG-700 pressure gauge.

Baseline and end-line surveys were also completed by one adult asthmatic participant in each home at the beginning and the end of the study, respectively, to collect information on demographics (e.g., gender, age, race, annual income, and education levels), housing characteristics (e.g., construction year, basement and attic construction details, number of occupants, number of bedrooms, and HVAC system type), and perceived indoor environmental conditions or behaviors that could affect those conditions (e.g., bathroom fan use, stove fan use, presence of dampness, musty smell, and air freshener use in the last 12 months). Contents of the baseline and end-line surveys are shown in Section 1 of the SI.

2.3. Instrumentation, calibration, and quarterly field measurements

Quarterly field measurement visits in each home were generally scheduled to last approximately one week but varied from 5 to 9 consecutive days depending on occupant availability for scheduling

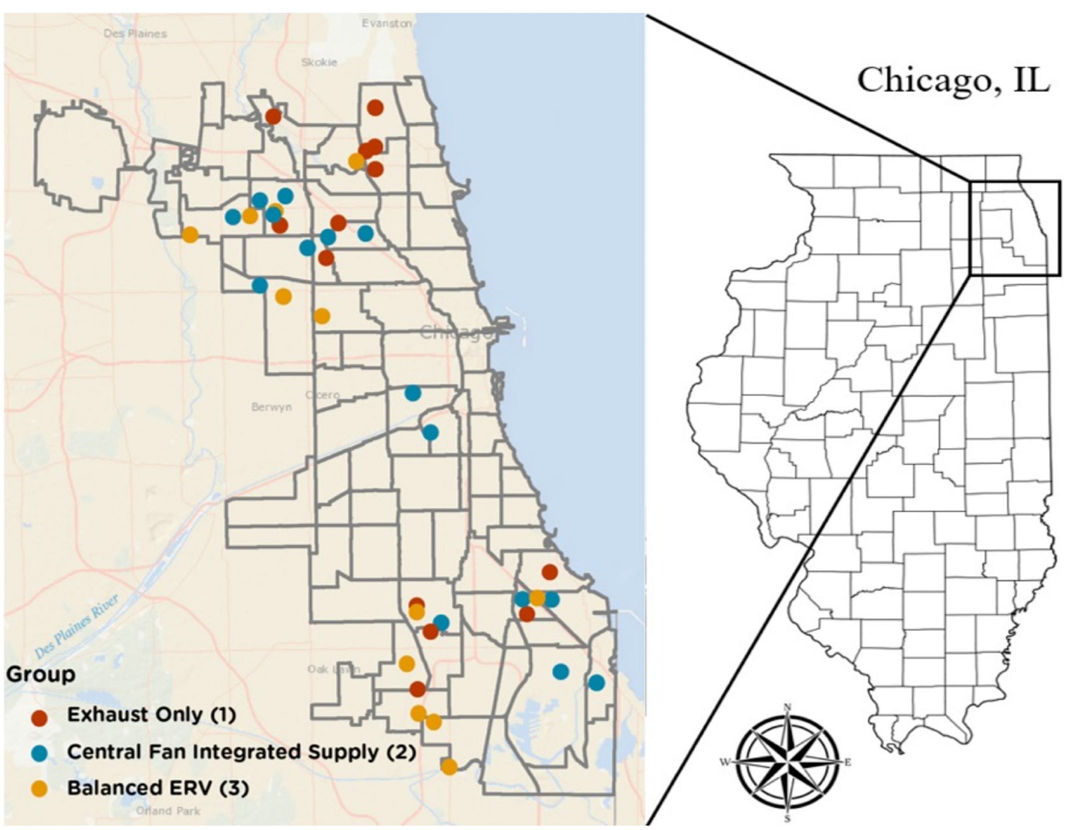

Fig. 2. Location of 40 participating study homes in 23 community neighborhoods across Chicago, IL.

equipment launch and retrieval. Field measurements thus included a total of 160 approximately weeklong home visits conducted in the year prior to the installation of mechanical ventilation systems and 140 approximately weeklong home visits conducted in the year after the installation of the mechanical ventilation systems. The lower number of post-installation field visits was because 20 homes did not receive their final visit due to the COVID-19 stay-at-home orders that began in Chicago in mid-March 2020. This resulted in over 2000 sampling days of data to analyze the impacts of the different types of residential mechanical ventilation systems on IAQ, indoor environmental conditions, and HVAC operation. This section describes the instruments used for each quarterly field measurement to measure HVAC operation, indoor and outdoor air quality, and indoor environmental conditions. Details of the field measurements and ventilation system retrofit schedules for each home are summarized in Table S1.

2.3.1. In-situ HVAC measurements

During each approximately weeklong field visit, we measured several parameters to characterize the in-situ performance of the forced-air heating, air-conditioning, and ventilation (HVAC) systems in the homes, including (i) HVAC system runtimes; (ii) power and energy consumption of the installed mechanical ventilation systems (when possible); and (iii) airflow rates of central air handling units. Instrumentation used for these in-situ HVAC measurements is summarized in Table S2.

To measure the operational runtimes of the central forced-air HVAC systems in homes that had them, we installed a Digi-Sense data logging vane anemometer on a conveniently accessible supply register to indicate whether the air handler fan was operating. After exploring the collected data, we defined a threshold velocity of 0.5 m/s to define periods of forced-air HVAC on and off status in the study homes. During the measurements prior to the installation of ventilation systems, this measurement primarily detected when the central HVAC system was either heating or cooling, as occupants seldom operated their systems in fan-only mode. During the measurements after ventilation system installation, this measurement detected when the central forced-air system was heating, cooling, and/or ventilating (i.e., delivering only outdoor air, if a ventilation system was connected to the central duct system). To separately detect periods of heating, cooling, and ventilating, we also attached an Onset HOBO U12 temperature and RH data logger on a supply register (Stephens et al., 2010a,b). For additional redundancy with the anemometer, we also attached an Onset HOBO UX90 Motor On/Off data logger on the air handling unit motor to obtain fan runtime data (Metzger and Norton, 2014), although many of these measurements were unsuccessful.

We estimated airflow rates through the central forced-air air-handling units in fan-only and heating or cooling mode (depending on the season) at each visit using a DG-700 pressure gauge to measure the system operating pressure using the static pressure probe tap that was left in place from the initial walkthrough visit. Field personnel recorded the operating pressure in the supply plenum at each site visit, which was used to calculate the airflow rate through the air handling unit during normal operation at each quarterly visit (The Energy Conservatory, 2006). For homes that received a powered ventilation system at the intervention stage (i.e., a powered CFIS ventilator or an ERV, as described in Section 2.4), we used an Onset HOBO UX120 plug load data logger to record energy consumption at 10-sec intervals. Since the HOBO UX120 is designed to monitor the energy consumption of AC-powered plug-in loads, only the powered CFIS systems and the ERVs in the balanced exhaust and supply systems were subjected to power and energy consumption measurements (HOBO Plug Load Logger (UX120-018) Manual, n.d.).

2.3.2. Indoor and outdoor air quality measurements

Time-resolved measurements of size-resolved particles (0.3–10 μm), ozone (O_3), nitrogen dioxide (NO_2), carbon dioxide (CO_2), carbon monoxide (CO), and temperature and relative humidity (RH) were conducted simultaneously inside and outside of each home throughout the duration of each approximately weeklong home visit. Integrated measurements of indoor formaldehyde (HCHO) were also made using a passive sensor cartridge deployed for the duration of each site visit. Table 1 summarizes the monitoring instruments that were deployed during the field site visits. The instruments were chosen via a combination of past experiences by both the research team and other researchers and considering portability and cost limitations. It is worth noting that the suite of instruments used herein does not allow for exhaustive characterization of all relevant constituents or pollutants found in homes and that may be affected by ventilation and/or filtration or that may affect asthma outcomes (Farmer et al., 2019; Shi et al., 2018; Liu et al., 2015; Krieger, 2010; Bornehag et al., 2004; Kanchongkittiphon et al., 2014; Dick et al., 2014), but rather targets a variety of conventional pollutants of both indoor and outdoor origin that are known to be associated with asthma outcomes in various populations (Ostro et al., 1994; Hansel et al., 2008; McCormack et al., 2008, 2011; Iskandar et al.,

Table 1
Summary of the indoor/outdoor air quality monitoring INSTRUMENTS used in the field study.

Parameter	Manufacturer/model	Logging interval	Manufacturer specifications	Location
Size-resolved particulate matter	MetOne GT-526	2 min	• Particle size range: 6 channels; 0.3 to 10 μm • Concentration rage: 0 to 105,900 particles/L • Accuracy: ±10% to calibration aerosol • Flow rate: 2.83 L/min	Indoor & outdoor
Ozone (O_3)	Aeroqual SM-50	1 min	• Range: 0–5 V signal; 0 to 0.5 ppm • Resolution: 12 bit	Indoor & outdoor
Nitrogen dioxide (NO_2)	Aeroqual Series 500	2 min	• Range: 0 to 1 ppm • Accuracy: ±0.02 ppm (0–0.2 ppm); ±10% (0.2–1 ppm) • Resolution: 0.001 ppm	Indoor & outdoor
Carbon dioxide (CO_2)	Extech SD800	1 min	• Range: 0 to 4000 ppm • Accuracy: ±40 ppm (<1000 ppm); ±5% (>1000 ppm) • Resolution: 1 ppm	Indoor & outdoor
Carbon monoxide (CO)	Lascar EL-USB-CO	1 min	• Range: 3 to 1000 ppm • Accuracy: ±7 ppm/±6% (whichever is greater) • Resolution: 0.5 ppm	Indoor & outdoor
Formaldehyde (HCHO)	GrayWolf FM-801	1-Week integrated analysis	• Range: <10 to 1000 ppb; <25 to 1230 $\mu g/m^3$ • Accuracy: ±4 ppb (<40 ppb); ±10% (≥40 ppb) • Resolution: 1 ppb	Indoor
Temperature and relative humidity	Onset HOBO U12	30 s	• Temperature range: −20 to 70 °C • Temperature accuracy: ±0.35 °C (from 0 to 50 °C) • RH range: 5 to 95% • RH accuracy: ±2.5% (from 10 to 90% RH)	Indoor & outdoor; supply register[a]

[a] Onset HOBO U12 data loggers were also installed on a supply register to measure HVAC system runtimes.

2012; Evans et al., 2014; Slaughter et al., 2003; Strickland et al., 2010), that are practical to measure, and that are plausibly influenced by the ventilation (and filtration) interventions. All instruments were placed inside a custom protective case tailored for indoor or outdoor environments (Fig. S1). The indoor monitoring case utilized a rolling portable tool cart (Azimi et al., 2018). The outdoor monitoring case utilized an outdoor deck box commonly used to store items outdoors while protecting them from rain, snow, and wind. Each monitoring box had small holes cut to allow air to be drawn in from openings using small CPU fans installed in an exhaust configuration, with an uninterruptable power supply (UPS) placed inside. The indoor monitoring box was placed in a convenient location, typically a bedroom or living room, where the recruited asthmatic adult(s) spent much of their time. The outdoor monitoring box was placed on a patio or in the backyard of each home in a convenient location. All homes had an accessible outdoor power outlet to power the monitoring boxes. All instruments were set to log with high temporal resolution (i.e., between 0.5 and 2 min depending on instrument capabilities). To the greatest extent possible, each pair of indoor/outdoor instruments was launched at the same time interval following the time on the computer used to launch equipment such that near-simultaneous indoor/outdoor measurement readings were recorded by each paired instrument. A total of four indoor boxes and four outdoor boxes were constructed and could be deployed simultaneously, with at least one backup box and multiple instrument backups available as needed.

Since multiple versions of each time-resolved monitoring instrument (e.g., PM, O_3, NO_2, and CO_2) were used indoors and outdoors to measure each parameter simultaneously, we conducted periodic co-location calibrations with each instrument. Calibrations were conducted before the beginning of the study and then quarterly between each round of seasonal field measurements in an unoccupied room in the Built Environment Research Group Laboratory at Illinois Institute of Technology (Fig. S1). One of two co-location calibration methods was performed for each instrument: (1) co-locations against factory-calibrated research-grade instruments (when available), and (2) co-locations against each other (using one instrument as an arbitrary reference). The research-grade instrument co-location calibration approach was applied only to the field-deployable O_3 and NO_2 monitors, comparing against a 2B Technologies Model 211 O_3 monitor and a 2B Technologies Model 405 $NO/NO_2/NO_X$ monitor, respectively. The field-deployable instrument-only co-location calibration approach was applied to the PM and CO_2 monitors, where one single monitor was chosen as an arbitrary reference for relative comparisons between data collected from the other co-located monitors (typically one that had been most recently factory-calibrated). The carbon monoxide (CO) monitors and formaldehyde (HCHO) strips were not calibrated due to instrument limitations. Additionally, we also conducted a set of in-situ indoor co-location measurements with a size-resolved filter-based gravimetric sampler (Sioutas Cascade Impactor) in a subset of 20 field visits in 16 homes (4 homes were sampled twice). These gravimetric co-location measurements were used to develop linear calibration factors to approximate equivalent gravimetric PM_1, $PM_{2.5}$, and PM_{10} integral mass concentrations from the mass concentration estimates made using optical particle counter (OPC) measurements, as described in full in Section 3.2 of the SI. These gravimetric calibration factors are applied to all indoor and outdoor OPC readings throughout the study to approximate mass concentrations.

While the combination of relative and absolute co-location calibration comparisons does not fully address absolute uncertainty in instrument readings, the simultaneous indoor and outdoor monitoring approach in the field using instruments that are, at minimum, calibrated against one another allows for useful comparisons, especially in indoor/outdoor concentration ratios (Chan and Singer, 2014). Moreover, periodic co-location comparisons against one another and/or against reference instruments over time allow for accounting for sensor drift, which has been shown to be especially important for electrochemical gas sensors such as those used to measure O_3 and NO_2 (Afshar-Mohajer et al., 2018). A full summary of co-location calibration procedures and results is included in Section 3 of the SI.

2.4. Selection and installation of ventilation system retrofits

Multiple types of mechanical systems are currently used to deliver ventilation air in U.S. residences and to meet the ventilation requirements of ASHRAE Standard 62.2 (ASHRAE, 2019), which is the most widely used residential ventilation standard in the U.S. Allowable and commonly used systems include exhaust-only, supply-only, and balanced exhaust and supply systems (Aldrich, 2014). These systems vary widely in the way that outdoor air is delivered into a home (Russell et al., 2007), in how well they can filter the incoming outdoor air (Stephens, 2015b; Rudd and Bergey, 2014; Less and Walker, 2014), and in their upfront costs and recurring direct and indirect energy costs for operation (Hun et al., 2013; Walker and Sherman, 2008; Logue et al., 2013). They also vary in how they are operated (i.e., continuously or intermittently).

After the first four approximately weeklong periods of field measurements in the first year of the study, we coordinated with a local contractor and study participants to assign and install ventilation system retrofits. The required ventilation rates for each home were calculated using ASHRAE 62.2-2016, which bases ventilation rates on the occupied floor area and the number of bedrooms. We did not give credit for existing air infiltration in the ventilation rate calculations. Each home then received one of three main types of residential mechanical ventilation systems (Fig. 3). The assignment of ventilation system type was pseudo-randomized, to the greatest extent possible, but subject to practical constraints including the feasibility of installation, costs of installation, the magnitude of required ventilation rates, and potential health and safety risks from a certain type of ventilation system. For example, exhaust-only systems draw ventilation air through cracks, leaks, and unintentional openings in the building envelope. Since these systems negatively pressurize the home relative to outdoors, there may be some potential risk of bringing outdoor contaminants indoors or drawing moist outdoor air into the wall cavity that could condense during the cooling season and lead to moisture problems. Therefore, homes with observable dampness or musty odor in the basement were generally not prioritized for exhaust-only systems. Conversely, supply-only systems draw outdoor air from a known intake location and deliver the air to the interior space. These systems positively pressurize the home relative to outdoors so that indoor air exits primarily through the building enclosure, likely minimizing contaminants entering through the building enclosure.

In this work, all supply-only systems were intermittent powered central-fan-integrated-supply (CFIS) ventilation systems that utilized the existing central air handler and ductwork. Our CFIS systems utilized a powered ventilator product with a motorized outdoor air damper and an automatic timer control to ensure that ventilation air is periodically supplied even when the system has not run to meet heating or cooling needs. Obviously, CFIS systems could not be installed in homes without central heating and/or cooling systems and ductwork, which made a portion of recruited homes ineligible for CFIS. Balanced ventilation systems are a combination of exhaust and supply methods providing approximately equal indoor exhaust and outdoor supply airflows. We prioritized the pairing of balanced systems with homes that could accommodate a dedicated, independently ducted system connected to an energy recovery ventilator (ERV). However, not all homes in this category had space or access for a fully ducted system; for these, we utilized the existing central ductwork.

The selection process for the type of ventilation system that each home was to receive began with a review of these practical factors. An initial priority list for each home was provided to a local contractor to

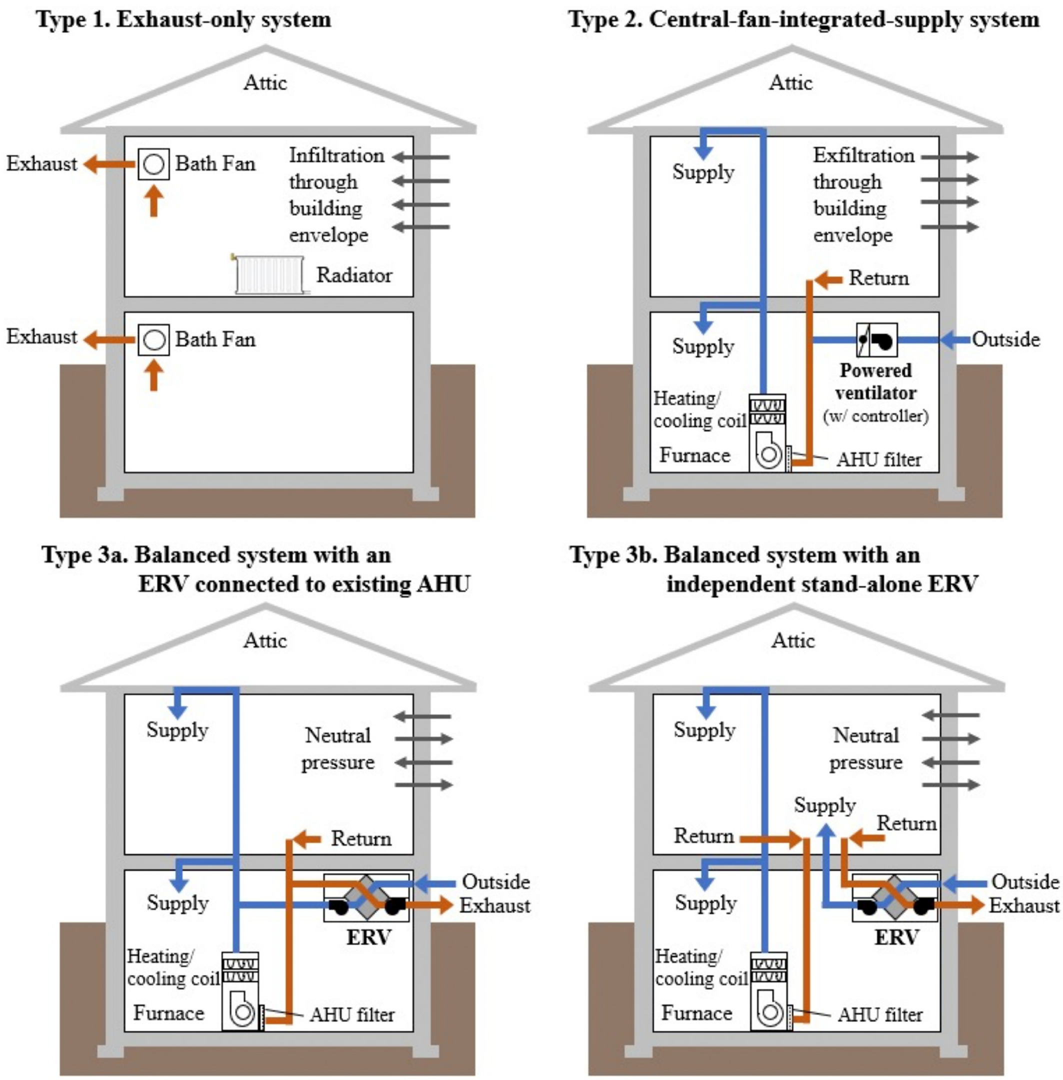

Fig. 3. Diagrams of the three main types of mechanical ventilation systems installed in the study homes.

guide their selection efforts in the field. Several manufacturers donated bathroom exhaust fans, powered CFIS ventilators and controllers, and ERVs of various sizes for installation in this study. The contractors were given the authority to make decisions on which of the three types of systems to install in each home while in the field, guided by the initial priority list but subject to on-site constraints, homeowner preference, and their own judgement for what the most appropriate and reasonably cost-effective solution would be. Ultimately, the three main types and makes and models of installed ventilation systems included:

- **Type 1: Continuous exhaust-only ventilation systems** – bathroom exhaust fans running continuously. One of two exhaust fans (either Broan ZB or Panasonic FV fans and accessories) was installed to meet ventilation requirements.
- **Type 2: Intermittent powered central-fan-integrated-supply (CFIS) ventilation systems** – in-line powered ventilators and automatic fan-cycler timers (both from Aprilaire) integrated into the existing air handling units. The timers were set to operate the air handler typically between 15 and 20 min out of every 60 min if not met by heating/cooling operation, selected by the contractors (see details below).
- **Type 3: Continuous balanced supply and exhaust ventilation systems** – combination systems that use both exhaust and supply ducts with energy recovery ventilator (ERV) units (either Broan ERV or RenewAire EV units and accessories). For homes with a central forced-air handling system and a finished basement, a multi-point ERV with full connection to the central air handler was installed (Type 3a) such that the ERV delivered outdoor air into the existing ductwork, operating continuously and independently from the air handler fan. For other homes, an independently ducted ERV (Type 3b) was installed. There was one exception that had a hybrid system where an ERV supplies the fresh outdoor air into the main return duct of a central air handler (Type 3a), while a dedicated exhaust duct pulls stale air from rooms (Type 3b). Air filters on the ERV cores were MERV 6 (Broan ERV110; 30 ppi washable foam) and MERV 8 (RenewAire EV130: spun-polyester media).

In general, homes without a central air handling unit were prioritized to receive either system type 1 (continuous exhaust-only) or system type 3 (continuous balanced with ERV with independent, dedicated ductwork). These fully ducted systems required significant construction efforts, typically removing portions of interior wall assemblies to run ductwork from the attic or basement into the house. Because of the excessive time and effort involved in installing dedicated balanced systems, typically only a single-point supply and single-point exhaust configuration was used, or the existing HVAC ductwork was utilized. Homes in which health and safety issues such as visible mold or moisture or visible (not damaged) asbestos materials were observed were prioritized for system type 2 (intermittent CFIS) to attempt to pressurize the building with outdoor air and prevent disturbances that could cause such health hazards to circulate, or system type 3 (balanced with ERV), which should not change the pressure difference across the envelope.

Additionally, while the contractors were on site for the ventilation system installation, they were instructed to check the existing HVAC filters in those homes with central forced-air heating or cooling systems. If a system had a low-efficiency filter, defined as less than approximately MERV 10, their filter was replaced with a MERV 10 electrostatically charged filter (provided by Tex-Air filters). If their existing filter was rated higher than MERV 10 or equivalent, occupants were allowed to continue to use their own filter. For those homes that received new filters, field personnel replaced filters with the same MERV 10 filter at every subsequent quarterly site visit. Details of the AHU filters used in each home are summarized in Table S8.

During (and after) the ventilation system installations, the contractors were given the authority to make decisions in response to homeowner complaints or preferences regarding the exact flow rate, runtime, and outdoor temperature thresholds for the intermittent CFIS systems. For example, the default upper and lower outdoor temperature thresholds for the powered ventilator controllers, above and below which the ventilator units would not operate to avoid bringing in excessively hot or cold air, were 35 °C and −6.7 °C. However, if homeowners complained or were concerned about excessively hot or cold air, the contractors could adjust these thresholds. The default runtime of powered ventilators was 20 min out of every 60 min, and the controllers automatically gave credit for heating and cooling operation while ventilating, although in a few homes the contractors set lower or higher runtimes in response to homeowner concerns. These adjustments were never lower than 15 min out of 60 min to meet the minimum ventilation rate requirements and never higher than 30 min out of 60 min to prevent a coil freeze-up. The powered ventilators were tied into the existing central air handlers such that when ventilation was called for by the controller, the air handler fan operated in tandem with the powered ventilator fan. Conversely, when heating or cooling was called for, the powered ventilator fan drew in outdoor air (unless the outdoor temperature was above or below the temperature threshold). Several example installation photos are also shown in Fig. S10.

Last, as part of the ventilation system retrofit installations, we also upgraded the furnace motor in 16 homes with central forced-air heating or cooling systems to evaluate the benefits of energy-efficient furnace motors for reducing electrical energy consumption. Permanent split capacitor (PSC) motors, which are the most common type of furnace motor in existing residential buildings (and in the study homes), were replaced with electronically commutated motors (ECMs), which can be programmed to operate over a broad range of speeds and deliver constant airflow for a variety of external static pressures. ECMs maintain high efficiency over a range of speeds, typically around 70% for motors that have fractional horsepower and above 80% for those at integral horsepower, whereas PSC motors have a lower efficiency with generally single-speed (e.g., 35–50% in airflow applications), especially when operating at less than full load (Lutz et al., 2006; Sachs et al., 2002; Yin et al., 2016; Fazli et al., 2015). The operational characteristics of homes that received ECMs as described below were not any different from those with PSC motors, and this paper does not investigate the energy savings from the ECMs.

2.5. Data processing and analysis

Resulting time-resolved measurement data from each indoor and outdoor monitoring instrument from each home visit were retrieved and processed after collecting the indoor and outdoor monitoring boxes. The storage capacity and battery life of each monitoring box were checked for the next measurement at the next scheduled field site visit. Data from each instrument were stored as comma-separated values (.csv) files, text documents (.txt), or spreadsheet (.xls) files in raw form, each with initially differing timestamps. Data were then processed into a standardized time-matched format for subsequent analysis using custom Python code. Calibration factors were then applied to the raw timestamp-matched data for subsequent data analysis and newly processed and merged data files were saved for use in subsequent analyses.

Prior to analysis, potential measurement errors in the resulting datasets that were likely caused by instrument failure or malfunctions were detected and excluded as potential outliers using a modified Z-score method (Iglewicz and Hoaglin, 1993). Time-varying 1- and 2-minute resolution data such as indoor and outdoor air pollutants, temperature and RH, and some collected continuous data in housing characteristics (e.g., construction year, total floor area, number of bedrooms and occupants, and ventilation rate measurements) were presented as mean, standard deviation (SD), median, interquartile range (IQR), and 10th-90th percentile range. Indoor HCHO concentrations that were observed to be lower than the limit of detection of the instrument (10 ppb) were replaced with half the LOD (EPA, 1990). Shapiro-Wilk tests were performed to check whether the measured variables had a normal distribution.

Testable hypotheses included: (i) reductions in time-averaged concentrations and indoor/outdoor (I/O) concentration ratios of pollutants with significant indoor sources (e.g., CO_2, $PM_{2.5}$, PM_{10}, and NO_2) would be observed in all three ventilation system groups in the year after the mechanical ventilation systems are installed compared to the prior year, (ii) the magnitude of changes in time-averaged I/O concentration ratios of pollutants with significant outdoor sources (e.g., O_3, $PM_{2.5}$, PM_{10}, and NO_2) would vary based on the type of ventilation system received because of differences in outdoor air and pollutant entry points, and (iii) there would be differences in indoor environmental conditions (e.g., temperature and RH) from year 1 to 2 based on the type of ventilation system received. To evaluate these hypothesized impacts of residential mechanical ventilation systems on indoor and outdoor air quality and environmental conditions, the Wilcoxon matched-pairs signed-rank test was used to compute the air quality difference between during the pre- and post-intervention period. All statistical analyses, including power analysis, were performed using Stata Version 15.1.

3. Results and discussion

3.1. Housing information and basic building performance testing

Selected summary information on housing characteristics obtained from baseline and end-line surveys and initial walkthrough assessments for all 40 homes is presented in Table S8. Table 2 summarizes the results of several housing characteristics, basic building performance testing, and calculated ventilation rate requirements (following ASHRAE 62.2-2016) for the entire study group and by each of the three types of ventilation system retrofits. One-way ANOVA was used to compare differences among the three groups. A summary of statistical power calculations for the comparisons in Table 2 is shown in Table S16.

A total of 13 homes received system type 1 (exhaust only, with 8 homes receiving one exhaust fan and 5 homes receiving 2 exhaust fans); 15 homes received system type 2 (intermittent powered CFIS); and 12 homes received system type 3 (balanced with ERV, with 7 homes integrating an ERV into the existing central forced-air system ductwork and 5 homes utilizing newly constructed stand-alone ductwork). All participating homes were built before 1970, with an average year of construction of 1923, and most were Chicago bungalows, as most recruitment occurred through the Chicago Bungalow Association. Therefore, the sample of homes is a convenience sample and is not representative of the distribution of homes in Chicago. The sample of homes does however represent a very typical style of vernacular

Table 2
Summary of study home characteristics overall and by ventilation system type.

Items	Total (n = 40)	Group 1 (n = 13)	Group 2 (n = 15)	Group 3 (n = 12)	One-way ANOVA[d]
	–	Exhaust-only	CFIS	Balanced	p-Value
Construction year					**0.012**
Mean ± SD	1923 ± 14	1920 ± 10	1918 ± 11	1933 ± 17	
Median (10th–90th)	1923 (1913–1931)	1924 (1913–1928)	1920 (1906–1927)	1926 (1917–1954)	
Total floor area (m^2)					0.613
Mean ± SD	220 ± 76	233 ± 73	205 ± 76	224 ± 84	
Median (10th–90th)	221 (125–300)	249 (149–325)	228 (96–290)	195 (161–294)	
Bedrooms (N)					0.685
Mean ± SD	3.4 ± 1.0	3.3 ± 1.0	3.3 ± 1.0	3.6 ± 1.0	
Median (10th–90th)	3.0 (2.0–4.0)	3.0 (2.2–4.0)	3.0 (2.0–4.0)	3.5 (3.0–4.0)	
Occupants (N)					0.963
Mean ± SD	3.0 ± 1.6	2.9 ± 1.6	3.1 ± 1.4	3.1 ± 1.9	
Median (10th–90th)	3.0 (1.0–5.1)	3.0 (1.0–4.8)	3.0 (1.4–4.6)	2.5 (1.1–5.9)	
Airtightness (L/s @ 50 Pa)					0.835
Mean ± SD	1817 ± 797	1755 ± 503	1766 ± 658	1943 ± 1217	
Median (10th–90th)	1755 (1110–2604)	1755 (1268–2508)	1808 (962–2548)	1521 (940–4017)	
ACH_{50}[a]					0.572
Mean ± SD	11.7 ± 5.1	11.0 ± 4.6	12.8 ± 6.1	10.9 ± 4.4	
Median (10th–90th)	10.5 (6.0–17.3)	9.3 (6.1–16.8)	12.3 (6.2–21.1)	9.6 (7.3–16.4)	
Air handler airflow rates (L/s)					0.897
Mean ± SD	410 ± 102	388 ± 201	417 ± 86	406 ± 103	
Median (10th–90th)	405 (293–565)	340 (239–555)	429 (301–521)	395 (307–564)	
Ventilation requirements[b] (L/s)					0.597
Mean ± SD	47 ± 14	49 ± 13	44 ± 13	48 ± 17	
Median (10th–90th)	49 (31–64)	52 (34–64)	50 (23–55)	42 (35–65)	
Measured ventilation airflow rates[c] (L/s)					**<0.001**
Mean ± SD	60 ± 19	50 ± 12	78 ± 14	47 ± 11	
Median (10th–90th)	55 (35–64)	52 (35–64)	77 (61–93)	42 (35–57)	

[a] Air changes per hour at 50 Pa.
[b] Ventilation requirements calculated based on ASHRAE Standard 62.2-2016.
[c] Ventilation airflow rate measurements made immediately after the installation of ventilation system retrofits.
[d] Bold values indicate p < 0.05.

architecture in Chicago, as there are over 80,000 bungalows in the city (CBA, 2021). Group 3 homes (balanced with ERV) were slightly newer, on average (one-way ANOVA $p = 0.012$). The average number of bedrooms was 3, ranging from 2 to 6; the average number of occupants was 3, ranging from 1 to 7; and the average total floor area was 220 m^2, ranging from 64 to 441 m^2. Most homes had a finished basement (67%) and finished attic (59%). Approximately three-quarters (73%) of participating homes were equipped with one or two central air handling units, while no dedicated residential mechanical ventilation system was installed in any homes prior to the study (although one home did have two of four bathrooms with exhaust fans running continuously upon first assessment). The majority of homes (90%) had a gas stove, while only 4 homes (10%) had an electric stove. About 62% of homes had an exhaust fan in at least one bathroom at baseline, but only 38% of homes had an exhaust fan in the kitchen. About 37% of the participants responded that they sometimes used the stove fan, and 39% responded that they never use an exhaust fan in the bathroom. In addition, about 18 participants (47%) responded that there had been water or dampness in their home at some point; 25 participants (63%) noticed musty smells; and 26 participants (67%) reported they used any air fresheners or deodorizers in the last 12 months.

The average baseline airtightness of the building envelope across the study homes was approximately 1805 L/s (3,824 cfm) at 50 Pa. These values translate to average air changes per hour at 50 Pa (ACH_{50}) of 11.7 across all study homes assuming a standard ceiling height of 2.7 m (9 ft). The average airflow rate through the central air handling units (in homes that had them) was 415 L/s (879 cfm). The average minimum required ventilation airflow rate calculated according to ASHRAE Standard 62.2-2016 was 47 L/s (100 cfm) across all homes, with negligible differences between the three home groups. There were no statistically significant differences in baseline airtightness ($p = 0.835$), ACH_{50} ($p = 0.572$), air handler airflow rates ($p = 0.897$), or ventilation requirements ($p = 0.597$) among the three ventilation retrofit groups. However, after the installation of mechanical ventilation systems, there were significant differences in measured ventilation airflow rates among the three groups ($p < 0.001$), most notably for intermittent CFIS systems, which had higher delivered flow rates to compensate for intermittent operation (as explored in more detail in Section 3.2).

Exhaust fan flow rates of the bathroom fans and kitchen fans were also measured during the initial home walkthroughs. Twenty-three homes (58%) had one or more bathroom exhaust fans, with an average (SD) flow rate of 22 (8) L/s [47 (18) cfm]. Nine homes (23%) had a kitchen exhaust fan that vented to the outside (several others had only recirculating fans), with an average (SD) flow rate of 50 (31) L/s [105 (65) cfm]. Full details from basic building performance testing, initial walkthrough assessments, baseline and end-line surveys, and calculated ventilation flow rate requirements are shown in the SI (Tables S8–S10).

3.2. In-situ HVAC measurements

Fig. 4 shows a distribution dot plot of the measured central HVAC system runtime for those homes that had central forced-air HVAC systems in the pre-intervention period (July 2017–August 2018) prior to receiving ventilation systems and in the post-intervention period (February 2019–March 2020) after homes received their assigned mechanical ventilation systems. Each dot represents the average HVAC system runtime data measured at each home for each season. More detailed HVAC system runtime data are included in Table S9. The average central air handler runtime during the measurements across 10 seasons from Summer 2017 to Winter 2020 was approximately 28.8% across all homes, systems, and seasons, with a standard deviation of 24.8% and a median of 23.5%. The minimum for a given visit was 0% and the maximum was 99.7%. These data are similar in magnitude to a recent study of HVAC runtimes in over 7000 homes in North America with smart thermostats, which reported a median of 18% across all homes in the data set (Touchie and Siegel, 2018).

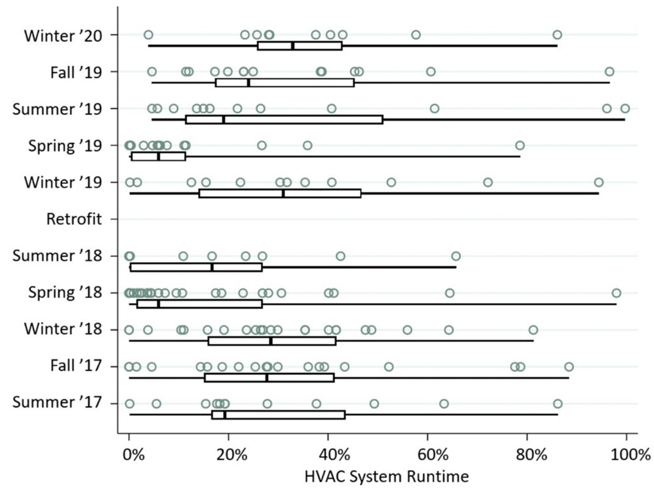

Fig. 4. Measured HVAC system runtime by season across all homes and visits.

The average central air handler runtime during the pre-ventilation period was approximately 28.3%, with a standard deviation of 23.4% and a median of 25.4%, while the average during the post-ventilation period was 29.4%, with a standard deviation of 26.8% and a median of 23.0%. There was no statistically significant difference in HVAC system runtimes between the pre- and post-intervention periods (t-test $p = 0.39$). This finding may be counterintuitive because of the expected intermittent CFIS system runtime and additional heating/cooling loads introduced by the ventilation systems. However, for the CFIS systems that operated intermittently on a timer, the logic controller gives 'credit' towards ventilation operation when the air handler operated within a given hour to meet heating or cooling needs; thus, there were no substantial increases in runtime, on average. Additionally, although this analysis does not control for differences in weather conditions before and after ventilation system installation, results suggest that HVAC runtimes were not drastically altered by the increased heating/cooling loads introduced by additional ventilation air. The average system runtime across all homes, systems, and seasons was highest during the winter (34%) and lowest in the spring (14%), which is consistent with expectations of increasing runtime with increased heating and cooling loads. In addition to negligible changes in central forced-air system runtimes, the average change in the airflow rate through the central air handling units between pre- and post-intervention periods across all study homes was only −2% (Table S12), which suggests that the combination of filter and fan change-outs did not substantively impact air handler flow rates.

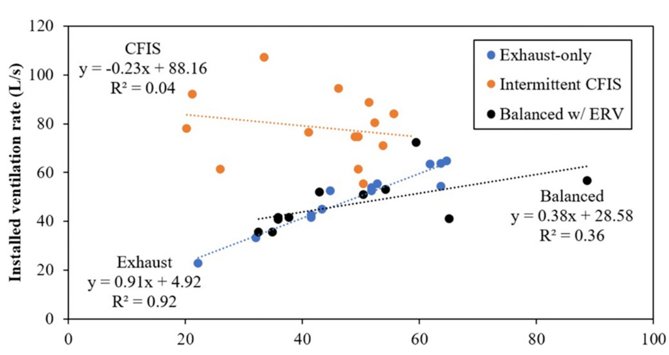

Fig. 5. Association between the ventilation requirements calculated based on ASHRAE Standard 62.2-2016 and measured ventilation flow rates of each ventilation system type. Blue, orange, black dots indicate flow rates in exhaust-only system, CFIS system, balanced system with an ERV, respectively. Dotted lines represent the linear regression line for each system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5 shows associations between the ventilation flow rate requirements for each home calculated based on ASHRAE Standard 62.2 and the measured ventilation flow rates of each ventilation system type as installed, grouped by the three system types. The continuous exhaust-only system shows a strong correlation between measured ventilation flow rates and required flow rates ($R^2 = 0.92$), while the intermittent CFIS system shows a very weak correlation ($R^2 = 0.04$). The continuous balanced system with an ERV shows a moderate correlation between measured ventilation flow rates and required flow rates ($R^2 = 0.36$). The varied strength of these correlations demonstrates how the continuous system types (both exhaust-only and balanced with ERV) were able to be sized and installed more closely following ASHRAE Standard 62.2 flow rate requirements than the intermittent CFIS systems. Conversely, the intermittent CFIS systems had to be sized and installed with greater flow rates to compensate for their intermittent operation, while other factors such as contractor concerns over delivering excessive untampered air led to high variability across homes in the magnitude of ventilation flow rates delivered while operating. Table S13 summarizes required and measured outdoor airflow rate, average runtime data, estimated cumulative annual delivered outdoor air flows (i.e., ventilation flow rate times annual average ventilation system runtime), and ventilation system power draw data for each of the study homes. The mean (SD) estimates of cumulative annual delivered outdoor air flows of the exhaust-only, CFIS, and balanced with ERV systems were estimated to be 1560 (390), 890 (280), and 1490 (350) 10^6 L, respectively. Additionally, Fig. S11 shows an example of time series power draw data for (a) an intermittent CFIS system and (b) a balanced system with an ERV, both measured using plug load data loggers.

3.3. Indoor and outdoor air quality data

3.3.1. Example time-series data

Fig. 6 illustrates an example of time-series data resulting from continuous measurements of indoor and outdoor CO_2, NO_2, O_3, and $PM_{2.5}$ made in one of the participating homes during one representative visit at the final visit of the study in February 2020, after receiving an exhaust-only system in 2019. Indoor CO_2 levels show intermittent increases well over 1000 ppm and subsequent decay over time while outdoor CO_2 levels remain relatively constant around 400 ppm, indicating the presence of occupants or other indoor sources. Fig. 6 also indicates that I/O ratios of CO_2 were always higher than 1 during this visit, as expected. There are also intermittent peaks of indoor NO_2 and $PM_{2.5}$ concentrations due to indoor sources and activities, followed by clear decays towards background levels. Conversely, indoor O_3 levels were consistently lower than outdoor levels and relatively constant over time, while outdoor levels varied throughout each day, which suggests that indoor O_3 primarily comes from outdoors (again, as expected). At the same time, a lack of variation in indoor O_3 concentrations may also be a function of instrument limitations, as experience with this instrument suggests a higher functional limit of detection than reported by the manufacturer.

3.3.2. Summary of indoor/outdoor pollutant concentrations and environmental conditions

Summary statistics for indoor and outdoor air pollutant concentrations and temperature and relative humidity measured in all homes at each season of the entire study period are summarized in Table S14. The average indoor and outdoor pollutant concentrations during pre- and post-intervention periods for all study homes are also summarized in Table S15. Average concentrations of indoor HCHO, CO, CO_2, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10} across all seasons varied widely across homes. Mean (SD) indoor concentrations across all homes were 21.4 (19.7) ppb for HCHO; 4.0 (2.5) ppm for CO; 719 (205) ppm for CO_2; 61.1 (7.7) ppb for NO_2; 10.3 (2.2) ppb for O_3; 9.7 (11.9) μg/m^3 for PM_1; 11.0 (13.4) μg/m^3 for $PM_{2.5}$; and 13.0 (14.7) μg/m^3 for PM_{10}. Concurrent mean (SD) outdoor concentrations across all homes were

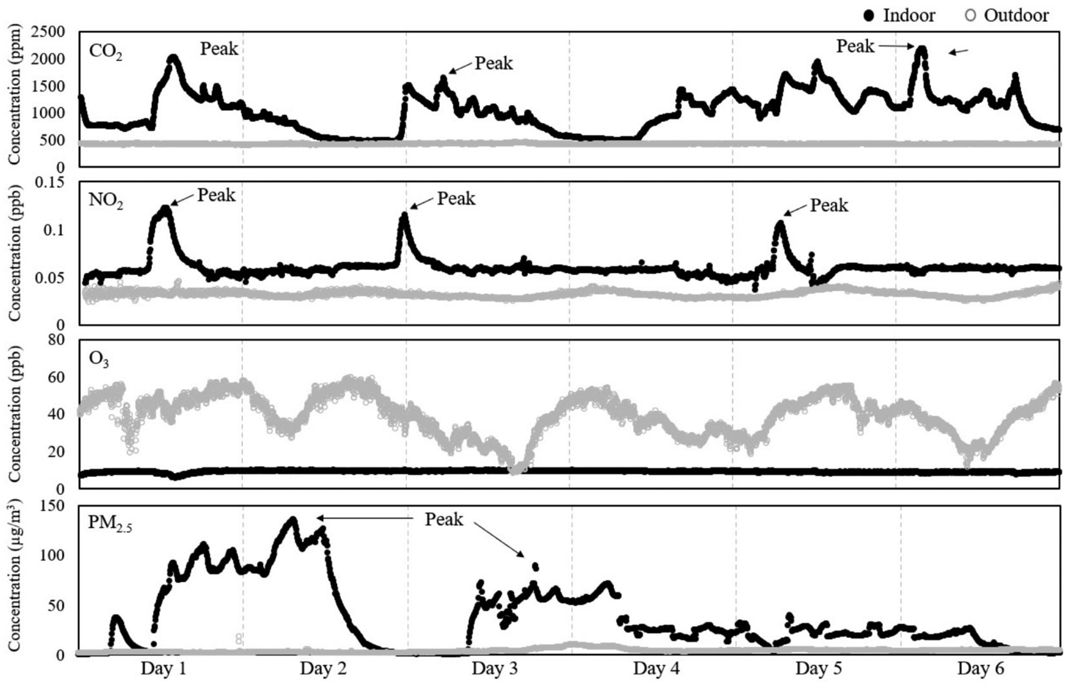

Fig. 6. Consecutive 6-day monitoring of indoor and outdoor CO_2, NO_2, O_3, and $PM_{2.5}$ concentrations in one of the study homes between February 19–24, 2020, after receiving an exhaust-only system in 2019.

2.0 (2.1) ppm for CO; 418 (12) ppm for CO_2; 80.3 (7.2) ppb for NO_2; 16.6 (3.5) ppb for O_3; 15.5 (4.2) μg/m^3 for PM_1; 16.3 (4.3) μg/m^3 for $PM_{2.5}$; and 18.3 (4.4) μg/m^3 for PM_{10}. Also, the mean (SD) indoor temperature and RH across all homes were 24.9 (1.9) °C and 38.0 (4.3) %, respectively, while mean (SD) outdoor temperature and RH across all homes were 17.9 (3.0) °C and 45.6 (5.7) %, respectively.

Within-home average indoor concentrations and environmental conditions across all seasons ranged as follows: from 5.0 to 90.3 ppb for HCHO; from 0.05 to 9.14 ppm for CO; from 463 to 1537 ppm for CO_2; from 50.4 to 105.5 ppb for NO_2; from 2 to 15 ppb for O_3; from 0.9 to 78.2 μg/m^3 for PM_1; from 1.0 to 87.8 μg/m^3 for $PM_{2.5}$; from 1.6 to 92.6 μg/m^3 for PM_{10}; from 19.7 to 29.9 °C for indoor temperature; and from 25.4 to 48.3% for indoor RH. Concurrent within-home average outdoor concentrations and environmental conditions across all seasons ranged as follows: from 0.01 to 6.50 ppm for CO; from 390 to 439 ppm for CO_2; from 59.4 to 100 ppb for NO_2; from 9.2 to 26.7 ppb for O_3; from 5.9 to 27.9 μg/m^3 for PM_1; from 6.2 to 28.5 μg/m^3 for $PM_{2.5}$; from 6.7 to 31.1 μg/m^3 for PM_{10}; from 5.7 to 24.3 °C for outdoor temperature; and from 34.5 to 59.6% for outdoor RH.

Mean (SD) indoor/outdoor ratios of pollutant concentrations across all homes were 1.72 (0.49) for CO_2; 0.77 (0.14) for NO_2; 0.65 (0.19) for O_3; 0.67 (0.84) for PM_1; 0.73 (0.91) for $PM_{2.5}$; and 0.75 (0.86) for PM_{10}. Within-home average I/O ratios of pollutant concentrations across all seasons ranged as follows: from 1.10 to 3.64 for CO_2; from 0.57 to 1.53 for NO_2; from 0.12 to 1.21 for O_3; from 0.05 to 5.05 for PM_1; from 0.05 to 5.36 for $PM_{2.5}$; from 0.06 to 4.84 for PM_{10}. It should be noted that I/O concentration ratios for CO were excluded during data quality assessment due to poor measurement performance of the low-cost sensors used to measure CO, which resulted in large amounts of missing data and many implausible I/O concentration ratios. Moreover, I/O ratios of these constituents are most relevant for providing a basis of comparison to other studies that have measured similar constituents in homes, as I/O ratios allow for controlling for variability in simultaneously measured outdoor concentrations (Chan and Singer, 2014; Weisel et al., 2004; Tham et al., 2021). For comparison, Fazli and Stephens (2018) summarized I/O ratios of several pollutants from a large number of residential field studies, primarily in North America, and reported that most I/O ratios were ~0.8–1.2 for $PM_{2.5}$, ~0.5–3 for NO_2 (depending heavily on stove type), and ~0.1–0.3 for O_3. Our resulting median I/O ratios of 0.77 for NO_2 and 0.73 for $PM_{2.5}$ are well in line with these ranges from the literature; however, our resulting median I/O ratio of 0.65 for O_3 is unrealistically high (Zhao and Stephens, 2016), again suggesting a lack of reliability in this low-cost instrument, especially at low concentrations expected inside homes. Thus, O_3 results herein should be interpreted with caution.

3.3.3. Impacts of all ventilation system retrofits on IAQ and environmental conditions

Summary statistics of the measured air pollutant concentrations as well as temperature and relative humidity measured indoors and outdoors of all homes during the pre-intervention and the post-intervention periods are shown in Table 3. Fig. 7 also shows I/O ratios for CO_2, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10} for both pre-intervention and post-intervention periods and the results of the Wilcoxon matched-pairs signed-rank tests, grouping all homes together for pre- and post-intervention comparisons. Each dot represents the I/O ratios of pollutants for each home at pre- and post-intervention periods. The hypothesis that indoor pollutant concentrations and I/O ratios are expected to decrease after the installation of residential mechanical ventilation systems is supported for indoor HCHO ($p < 0.001$), indoor CO_2 ($p < 0.001$), indoor particles (PM_1, $PM_{2.5}$, and PM_{10}; all $p < 0.001$), and I/O ratios of CO_2 ($p = 0.001$), NO_2 ($p = 0.008$), PM_1 ($p < 0.001$), $PM_{2.5}$ ($p = 0.002$), and PM_{10} ($p = 0.007$). Mean relative reductions in I/O ratios in the post-intervention period compared to the pre-intervention period were approximately 12%, 10%, 42%, 39%, and 33%, for CO_2, NO_2, PM_1, $PM_{2.5}$, and PM_{10}, respectively. There were no statistically significant differences in I/O ratios for O_3. A summary of statistical power calculations for the comparisons in Table 3 and Fig. 7 is shown in Tables S17 and S18.

These effects are largely intuitive, as introducing more outdoor air through any of the types of mechanical ventilation used herein would be expected to reduce indoor concentrations of pollutants with major indoor sources such as CO_2, NO_2, and PM of various sizes. The largest mean reductions in I/O ratios across all pollutants were for the three PM metrics, which may be attributable not only to the addition of

Table 3
Summary of indoor and outdoor pollutant concentrations, environmental conditions, and I/O ratios of pollutants measured during pre- and post-intervention periods.

Variable	Pre-intervention (n = 40)[a]		Post-intervention (n = 40)[b]		Wilcoxon's signed-rank test	
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Z	P[c]
Indoors						
HCHO (ppb)	31.2 (23.5)	23.5 (14.5–42.4)	11.7 (6.5)	11.2 (6.9–13.9)	−4.920	**<0.001**
CO (ppm)	4.20 (2.52)	4.61 (1.77–6.06)	3.80 (2.51)	3.87 (1.74–5.22)	−0.330	0.742
CO_2 (ppm)	779 (233)	712 (629–942)	659 (152)	632 (536–715)	−4.174	**<0.001**
NO_2 (ppb)	62.0 (9.3)	60.1 (56.6–65.4)	60.3 (5.8)	59.2 (56.3–63.3)	−1.586	0.113
O_3 (ppb)	10.5 (1.5)	10.6 (9.3–11.5)	10.1 (2.7)	10.4 (8.1–12.5)	−0.504	0.614
PM_1 (μg/m³)	12.99 (14.60)	7.80 (6.01–12.81)	6.43 (7.32)	3.79 (2.59–6.05)	−3.723	**<0.001**
$PM_{2.5}$ (μg/m³)	14.41 (16.42)	8.74 (6.72–14.34)	7.64 (8.81)	4.24 (3.04–7.12)	−3.468	**<0.001**
PM_{10} (μg/m³)	17.10 (17.74)	10.73 (9.31–16.80)	8.98 (9.85)	5.44 (3.78–8.24)	−3.481	**<0.001**
Temp (°C)	24.6 (1.8)	25.1 (23.3–25.6)	25.0 (2.2)	25.5 (23.8–26.5)	−2.090	**0.037**
RH (%)	39.2 (3.7)	39.3 (37.1–41.6)	36.9 (4.6)	36.7 (33.5–40.3)	2.682	**0.007**
Outdoors						
CO (ppm)	1.37 (1.26)	0.97 (0.35–2.32)	2.51 (2.46)	2.67 (0.11–5.26)	1.856	0.064
CO_2 (ppm)	425 (8)	425 (419–431)	410 (10)	411 (403–418)	−4.981	**<0.001**
NO_2 (ppb)	78.1 (8.5)	76.9 (72.1–82.5)	82.6 (4.7)	82.7 (79.0–85.1)	2.803	**0.005**
O_3 (ppb)	15.6 (1.9)	15.8 (14.1–17.1)	17.6 (4.3)	17.4 (14.7–20.6)	2.386	**0.017**
PM_1 (μg/m³)	15.19 (3.67)	14.85 (13.23–17.43)	15.87 (4.80)	16.04 (12.88–18.47)	1.028	0.304
$PM_{2.5}$ (μg/m³)	16.06 (3.81)	15.68 (13.96–18.32)	16.45 (4.87)	16.57 (13.25–19.22)	0.773	0.440
PM_{10} (μg/m³)	18.98 (3.79)	18.85 (16.92–21.73)	17.55 (4.92)	17.85 (14.33–20.30)	−1.297	0.195
Temp (°C)	19.2 (2.6)	19.2 (17.8–20.4)	16.5 (2.9)	16.6 (15.5–18.2)	3.985	**<0.001**
RH (%)	43.5 (4.9)	44.0 (40.4–45.8)	47.8 (5.6)	48.1 (43.3–52.3)	−2.957	**0.003**
I/O ratios						
CO_2	1.83 (0.56)	1.64 (1.46–2.20)	1.61 (0.38)	1.51 (1.35–1.75)	−3.239	**0.001**
NO_2	0.81 (0.17)	0.78 (0.69–0.88)	0.73 (0.09)	0.71 (0.67–0.78)	−2.675	**0.008**
O_3	0.68 (0.13)	0.68 (0.60–0.73)	0.62 (0.23)	0.61 (0.37–0.72)	−1.862	0.063
PM_1	0.85 (0.92)	0.60 (0.42–0.76)	0.49 (0.73)	0.24 (0.16–0.49)	−3.414	**<0.001**
$PM_{2.5}$	0.90 (0.98)	0.61 (0.43–0.80)	0.55 (0.81)	0.27 (0.19–0.58)	−3.118	**0.002**
PM_{10}	0.90 (0.89)	0.63 (0.46–0.82)	0.60 (0.82)	0.29 (0.22–0.58)	−2.715	**0.007**

SD: standard deviation; IQR: interquartile range.
[a] Sample includes the average across all quarterly pre-intervention visits at the 40 study homes (N = 160 visits).
[b] Sample includes the average across all quarterly post-intervention visits at the 40 study homes (N = 140 visits).
[c] 95% confidence level for a two-tailed test of Wilcoxon's signed-rank test; bold values indicate $P < 0.05$.

mechanical ventilation systems but also the upgrade of homes with heating and cooling systems to at least MERV 10 filtration. Moreover, the largest impact on I/O ratios for PM was for PM_1, which comprises smaller particles for which ventilation or air exchange is an important loss mechanism (Noris et al., 2009; Boedicker et al., 2021). We also expected to observe an increase in I/O O_3 ratios given that ambient air is the predominant source in homes and that increasing ventilation rates would tend to bring in more O_3; instead, a slight, although not statistically significant, the reduction was observed. However, it is worth noting that we have limited confidence in this low-cost instrument to reliably measure indoor O_3 concentrations at these low levels.

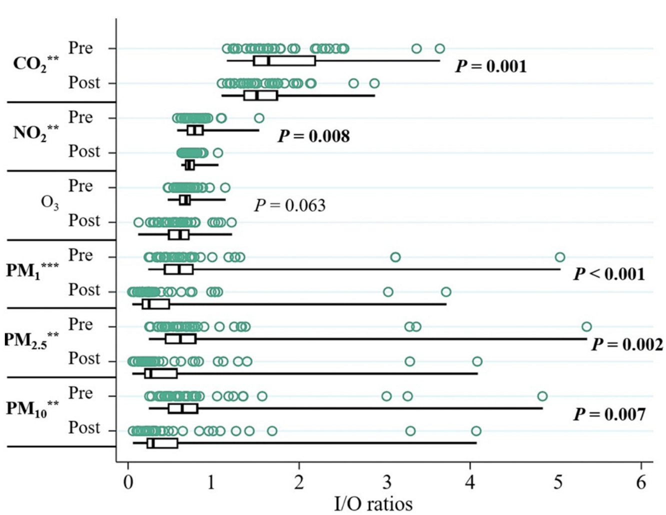

Fig. 7. I/O ratios of pollutants for all ventilation system types measured during pre- and post-intervention periods. Symbols denote: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Outdoor temperatures were significantly lower during the post-intervention visits than during the pre-intervention visits (mean of 16.5 °C vs. 19.2 °C; $p < 0.001$), but mean indoor temperatures were essentially constant despite a statistically significant difference (mean of 25.0 °C vs. 24.6 °C; $p = 0.037$). This suggests that the introduction of ventilation systems did not meaningfully alter indoor temperature conditions. Outdoor RH was significantly higher during post-intervention visits compared to pre-intervention visits (mean of 47.8% vs. 43.5%; $p = 0.003$), while indoor RH was significantly (but only slightly) lower during post-intervention visits compared to pre-intervention visits (mean of 36.9% vs. 39.2%; $p = 0.007$). A mean difference of ~2% RH is within instrument uncertainty (Table 1), which suggests that introducing ventilation air did not meaningfully impact indoor RH conditions. Some of these small differences in temperature and RH are also attributable to differences in weather conditions during field visits, as the seasons for field visits pre- and post-intervention were not perfectly aligned (i.e., July 2017–August 2018 for pre-intervention visits and February 2019–March 2020 for post-intervention visits).

3.3.4. Impacts of specific ventilation system retrofits on IAQ and environmental conditions

The impacts of each of the three types of ventilation system retrofit on indoor pollutant concentrations, environmental conditions, and I/O pollutant concentration ratios are summarized in Table 4. I/O concentration ratios are also summarized in Fig. 8. A summary of statistical power calculations for the comparisons in Table 4 and Fig. 8 is shown in Table S18. Focusing first on comparisons of I/O ratios for constituents that had concurrent indoor and outdoor measurements (i.e., CO_2, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}), the magnitudes of mean differences in I/O pollutant concentrations ratios were generally largest in the balanced with ERV (Group 3) homes for most pollutants and smallest in the intermittent CFIS (Group 2) homes. Mean differences in I/O ratios for the balanced with ERV (Group 3) homes pre- and post-intervention were

Table 4
Impact of specific ventilation system types on indoor and outdoor air quality, environmental conditions, and I/O ratios of measured pollutants.

Variable	Exhaust system ($n = 13$)			CFIS system ($n = 15$)			Balanced system with ERV ($n = 12$)		
	Δ Mean (post-pre)	Z	P[a]	Δ Mean (post-pre)	Z	P[a]	Δ Mean (post-pre)	Z	P[a]
Indoors									
HCHO (ppb)	−15.8	−2.691	0.007***	−22.3	−2.840	0.005***	−20.0	−2.824	0.005***
CO (ppm)	−0.90	−0.804	0.422	0.08	0.345	0.723	−0.38	−0.533	0.594
CO_2 (ppm)	−164.7	−2.830	0.005***	−28.7	−0.966	0.334	−185.9	−2.903	0.004***
NO_2 (ppb)	−3.48	−1.782	0.075*	−0.50	−0.454	0.650	−1.49	−0.392	0.695
O_3 (ppb)	−0.48	−0.245	0.806	−0.31	−0.227	0.820	−0.25	−0.236	0.813
PM_1 (μg/m^3)	−7.12	−1.712	0.087*	−5.34	−2.385	0.017**	−7.50	−2.510	0.012**
$PM_{2.5}$ (μg/m^3)	−7.42	−1.363	0.173	−4.98	−2.215	0.027**	−8.31	−2.590	0.010**
PM_{10} (μg/m^3)	−8.13	−1.083	0.279	−6.24	−2.385	0.017**	−10.45	−2.746	0.006***
Temp (°C)	0.49	1.084	0.278	0.41	1.137	0.256	0.66	1.374	0.170
RH (%)	−0.84	−0.419	0.675	−3.40	−2.442	0.015**	−2.71	−1.412	0.158
Outdoors									
CO (ppm)	0.83	0.356	0.722	1.66	2.191	0.028**	0.85	0.652	0.515
CO_2 (ppm)	−19.5	−3.183	0.002***	−15.5	−3.068	0.002***	−9.27	−1.923	0.055*
NO_2 (ppb)	3.13	0.874	0.382	2.64	1.306	0.191	8.32	2.275	0.023**
O_3 (ppb)	2.25	1.363	0.173	1.57	1.023	0.307	2.16	1.647	0.100
PM_1 (μg/m^3)	1.38	0.943	0.345	0.71	0.682	0.496	−0.11	0.039	0.969
$PM_{2.5}$ (μg/m^3)	1.14	0.804	0.422	0.37	0.454	0.650	−0.40	−0.157	0.875
PM_{10} (μg/m^3)	−0.55	−0.454	0.650	−1.55	−0.454	0.650	−2.23	−1.726	0.084*
Temp (°C)	−3.43	−3.180	0.002***	−2.93	−2.215	0.027**	−1.55	−1.296	0.195
RH (%)	6.98	2.411	0.016**	3.53	1.533	0.125	2.42	1.216	0.224
I/O ratios									
CO_2	−0.31	−2.341	0.019**	−0.01	−0.170	0.865	−0.41	2.746	0.006***
NO_2	−0.09	−1.642	0.101	−0.03	0.852	0.394	−0.11	2.197	0.028**
O_3	−0.06	−1.153	0.249	−0.07	0.938	0.349	−0.07	0.706	0.480
PM_1	−0.46	−2.132	0.033**	−0.21	−1.931	0.054*	−0.45	−1.961	0.049**
$PM_{2.5}$	−0.45	−1.782	0.075*	−0.16	−1.704	0.088*	−0.46	−1.961	0.049**
PM_{10}	−0.35	−1.013	0.311	−0.15	−1.761	0.078*	−0.45	−1.961	0.049**

P-values:
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.
[a] 95% confidence level for a two-tailed Wilcoxon's signed-rank test.

−0.41, −0.11, −0.07, −0.45, −0.46, and −0.45 for CO_2, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}, respectively, with $P < 0.05$ for all but O_3. For interpretation, a mean decrease in the I/O $PM_{2.5}$ ratio of 0.45 for the balanced with ERV (Group 3) homes is ~50% lower on a relative basis than the average pre-intervention I/O $PM_{2.5}$ ratio of 0.90 across all homes, while a decrease of 0.11 in the I/O NO_2 ratio corresponds to a ~14% relative reduction from the pre-intervention average of 0.81 across all homes. Next, mean differences in I/O ratios for the continuous exhaust (Group 1) homes pre- and post-intervention were −0.31, −0.09, −0.06, −0.46, −0.45, and −0.35 for CO_2, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}, respectively, with $P < 0.05$ for CO_2 and PM_1 and $P < 0.1$ for $PM_{2.5}$. Last, mean differences in I/O ratios for the intermittent CFIS (Group 2) homes pre- and post-intervention were −0.01, −0.03, −0.07, −0.21, −0.16, and −0.15 for CO_2, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}, respectively, with no constituent comparisons with $P < 0.05$ and $P < 0.1$ only for PM_1, $PM_{2.5}$, and PM_{10}.

These comparisons of I/O ratios suggest that there was a reduction in I/O ratios for all measured constituents among all three ventilation system groups, on average, but with varying magnitude and levels of statistical significance. Reductions in I/O ratios for estimates of PM_1 and $PM_{2.5}$ were generally the greatest in magnitude compared to the other measured constituents, suggesting that there were benefits to combining increased ventilation and higher efficiency particle filtration, especially in homes with central heating and cooling systems. Moreover, there were apparent benefits to providing ventilation flow continuously rather than intermittently, which may be attributed to inconsistent timing between intermittent mechanical ventilation runtimes and intermittent indoor pollutant sources and/or variability in the amount of ventilation flow delivered in the homes with intermittent CFIS systems (see Fig. 5). For comparison, the intermittent CFIS systems delivered an estimated ~42% lower amount of cumulative annual outdoor air volumetric flow (i.e., the delivered ventilation flow rate times the annual average ventilation system runtime) compared to the continuous exhaust-only and balanced with ERV systems, on average, with $p < 0.001$ from one-way ANOVA (Table S13).

Results in Table 4 also suggest that all three ventilation system types reduced indoor HCHO concentrations ($P < 0.05$) and maintained similar indoor temperatures during pre- and post-intervention periods with no significant differences ($P > 0.05$). There were also no significant differences in indoor RH between pre- and post-intervention periods in homes with exhaust systems or balanced systems, but there was a significant decrease in RH in homes with intermittent CFIS systems ($P = 0.015$). Slightly higher mean indoor temperatures were observed for all system types during the post-intervention period despite field visits being conducted during times of significantly lower outdoor temperatures compared to the pre-intervention visits. Similarly, mean indoor RH conditions were lower during post-intervention despite mean RH being higher outdoors during those times.

3.3.5. Costs and benefits of ventilation system retrofits

Here we evaluate the initial installed costs of the ventilation system retrofits in context with their impacts on IAQ. Table S11 provides full details of the total initial costs, including upfront costs, installation costs (including painting and other relevant costs), and miscellaneous costs (which includes additional contractor costs such as required health and safety repairs, running blower door tests, etc.) of each ventilation system installed in each home. ECM replacement costs are also shown in Table S11 and included in the summary of the total costs, but ECM costs are considered as optional add-on costs rather than required costs for installing ventilation system retrofits in homes with central air handlers, as they did not alter air handler operational runtimes and only impact energy use as tested herein (and not IAQ). Average upfront

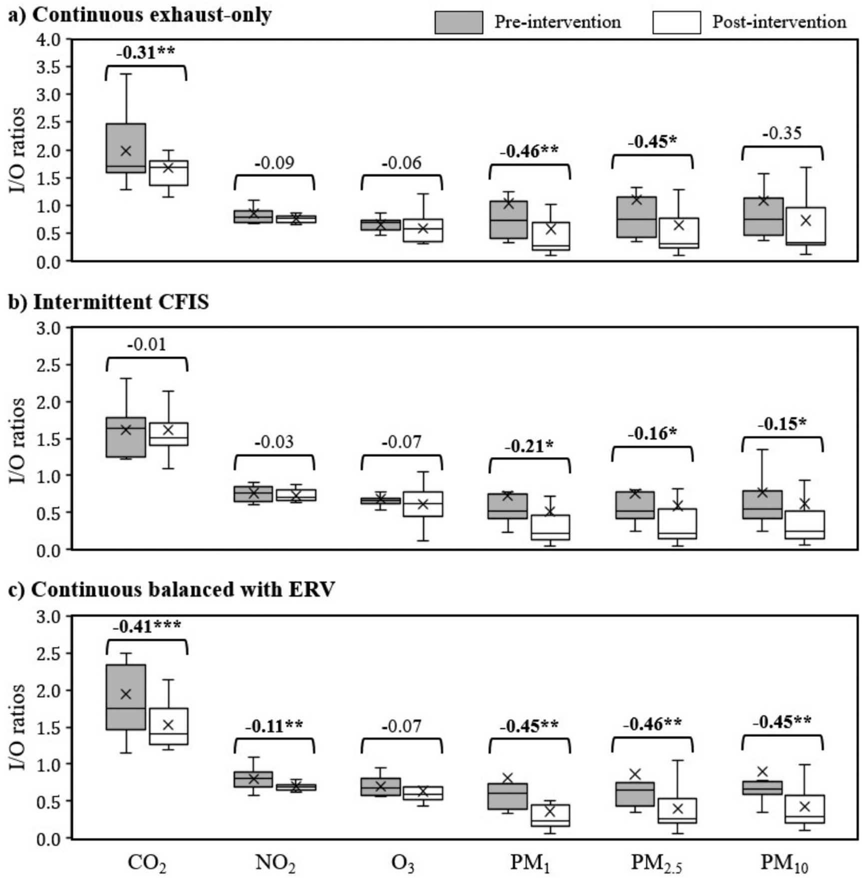

Fig. 8. I/O ratios of pollutants measured during pre- and post-intervention periods by specific ventilation system type. Numerical values shown indicate the difference in the mean value of the I/O ratio of pollutants between pre- and post-intervention periods. Symbols denote: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

retail costs of the exhaust-only, CFIS, and balanced with ERV systems were approximately \$180, \$330, and \$880 per unit installation, respectively. Average installation costs for the exhaust-only, CFIS, and balanced with ERV systems were approximately \$915, \$790, and \$1790 per unit installation, respectively. (Note that since some homes received more than one exhaust fan, upfront and install costs are twice as high per home as those homes with only single installations). Miscellaneous costs ranged from \$0 to \$225 per home. The combination of upfront, installation, and miscellaneous costs (e.g., blower door tests and health and safety repairs) across the three home groups led to the average total installed costs (not including any ECM fan motor replacement costs) of approximately \$1650, \$2310, and \$3150 for the exhaust-only, CFIS, balanced with ERV systems, respectively. As described previously, the mean reduction in I/O ratios for all constituents that had concurrent indoor and outdoor measurements (i.e., CO_2, NO_2, O_3, PM_1, $PM_{2.5}$, and PM_{10}) was 0.29, 0.11, and 0.33 for the exhaust-only, CFIS, balanced with ERV systems, respectively. Clearly, on a basis of first costs and pollutant reduction effectiveness, the intermittent CFIS system delivered the lowest performance. Of the continuous systems, the exhaust-only retrofits were more cost-effective on this basis of first costs and pollutant reduction effectiveness, but this comparison has not yet considered operating costs. A full life cycle cost comparison will be conducted in future work.

4. Conclusions

This paper presents a detailed overview and results of the Breathe Easy Project, a >2-year longitudinal, pseudo-randomized, crossover study, designed to assess indoor air quality (IAQ) and adult asthma outcomes before and after installing residential mechanical ventilation systems (including continuous exhaust-only, intermittent CFIS, and continuous balanced system with ERV) in 40 existing homes in Chicago, IL. The results herein demonstrate that the ventilation system retrofits had statistically significant impacts on reducing I/O ratios of CO_2, NO_2, PM_1, $PM_{2.5}$, and PM_{10} across all 40 homes, with mean relative reductions ranging from 33–42% for PM to 10–12% for CO_2 and NO_2. Average indoor temperature and relative humidity were essentially constant pre- and post-retrofit despite a statistically significant difference (within instrument uncertainties), suggesting that the introduction of ventilation systems did not meaningfully alter indoor environmental conditions. The largest magnitude and number of reductions in I/O ratios were observed in the homes that received continuous balanced systems with an ERV, followed by those that received continuous exhaust-only systems. There were only weak statistically significant reductions in I/O ratios in homes that received an intermittent CFIS system ($P < 0.1$). An assessment of initial installed costs suggests the continuous exhaust-only system may be a cost-effective retrofit solution for improving IAQ, but further analysis will consider life cycle operational costs and explore the impacts of each system type on adult asthma outcomes in this population. The results herein provide new insight into how different types of residential mechanical ventilation systems impact IAQ and indoor environmental conditions, which can be used to inform builders, contractors, designers, homeowners, and housing agencies tasked with prioritizing residential ventilation retrofits.

CRediT authorship contribution statement

Conceptualization, funding acquisition, and project administration: Brent Stephens, Anna McCreery, Amanda Gramigna, Anne Evens, Rachel Scheu.

Participant management: Griselda Baca, Amanda Gramigna.

Survey implementation and administration: Anna McCreery, Griselda Baca, Amanda Gramigna.

Field measurements and assessments: Insung Kang, Parham Azimi, Tim Crowder, Brent Stephens.

Data curation and processing: Kari Abromitis, Mingyu Wang, Insung Kang, Parham Azimi, Yicheng Zeng, Anna McCreery.

Statistical analysis: Insung Kang.

Writing – original draft: Insung Kang.

Writing – review and editing: All authors.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150129.

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