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ORIGINAL ARTICLE

Venting for health: indoor air quality improvements from upgraded ventilation systems in multifamily high-rise housing

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Abstract The impact of sealing ventilation shafts, installing self-balancing dampers and larger capacity exhaust fans on indoor air quality has not yet been thoroughly investigated. We examined IAQ outcomes in two groups of high-rise multifamily public housing. Both study and control group dwellings received ventilation shaft cleaning. The study group also received higher horsepower rooftop fans and ventilation shaft sealing to prevent leakage, and self-balancing dampers. We conducted interviews with residents 1 year before ventilation work and again 1 year after ventilation work completion ($n = 96$ households; 45 in the study group and 51 in the control group) that asked about housing conditions. In some dwellings, we also tested airflow and indoor air quality, including volatile organic compounds, carbon dioxide (CO_2), and formaldehyde. Ventilation improved in the study group and decreased in the control group. Across both groups, dwellings had statistically significant decreases in musty odors and presence of cockroaches. The study group's ventilation upgrades increased airflow inside those dwellings, and the airflow in study group bathrooms was significantly better than that of control group bathrooms. These increased ventilation rates were associated with statistically significant improvements in relative humidity, CO_2, and formaldehyde in the study group. Enhanced ventilation should be implemented in multifamily housing to improve indoor air quality.

Keywords Ventilation · Healthy housing · Allergy · Indoor air quality · Shaft sealing

Introduction

With well-balanced exhaust ventilation, sealed shafts, and compartmentalization of apartments in multifamily buildings, each apartment is equally depressurized with respect to the outdoors. Pressure differences between dwellings are minimized, and make-up air in any apartment is most likely to come from the outside, through cracks or leakage in the exterior walls or from the corridor, not from adjacent apartments. A previous study showed that sealing ventilation shafts and using self-balancing dampers at each exhaust vent can improve ventilation across dwellings in a building, but that study did not examine occupant health or indoor air quality (IAQ) (Steven Winters Associates 2011).

This new study was conducted to close this research gap by evaluating the impact of enhanced ventilation treatments (i.e., reducing air leakage from ventilation shafts, improving rooftop fans, and installing self-balancing dampers in bathrooms) on IAQ.

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Well-designed and well-maintained ventilation of residential dwellings removes or dilutes contaminants such as carbon dioxide (CO_2) and formaldehyde (HCHO), and mitigates moisture (ASHRAE 62.2–2016; WHO 2009; WHO 2010; Flannigan and Morey 1996) from people, materials and processes. Ventilation studies carried out during weatherization or other building improvements have found associations between improved ventilation and better health (Wargocki et al. 2002; Seppänen 2004; Wilson et al. 2016; Francisco et al. 2017). Usually, increased ventilation improves health, although there can be adverse health effects if the ventilation is not properly sized, installed, and operated (Seppänen and Fisk 2002). Improved ventilation can reduce triggers of adverse health effects, including airborne infectious bacteria and viruses, allergens, and irritants (Li et al. 2007; Sundell et al. 2011). Improved ventilation can also decrease home dampness. Damp environments are conducive to house dust mites, mold, and other risk factors and are related to poor respiratory health (Institute of Medicine 2004; Mendell et al. 2011). One meta-analysis showed that building dampness and mold are associated with approximately 30 to 50% increases in respiratory and asthma-related health problems (Fisk et al. 2007).

The need for an effective ventilation system is typically more important in multifamily dwellings than single family homes because such buildings have more occupants and pollution-generating activities per square foot, and apartments tend to have much less exterior shell area for natural ventilation. Typically, only 10–20% of an apartment's enclosure contains exterior walls and windows, with the balance made of interior partitions separating apartments. Odor and environmental tobacco smoke (ETS) transfer between apartments is a common complaint in multifamily buildings (Bohac et al. 2007a, b).

Implementing an effective and efficient ventilation system is inherently more complicated in multifamily buildings than in single-family buildings. Roof-mounted exhaust fans are typically used to exhaust air via a central riser shaft, with grilles in bathrooms or kitchens in each apartment on each floor (Figure S-1) (National Center for Healthy Housing 2009). Too often, these central roof exhaust ventilation systems do not work as designed because of the following:

1. Over 50% of the total airflow exhausted by roof fans is drawn through leaky air shafts due to inadequate duct- or chase-sealing practices.
2. High-rise multifamily buildings experience large wind and stack effects, which can result in unplanned, inefficient infiltration. These forces pressurize some apartments while substantially depressurizing others, making it difficult to balance the systems and provide the proper airflow to each apartment.
3. Owners, maintenance staff, contractors, weatherization entities, and energy auditors sometimes do not know how to properly inspect, tune, and upgrade existing central exhaust ventilation systems (Steven Winter Associates 2011).

When multifamily buildings use central roof exhaust ventilation, dwellings on the floors closest to the roof top fan often have higher ventilation rates than the lowest floors, and it is difficult to properly balance the system, leading to trade-offs between energy efficiency, indoor air quality (IAQ), and comfort (National Center for Healthy Housing 2009). When roof fan speeds are set to optimize the ventilation rates on the lowest floors, the building's average ventilation rate is higher than recommended, and property owners pay an energy penalty due to more conditioned (heated or cooled) air than necessary being exhausted outside. When fan speeds are set to optimize upper or middle floor ventilation rates, there is no energy penalty, but the lower floors do not get recommended levels of air exchange and can therefore suffer poor IAQ and discomfort.

In addition, under certain conditions, central exhaust ventilation systems can actually *increase* pollutant transfer between apartments. If the fan is not operating, the shaft can serve as a conduit for air and pollutants to circulate among apartments, due to wind or stack effect. Roof fans may be off due to poor operations and maintenance and/or time clocks installed to operate fans for only a fraction of the day (to save energy). When roof fans are operating, odor and contaminant transfer between apartments can still occur if the fans are undersized or there is excessive leakage from the shafts. If one apartment is significantly over-ventilated compared with adjacent apartments, it likely draws some make-up air from adjacent apartments. A tracer gas-based evaluation of six Minnesota buildings found that "the average fraction of inter-unit flow was 2% for the units on the lowest floor, 7% for the units in the middle floors, and 19% for the units on the upper floors" (Bohac et al. 2007a, b).

This study examines the effect of reducing air leakage from ventilation shafts, improving rooftop fans, and installing self-balancing dampers in bathrooms on IAQ.

Methods

Ventilation upgrades were conducted in three 14-story public housing buildings ($n = 325$ total dwelling units) in New York City. Each dwelling had a single bathroom with a vent connected to central ventilation shafts leading to rooftop exhaust fans. Each building had eight ventilation shafts. The first (Building A) and third (Building C) buildings had seven rooftop exhaust fans, while the second (Building B) building had six exhaust fans. All fans were set to run continuously. As displayed in Figure S-2, two shafts were served by a single rooftop exhaust fan in some locations.

This study measured IAQ 1 year before ventilation work was conducted (i.e., the winter of 2011/2012) and 1 year after ventilation upgrade work was completed (i.e., winter of 2014/2015). Ventilation flow rates were also measured 1 year before ventilation work and 3 months after ventilation upgrades.

Ventilation upgrades and ventilation tests

All dwellings in Building A and half the dwellings in Building B received enhanced ventilation upgrades and were classified as study group dwellings. Dwellings in Building C and the remaining dwellings in Building B received standard ventilation treatments and were classified as control group dwellings. In all three buildings, upgrades began with manually cleaning all ventilation shafts. The 12 study group exhaust air shafts were sealed by applying a surface coating composed of a vinyl acetate polymer (Aeroseal) that substantially reduced unplanned air flows through cracks and crevices. Next, self-balancing dampers were installed in all bathroom vents in the study group. Ten new, higher horsepower rooftop fans were installed to serve the 12 sealed study group shafts, and the existing 10 fans serving the other 12 control group shafts were inspected and repaired as needed. The extra horsepower fans were needed to work with the self-balancing dampers.

Airflow was expected to increase substantially for the study group dwellings that had new fans and tighter ductwork. Blower doors were used to measure total roof fan airflow on the twenty roof fans in 2012 (1-year pre-treatment) and in summer 2014 (3 months post-treatment). Exhaust airflow of bathroom exhaust vents was measured using flow hoods.

Dwelling ventilation tests were conducted using a convenience sampling approach of available dwellings across all three buildings. Households did not have to be enrolled in the study to have their dwellings' ventilation tested. Inspectors were instructed to test dwellings to allow an assessment of the impact of the self-balancing dampers. Sixty-five dwellings were tested nearly simultaneously at baseline. Thirty dwellings were tested nearly simultaneously post-treatment.

Tests of total roof exhaust fan airflow were conducted on functioning roof fans. At baseline, eight of ten roof fans in study units and eight of ten roof fans in control units were functioning. All roof fans functioned after upgrades were completed; 3 months after upgrades were done, only nine of ten study group roof fans and six of ten control group roof fans were functional. When reporting on the magnitude of exhaust improvements, non-functioning roof fans were excluded. When reporting on the association between ventilation and IAQ, the ventilation rates in dwellings without functioning roof fans were assumed to be zero.

Self-reported interview

This study was approved by Chesapeake Institutional Review Board (now Advarra), a fully accredited IRB by the Association for the Accreditation of Human Research Protection Programs. Following an informed consent process, one hundred twenty-four households in the three buildings chose to participate. Field staff asked an adult respondent specific questions about their health and the health of up to four children living in the dwelling, as well as questions about the dwelling's condition. This manuscript focuses solely on the housing and IAQ conditions and does not review the health outcomes. For this manuscript, the interview was used to determine if self-reported housing conditions changed between baseline and 1 -year post-treatment within and between the two groups. If between group comparisons were not significant, the two groups were pooled.

Indoor air quality measurements

Field staff recruited 16 dwellings in Buildings A and C to have IAQ tests conducted before and 1 year after ventilation improvements. Staff collected air samples simultaneously for a nominal 24-h period using standard sampling and analytical methods:

- Formaldehyde (HCHO): UMEX-100 passive badges with EPA method TO-11A analysis (US EPA 1999);
- Volatile organic compounds (VOCs): summa canisters with EPA method TO-15 analysis (US EPA 1999);
- Carbon monoxide (CO) and carbon dioxide (CO_2): The same summa canisters and EPA method TO-25C analysis (Method 25C 2012)

Staff collected outdoor air samples for these same contaminants on the roofs of both buildings, approximately 20 ft from all exhaust fans.

Data analysis

Interview data analysis The final analysis dataset included data from residents who completed both a baseline and one-year post-treatment interview. Of the 124 residents interviewed at baseline, 96 participated in the 1-year post-treatment interview. The dataset included 45 residents living in study group dwellings and 51 residents living in control group dwellings.

SAS version 9.4 was used for all analyses (SAS 2010). For dichotomous variables (e.g., yes/no), the Cochran-Mantel-Haenszel (CMH) test was used to determine if the percent “yes” was different at baseline vs post-treatment. Weighted Least Squares (WLS) was used to determine if the change in percent “yes” from baseline to 1-year post-treatment for the study group differed from the change for the control group. For continuous variables (e.g., age), a two-sample t test was used. For nominal variables, a Fisher’s exact test was used to determine if the baseline study group percentages differed from baseline control group percentages. For continuous variables, the baseline group means were compared using two-sample t tests.

IAQ data analysis At baseline, staff conducted air sampling in 16 dwellings in two buildings, seven in the study group and nine in the control group. At 1-year post-treatment, staff completed air sampling in 10 of the original 16 dwellings (five from each group). An extra household in each group was recruited for post-treatment testing, resulting in six in each group. The geometric mean was used as the measure of central tendency because the distributions of air contaminants were skewed. Linear models were used to predict the logarithms of air contaminant levels based on the visit, treatment group and their interaction. These models tested whether there was a change in the geometric mean contaminant level from baseline to post-treatment and if the relative change in geometric mean levels differed between the two treatment groups.

Ventilation data analysis Paired t-tests were used to determine whether there were significant changes in geometric mean airflow from baseline to post-treatment for the two groups.

Results

Ventilation performance

Before ventilation treatments, the mean flow rate of the eight operational study group roof fans was 451 cubic feet per minute (CFM) compared with 450 CFM for the six operational control group roof fans. Three months after treatments were completed, mean airflow increased 67% for the replacement (enhanced treatment) fans (752 CFM; $p < 0.001$), while mean airflow did not change significantly for the repaired (standard treatment) fans (493 CFM; $p = 0.662$) (Table S-1).

Within each group, the total potential exhaust per dwelling was calculated by summing the airflow of all fans, including those that were non-operational (CFM = 0), and then dividing by the dwellings served. At baseline, the average potential exhaust ventilation per study dwelling was 23.1 CFM and the average potential exhaust ventilation per control dwelling was 25.0 CFM. Three months post-treatment, the average potential exhaust ventilation per study dwelling increased to 44.3 CFM, while the average potential exhaust ventilation per control dwelling fell to 19.0 CFM. Although the mean airflow for operational fans serving control dwellings was basically the same before and after work, the change from 8 operational fans to 6 operational fans caused the drop in average potential exhaust per dwelling.

At the bathroom exhaust vents, the mean airflow extrapolated across all study group dwellings nearly tripled, from 12.7 to 37.7 CFM (+ 197%), while in control group dwellings, mean bathroom fan airflow declined from 13.5 to 8.9 CFM (− 34%). The efficiency of the study dwelling ventilation systems (mean airflow/potential average exhaust) improved from 43 to 80%. The efficiency improved in the control dwellings from 44 to 58%.

Housing conditions

Baseline housing condition data were collected for 124 dwellings, with 96 retained at post-treatment (study group = 45; control group = 51).

Residents reported some statistically significant changes in housing conditions (Table 1). There was no significant difference in the changes reported in study group vs. control group dwellings so the control and study groups were pooled. Across all dwellings, observations of water/dampness during the prior 12 months significantly declined from 60 to 29% and reports of mildew odors/musty smells during that same period also significantly declined from 53 to 33% ($p < 0.001$ and $p = 0.002$, respectively). For both groups, there was no significant change in dehumidifier use between baseline and 1-year post-treatment (16 to 15%); however, the daily use of window fans significantly increased from 27 to 51%. Resident observations of cockroaches and mice or rats declined significantly from 81 to 51% and 14 to 3%, respectively. Residents also reported an improvement in the ability to clean the dwelling. There was no significant change in smoking behavior between study periods.

Indoor air quality

CO_2 At baseline for dwellings in both groups combined, the indoor and outdoor CO_2 means (GM) were 819 ppm and 655 ppm, respectively (Table 2). These results can be compared with typical indoor levels of 500–1000 ppm and outdoor levels of 350–450 ppm (Seppänen and Fisk 2004). The geometric mean baseline indoor levels for each group were within 10% of each other: enhanced ventilation (868 ppm) vs. standard ventilation (782 ppm).

Mean outdoor CO_2 levels at the two rooftops declined 37% between baseline and post-treatment, but during the same period, indoor GM CO_2 readings declined 11% considering both groups together. There was a statistically significant difference observed between the treatment groups: the study group mean CO_2 level *declined* 36%, while the control group mean level *increased* 22% ($p = 0.003$). During post-treatment sampling, the maximum level among the study group dwellings was 720 ppm, while five of the six control group dwellings had indoor CO_2 levels above 720 ppm.

Formaldehyde (HCHO) At baseline, the GM outdoor rooftop HCHO level was 9 ppb, but the GM indoor level was 31 ppb. Half of the indoor readings were above 27 ppb, the level California considers elevated for schools (LEED User 2014). The mean baseline levels for the two treatment groups were within 10% of each other: study group (32 ppb) vs. control (31 ppb).

Mean rooftop outdoor HCHO levels declined 7% between baseline and post-treatment. During the same period, indoor HCHO readings declined 47% ($p = 0.01$) considering both groups together. The decline of the HCHO level (61%) in study group dwellings was significant ($p = 0.009$), but the decline in control group dwellings (28%) was not ($p = 0.302$). There was no significance difference between the treatment groups ($p = 0.191$).

Total volatile organic compounds (TVOCs) At baseline, the GM indoor TVOC level was 78 ppb, and the GM rooftop outdoor level was 23 ppb. The study group GM baseline level was 175% higher (100 ppb) than that of control group dwellings (57 ppb) (Table 2).

Mean outdoor rooftop TVOC levels declined 77% between baseline and post-treatment. During the same period, GM indoor TVOC readings declined 71% ($p < 0.001$) considering both groups together. The GM TVOC levels declined by similar amounts in the two treatment groups (71 and 72%; $p = 0.932$).

Other IAQ findings The study also tested CO levels. All results at baseline and at follow-up were below the detection limit of 5 ppm and are therefore not shown in Table 2.

Indoor and outdoor temperatures and humidity levels were also recorded on the sampling dates. During the baseline sampling visit in October 2012, the exterior temperature was 71° F and indoor temperatures ranged from 73 to 80° F. The GM temperature was the same in both study group and control group dwellings (78°F).

Table 1 Resident-reported housing conditions from interviews conducted before and 1 year after ventilation upgrades, study group and control group combined

Condition	Number of homes (*n*)	Before	1 year after	*p* value
Excessive water/dampness	92	60%	29%	< 0.001**
Mildew odor/musty smell	95	53%	33%	0.002**
Dehumidifier used	94	16%	15%	0.808
In last 30 days, used fan in open window every day	93	27%	51%	< 0.001**
In last 30 days, opened window every day	95	84%	91%	0.134
Problems with cockroaches	96	81%	51%	< 0.001**
Problems with mice or rats	96	14%	3%	0.002**
Dwelling hard to clean	95	17%	5%	0.008**
Cigarette, cigar pipe smoke	96	33%	35%	0.670

**$p < 0.05$

Considering both groups together, indoor baseline relative humidity (RH) was in the 40–50% range with outdoor RH of 49%.

Full descriptive statistics for indoor air quality measures are provided in Table S-2.

During the 1-year post-treatment sampling visit in spring 2015, the outdoor temperature was 58° F and indoor temperatures ranged from 63 to 73° F. The GM temperature in control group dwellings (69° F) was cooler than in study group dwellings (73° F). Post-treatment RH levels also varied by treatment group: the GM RH was 46% in control group dwellings (range: 43–53%) compared with 36% in study group dwellings (range: 30–40%), and 35% for outdoor RH. The decline of the GM RH level (23%) in study group dwellings was significant ($p = 0.002$), but the decline in control group dwellings (3.5%) was not ($p = 0.632$). There was a significant difference between the declines in the treatment groups ($p = 0.043$).

Discussion

This study offered a unique opportunity to investigate enhanced ventilation improvements in a multi-family, high-rise affordable housing environment. The control group had the roof fans associated with those dwellings repaired and received ventilation shaft *cleaning*, while the study group dwellings also received higher horsepower rooftop fans, ventilation shaft *sealing* to prevent leakage, and self-balancing dampers. The study offers support for the implementation of package of the improvements that were made to the study group ventilation systems.

The study group dwellings connected to ventilation shafts that received more powerful roof fans increased their potential mean airflow by 70%, but the actual flow of air out of the dwellings tripled, suggesting that the shaft sealing may have helped minimize unwanted leakage and improve ventilation performance. Future studies should collect fan horsepower data. Ventilation rates in the control group dwellings did not significantly change and in fact declined when non-operating fans were considered. Although air sampling was limited, statistically significant changes in IAQ were observed in the study dwellings but not the control dwellings. Carbon dioxide levels declined 36% in the study group dwellings while they *increased* 22% in the control group dwellings. Another study on improved ventilation also showed improvements in CO_2 levels (Francisco et al. 2017). Formaldehyde levels also declined significantly in study group dwellings (−61%), while the decline (−28%) was not significant in control group dwellings. Relative humidity significantly declined (−23%) in study group dwellings, but not in control group dwellings (−4%).

Improved ventilation was observed in the study dwellings connected to sealed shafts and improved fans. Although ventilation did not improve in the control dwellings, residents did not report statistically significant differences in water/dampness/mold between the two groups. Across all dwellings, significant improvements in reports of water/

Table 2 Indoor air quality before and 1 year after ventilation upgrades

Air measure	Number of samples[a] (n)	Geometric mean			
		Before	1 year after	Percent change	p value[b]
Carbon dioxide (ppm)					
Outdoor	2	655	415	−37%	
Indoor combined	16/12	819	729	− 11%	0.317
Study group indoor	7/6	868	577	− 36%	0.004**
Control group indoor	9/6	782	950	22%	0.150
Formaldehyde (ppb)					
Outdoor	2	9	8.4	− 7%	
Indoor combined	16/12	31	17	− 47%	0.010**
Study group indoor	7/6	32	13	− 61%	0.009**
Control group indoor	9/6	31	21	− 28%	0.302
Total volatile organic compounds (ppb)					
Outdoor	2	23	5.1	− 77%	
Indoor combined	16/12	78	22	− 72%	< 0.001**
Study group indoor	7/6	57	17	− 71%	0.003**
Control group indoor	9/6	100	28	− 72%	0.001**
Relative humidity (percent)					
Outdoor	1	49%	35%	− 31%	
Indoor combined	16/12	47%	41%	− 13%	0.018**
Study group indoor	7/6	47%	36%	− 23%	0.002**
Control group indoor	9/6	48%	46%	− 4%	0.632
Temperature (°F)					
Outdoor	1	71	58	− 18%	
Indoor combined	16/12	78	71	− 9%	< 0.001**
Study group indoor	7/6	78	73	− 6%	0.002**
Control group indoor	9/6	78	69	− 12%	< 0.001**

**$p < 0.05$

[a] Number of samples for Before ventilation upgrade/1 year After ventilation upgrade if different sample sizes are employed

[b] The p values from the tests that the relative change in GM levels differed between the two treatment groups were 0.003** CO_2, 0.191 HCHO, 0.932 TVOC, 0.043** RH and 0.166 temperature

dampness and mold/musty odors were observed. Observations of cockroaches and rodents also declined most likely due to reduced home moisture (Kercsmar et al. 2006).

There was a statistically significant decline in total VOC levels in both the study and control groups. This was surprising given the differences in the ventilation between the two groups. The percent declines in total VOC levels were more likely aligned to changes in outdoor levels than to any changes in ventilation.

Limitations and strengths

A limitation of this study is that it was not feasible to enroll dwellings that received no treatments. Such dwellings could have served as a different type of control group when statistically significant changes in both treatment groups combined were observed. A previous ventilation study in the context of weatherization had a similar finding: that the use of a ventilation standard (even an outdated one) showed positive health and indoor air quality effects (Francisco et al. 2017). It was also not feasible to randomize households for air sampling.

A separate focus of this research project was on resident health. The health results are available from the authors. This study was designed to enroll enough residents to test the health hypothesis. Data collection of IAQ measures was limited by financial constraints; future studies should consider using the data presented here to determine the needed statistical power to better understand changes in air quality.

The use of self-reported data is both a strength and a weakness. Residents are more knowledgeable about the conditions in their apartment. On the other hand, self-reported data may lack objectivity and could be affected by factors not necessarily related to housing. Objective air sampling found significant differences between relative humidity between the two groups, but residents did not report a difference in dampness. Multiple objective and self-reported air quality metrics should be measured in future studies. Although we did not collect detailed information on occupant behaviors such as cooking, the fact that we had a study and control group is likely to minimize bias. Future studies should collect additional data on occupant behavior, status of ventilation, and energy use.

This study is not able to draw empirical conclusions about the efficacy of the self-balancing dampers installed in all bathroom vents. However, the design of the heating systems in these buildings makes it unlikely that these dampers had the intended impact. A fundamental engineering principle of such dampers is that they operate effectively when “each apartment is depressurized with respect to the outdoors equally.” This condition was not present at this building complex. Residents did not have thermostats to regulate their dwelling temperature, so they used natural ventilation via windows. At baseline, over half of the residents reported that their dwellings were thermally uncomfortable during the winter prior to the interview, with anecdotal reports that they were too hot. Over 84% of residents at baseline and 91% at post-treatment reported opening their windows on a daily basis during the month before their interviews. With windows open, dwellings are no longer depressurized, eliminating the pressure differential required for the dampers to operate.

The beneficial effect of the dampers and the ventilation system as a whole is also defeated if the roof fans are not operational. One in ten replaced fans and four in ten repaired fans were not operational 3 months after work was completed, although precise estimates of when fans stopped working was not possible. Future research should obtain better measures of fan operational status. Anecdotally, the replaced fan may have been intentionally disabled because one or more residents complained that the noise of the new fan was too loud. It is highly likely that the dampers did not work as intended at this complex, but this result is not transferable to other settings where the dwellings are depressurized and the roof fans are operational.

Conclusions

We found that across both groups, dwellings were drier and had less musty odors after ventilation upgrades were complete. Further study is needed to better understand the association between the intervention and the health outcomes. The installation of appropriately sized roof fans and shaft sealing increased the airflow from dwellings along those ventilation shafts. The increased ventilation rates were associated with reductions in relative humidity, carbon dioxide, and formaldehyde in these dwellings. Sealed exhaust shafts and properly sized and operating exhaust fans should be implemented and well-maintained in multifamily housing. The need for proper maintenance and for educating residents and property managers about how to maintain good ventilation (even if noisy) is critical.

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Compliance with ethical standards This study was approved by an Institutional Review Board.

Conflict of interest The authors declare no conflicts of interest for this study.

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