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The effects of an energy efficiency retrofit on indoor air quality

Abstract To investigate the impacts of an energy efficiency retrofit, indoor air quality and resident health were evaluated at a low-income senior housing apartment complex in Phoenix, Arizona, before and after a green energy building renovation. Indoor and outdoor air quality sampling was carried out simultaneously with a questionnaire to characterize personal habits and general health of residents. Measured indoor formaldehyde levels before the building retrofit routinely exceeded reference exposure limits, but in the long-term follow-up sampling, indoor formaldehyde decreased for the entire study population by a statistically significant margin. Indoor PM levels were dominated by fine particles and showed a statistically significant decrease in the long-term follow-up sampling within certain resident subpopulations (i.e. residents who report smoking and residents who had lived longer at the apartment complex).

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Practical Implications

The results presented here provide insight into the indoor air quality before, immediately after, and 1 year after an energy efficiency retrofit on a federal-subsidized senior apartment complex. With increasing focus on building energy efficiency, it is critical to evaluate possible relationships between resident health and changes in indoor environmental quality. Initially, formaldehyde exposure was quite high for all study participants, but an overall decrease was measured a year after the construction was completed. Particulate matter, however, was largely impacted by resident behavior (such as smoking), and a long-term decrease was only observed when combined with particular subpopulations.

Introduction

As buildings become more energy efficient, there are concerns about long-term effects of changes in construction practices, materials and building operation. The need for reduced energy consumption, driven by rising energy costs and the desire to eliminate dependence on fossil fuels, has become a national priority. A common approach is to seal the building envelope, reducing air leakage and unnecessary usage of heating and cooling units. However, by reducing ventilation rates, pollutants could become trapped and increased exposure to toxins becomes a concern (Fisk, 2000; Jones, 1999; Weschler and Shields, 2000).

The risk of increased exposure lies in the fact that Americans spend up to 90% of their time indoors, whether at work, school, or in their homes (U.S. EPA, 1989; Wallace et al., 2006). Mitigating exposure and understanding the sources, fate and transport of indoor pollutants is of utmost importance (Lee et al., 2002; Wallace et al., 2006). The most vulnerable populations affected are children, the elderly, and people with existing respiratory diseases. In addition, low-income populations are less likely to have access to indoor air pollution intervention information, making low-income seniors a population most impacted and least able to respond to the burdens of a toxic indoor environment (Williams et al., 2000).

Therefore, a combination of increased time spent indoors and energy efficiency building practices has created the need to assess the impact of renovations on indoor environmental quality and human health. The U.S. Department of Housing and Urban Development promotes energy conservation and healthy home environments and has funded research on the potential impacts of ‘green’ building methods on both indoor environments and resident health (US HUD, 2009). It has been suggested that ‘green’ housing solutions may actually be detrimental to resident health, by not taking into account low-risk building materials and neglecting indoor air quality during the design process (Wargo, 2010). However, a recent study illustrated the potential for overall improvements in indoor air quality when retrofit measures are implemented with the simultaneous aims of saving energy and improving indoor environmental quality (Noris et al., 2013). Here, we evaluate impacts on indoor air quality as it relates to particulate matter and volatile carbonyl concentrations, specifically formaldehyde, acetaldehyde, and acetone.

The US EPA considers particulate matter, or PM, as a major concern due to the ability of particles with diameters <10 μm (PM_{10}) to pass through the throat and nose and into the lungs. This, in turn, has an impact on both lung and heart health (Dockery et al., 1993; Pope and Dockery, 2006). There have also been many studies connecting outdoor PM exposure to increased mortality rates and respiratory diseases (Davidson et al., 2005; Englert, 2004; Fann et al., 2012; Li et al., 2003). Due to these findings, National Ambient Air Quality Standards (NAAQS) were set to regulate annual ambient concentrations of PM_{10} at 150 $\mu g/m^3$ and $PM_{2.5}$ at 35 $\mu g/m^3$. No limits have been established for indoor PM levels, even though more evidence of indoor PM exposure being linked to negative health effects is surfacing (Koenig et al., 2005).

Carbonyls, especially formaldehyde, are ubiquitous in the indoor environment and have been associated with both chronic and acute health effects. The main sources of indoor formaldehyde include the degradation of additives used in wood-based building materials, furniture, and sealants as well as combustion and chemical reactions common to the indoor environment (Destaillats et al., 2006, 2011; Hodgson et al., 2002; Sidheswaran et al., 2013; Singer et al., 2006). Potential health concerns include irritation to the eyes, nose, throat, and lungs. Chronic exposure to formaldehyde has also been shown to lead to asthma symptoms, allergic sensitization, and overall reduction of lung function (LBNL, 2008; Salthammer et al., 2010; California EPA, 2007). Formaldehyde has been listed among the top five indoor pollutants causing chronic health effects in US residences (Logue et al., 2012), has been identified as a potential carcinogen by the US EPA (group B1, US EPA, 1999a), and classified as carcinogenic to humans (Group 1) by the International Agency for Research on Cancer (IARC, 2012). Acceptable exposure levels for formaldehyde determined by various countries have been summarized by Salthammer et al. (2010). In 2007, the California EPA established an 8-h Reference Exposure Level (REL) of 7 ppb and an acute REL of 44 ppb. Health Canada, however, has 8-h REL of 40 ppb, over five times higher than the CA EPA requirements (2006). In 2010, the World Health Organization released a less stringent guideline of 80 ppb for both short-term and long-term risks (WHO, 2010).

This research is a subset of a larger study evaluating the overall impact of an energy efficiency retrofit on a vulnerable population, including cost effectiveness and health benefits (Ahrentzen et al., 2013). Here, particulate matter and volatile carbonyl concentrations are the benchmark for measuring how the retrofit affects the indoor air quality both immediate post-renovation and 1 year following renovation. We seek to understand what sources and behaviors may impact increased PM and aldehyde exposure. We also examined whether indoor air quality improvements resulted in changed health conditions or health-related behaviors (such as improved sleep).

Materials and methods

Sampling campaign and health survey

A study was conducted at a local apartment complex, operated by the City of Phoenix Housing Department, for seniors who qualify for subsidized rent. Originally built in the early 1970s, this three-story, 116-unit structure underwent unit renovations and energy efficiency improvements in spring and early summer of 2011. The HVAC system for each apartment included a through-wall package terminal air conditioner (PTAC) unit, a bathroom exhaust fan, a range hood exhaust fan, and doors and windows. The retrofit of each apartment included upgrades in PTAC units, both exhaust fans, and installation of energy efficient, double pane exterior windows and sliding glass balcony doors. Other improvements included installation of low VOC flooring, new cabinetry (natural oak product), paint (zero VOC), low VOC carpet and carpet pad (Green Label Plus Certified), Energy Star kitchen appliances (refrigerator, electric range, microwave, and garbage disposal), and the addition of a bedroom ceiling fan.

Researchers tested air quality in the self-contained apartments a total of three times: in the summers of 2010, 2011, and 2012. Panel 1, before the renovation, was conducted during the summer of 2010. Panel 2 was conducted immediately after construction was completed from late April through September 2011. One year later, Panel 3 was conducted from June through early August 2012. For air quality sampling, a total of 72 apartments were studied in Panel 1, which have been reported separately (Frey et al., 2014). A total of 55 and 53 units were studied in Panels 2 and 3, respectively. However, only 47 units participated in all three panels, corresponding to an attrition rate of 35%. As the research design was a longitudinal panel study examining the changes in each resident's apartment over time, data from residents in the first panel who did not participate in later panels were eliminated from the analyses. This type of research design, however—in which each apartment is its own control group—allowed us to examine improvements or changes from the first to subsequent panels using paired *t*-tests and fixed-effects regression models, which worked effectively with this smaller sample size.

Simultaneous measurements of indoor air pollutants, particulate matter and volatile carbonyls were collected in the living room and kitchen, and outdoor pollutant concentrations on the balcony of each unit. All units have 619 ft^2 of livable space and are identical in interior layout and are all-electric homes (i.e. no fireplaces, gas stoves, etc.) with individual through-wall package terminal air conditioner (PTAC) units. One-hour samples were collected in each unit between the hours of 9 am and 5 pm. Repeated testing in a subset of units (7% replicate) ensured that no time-of-day bias was present. The summer season was selected for sampling as local hot weather would result in the apartment units being sealed (i.e. windows closed) with air conditioning running. During instrument setup and sampling, residents did not cook, smoke, or clean.

At the same time as air quality testing, a health survey of over 100 questions was given to the residents to solicit information about personal habits and self-reported health conditions. Performing the air quality measurements and questionnaire simultaneously ensured that resident activities (i.e. cooking, smoking) did not bias the data and would not be present during sampling.

The indoor air quality testing, presented here, is a subset of a larger-scale study in which cost efficiency and health benefits of the renovations were also analyzed (Ahrentzen et al., 2013). Additional information about temperature, humidity, air leakage, and the health questionnaire can be found in that report. While 1-h sampling periods are relatively short and may be more susceptible to short-term sources, the sampling plan was carefully designed to minimize the impact of resident activity during sampling, thus reducing that risk. In addition, the sampling plan and the panel survey research design maximized the number of participants to account for an expectedly high attrition rate among a low-income elderly population over a 2-year period. Short-duration samples allowed coordinating for a large number of units over the month-long sampling period obtaining a representative data set for the building. Although cross-contamination across different units could impact the results of this study (e.g. due to all units sharing common vertical exhaust ducts), it was not quantified. In addition, because ventilation rates were not tracked during sampling, changes in concentrations could be due to either changes in sources or changes in ventilation rates.

PM measurements

Indoor air quality sampling included real-time measurement of PM using TSI DustTrak DRX aerosol monitors (model 8533; TSI, Inc., Shoreview, MN, USA) sampler. This instrument contains a light-scattering laser photometer to detect various particle sizes, including PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM-total. The maximum size measured for the PM-total is approximately 15 μm based on manufacturer specifications. Three samplers were deployed to the apartment kitchen, living room, and balcony to simultaneously collect particle data over a 1-h period during which the resident was given the health survey. By sampling both indoor and outdoor air, we are able to calculate indoor/outdoor ratios with the goal of quantifying the impact of infiltration of outdoor particles vs. indoor sources on indoor air quality. Dusttraks were labeled and used in a consistent manner among units, were calibrated prior to the study, and tested for reproducibility by collocated sampling. While Dusttraks have been shown to overestimate PM compared with gravimetric measurements, the use of a consistent sampling platform was designed to minimize bias due to sampling technique (Jenkins et al., 2004 and Wallace et al., 2011).

Carbonyl measurements

Samples of indoor and outdoor formaldehyde, acetaldehyde, and acetone were collected using commercial samplers containing dinitrophenyl hydrazine (DNPH)-coated silica gel (Sep-Pak XPoSure Aldehyde Sampler, # WAT047205; Waters Corp., Milford, MA, USA). The cartridges were preceded by an ozone scrubber (Sep-Pak Ozone Scrubber, # WAT054420; Waters Corp.) to eliminate ozone from the incoming air. Air was drawn through the samplers by means of pumps operating at ~2 L/min (determined with a precision better than ± 3%). Samples were collected over 1-h periods using portable gas pumps (Universal XR Pump, Model PCXR4; SKC Inc., Eighty Four, PA, USA). The sampling flow of each pump was calibrated in the laboratory before and after the sampling period using a bubble flow meter and a primary airflow calibrator (Gilibrator-2 Sensidyne, St. Petersburg, FL, USA). Three samples were collected simultaneously with and in close proximity to the PM samplers in the living room, kitchen, and balcony of each unit.

After collection, each DNPH cartridge was capped, labeled, and stored at 4°C until it was extracted and analyzed. Acetonitrile extracts were analyzed by high-performance liquid chromatography (HPLC) with UV detection at 360 nm following a US EPA method (US EPA, 1999b). The concentration value reported in each case corresponded to a time-integrated average over the sampling period. Calibration curves for quantification were determined with authentic standards of the dinitrophenylhydrazones of formaldehyde, acetaldehyde, and acetone (Sigma-Aldrich). The detection limit for each volatile carbonyl was typically 10 ng or lower, corresponding to air concentrations < 0.1 ppb. Laboratory and field blank samples (at least three laboratory and six field blanks) were also analyzed, showing non-detectable values of the three analytes.

Reported health measures

The resident survey created and used in this study contained over one hundred fixed-response and open-ended questions pertaining to health conditions, resident assessments of the environmental quality of their apartments, and household activities and behaviors relevant to environmental quality. The health-related questions were derived from standardized instruments developed by the Centers for Disease Control: the National Health Interview Survey (NHIS) and the Behavioral Risk Factor Surveillance System (BRFSS). The same questions were asked of residents at each panel. Pertinent to the analyses presented here were questions regarding smoking behavior; use of cleaning and odor-masking products; an index of respiratory conditions (derived from single questionnaire items pertaining to snoring, asthma, emphysema, hay fever, bronchitis, sinusitis); index of quality of health/life (derived from three questionnaire items); index of emotional distress (derived from six standardized questionnaire items; see Pilkonis et al., 2011); and sleep (number of hours).

Results and discussion

While the effectiveness of the retrofit is beyond the scope of this particular manuscript, energy and water savings have been quantified. To summarize, the retrofit resulted in a reduction of 12.6% in water consumption and 19.4% in electricity consumption based on analysis of 39 months of metered electrical and water use between July 2009 and September 2012 (Ahrentzen et al., 2013).

Data analyses procedures

As mentioned previously, the particulate matter (PM) and aldehyde concentrations of each resident's kitchen, living room, and balcony were recorded. However, because linear correlations between an apartment's kitchen and living room PM data were 0.90 or higher, measurements were combined from these rooms into one composite measure (by averaging room-level data) to represent the unit.

Trends are evaluated as the change of conditions between Panels 1 and 2, labeled the 'Short Term' and between Panels 1 and 3, labeled the 'Long Term' where only units that participated in both Panels are included in the statistical analysis. Given the panel research design, we used fixed-effects models when comparing differences in an apartment's conditions between panels (all statistics presented will be fixed-effects regressions, unless otherwise noted). As we did not have a control group but did have a longitudinal panel research design, these models were quite appropriate to the panel nature of our study, where each individual's apartment acts as his or her own control. There are two basic data requirements for using fixed-effects methods (Allison, 2005), both of which were addressed in our study: (i) the dependent variable must be measured for each unit on at least two occasions and those measurements must have the same metric and (ii) the predictor variable must change in value across those two occasions for some substantial portion of the sample.

Sample characteristics

The questionnaire given to residents during testing was essential to characterize the demographics of the apartment units sampled. Most units (88%) were occupied by a single individual. Average age of residents at the beginning of the study was 73 years, and 65% reported at least one respiratory health problem at the first panel. The average length of stay of living in the apartment was 5.5 years.

Behavioral questions most relevant to the data reported here are summarized in Table 1. In addition, this resident behavior information aids in the interpretation of the indoor air quality data collected, and a

Table 1 Examples of relevant questions asked to residents during air sampling. This is a subset of a questionnaire of over 100 questions

Relevant questionnaire inquiries
Do you smoke?
Do you use bug sprays?
Do you use anything to change the smell of the air in your home more than once per week?
If yes, does that include candles? Incense? Air freshener? Or Other?

Table 2 Questionnaire responses for each panel, number of responses (percentage)

	Total units	Smoker (%)	Use insecticide (%)	Change smell of air (%)
Panel 1	72	16 (22)	17 (24)	46 (64)
Panel 2	55	9 (17)	19 (36)	34 (64)
Panel 3	53	11 (21)	1 (2)	33 (62)

summary of participant behavioral data is presented in Table 2 below.

Particulate matter

Mean and median indoor concentrations, as well as indoor outdoor ratios, can be found in Table 3. Based on all indoor/outdoor ratios being greater than 1, measured levels of indoor PM often far exceeded measured outdoor concentrations, an indication of the importance of indoor PM sources for the units participating in the study. Although indoor particle concentration averages are higher, they are also widely variable compared with outdoor PM concentrations, although part of the difference may be due to varying particle morphology between indoor and outdoor PM, which alters instrument response. When comparing Panel 1 indoor PM_{10} to outdoor PM_{10}, there is a mean difference of 42 ($\mu g/m^3$) (paired *t*-test: $t = 2.665$, $P < 0.01$) and a low correlation of 0.29 ($P < 0.05$). This trend is also found in Panels 2 and 3. However, as the bias of PM mass concentrations has been reported with the use of light-scattering instruments, the focus will be on the relative change of PM concentrations between panels.

The ranges of PM_{10} concentration were 8–783, 13–1375, and 11–600 $\mu g/m^3$ for Panels 1, 2, and 3, respectively. The best way to visualize these concentrations and changes between the short and long term is through a cumulative frequency plot, as seen in Figures 1 and 2.

While mean PM counts did show changes over time, the variance was so large that statistical significance was not achieved. Overall, there was no statistically significant change in PM levels before the renovation and afterward (either in the short or long term). However, if the top 25th percentile of Panel 1 (who also participated in Panel 3) is isolated, there is a statistically significant decrease in both $PM_{2.5}$ and PM_{10} in the long term (paired *t*-test, $N = 13$ of 53: $t = 2.167$, $P < 0.05$ and $t = 2.219$, $P < 0.05$, respectively).

One of the largest factors connected to increased indoor PM concentrations was smoking. This is shown specifically for each panel in Table 4. Mean and median $PM_{2.5}$ concentrations and indoor/outdoor ratios are given.

Statistical analysis using various covariates was used to see if resident demographics or habits had an impact. In the short term, the resident's length of stay, whether the resident smoked, and use of odor-masking products were covariates that had statistical impact.

In the short term (between Panels 1 and 2), both $PM_{2.5}$ and PM_{10} concentrations increased as the length of time residents lived at the apartment complex increased ($PM_{2.5}$ $t = 3.063$, $P = 0.003$; PM_{10} $t = 3.041$, $P < 0.003$). However, the indoor/outdoor ratios decreased with length of time living there (I/O $PM_{2.5}$ $t = 3.721$, $P < 0.001$; I/O PM_{10} $t = 3.732$, $P < 0.001$); no coherent or consistent explanation could be found for this association. The units of those residents who used odor-masking products showed increased levels of $PM_{2.5}$ and PM_{10} in the short term ($PM_{2.5}$ $t = 1.963$, $P = 0.052$; PM_{10} $t = 1.972$, $P = 0.051$), but there was no similar change of indoor/outdoor PM ratios. Not surprisingly, PM concentrations and I/O ratios were significantly higher in homes of those residents who smoked than in the units of non-smokers ($PM_{2.5}$ $t = 3.717$, $P < 0.001$, PM_{10} $t = 3.960$, $P < 0.001$; I/O

Table 3 Means and medians for particulate matter concentrations and indoor/outdoor ratios for all three panels. Panel 1 ($N = 72$) from 2010, Panel 2 ($N = 55$) from 2011, and Panel 3 ($N = 53$) from 2012

		$PM_{2.5}$			PM_{10}		
		Indoor concentrations ($\mu g/m^3$)	Outdoor concentrations ($\mu g/m^3$)	Indoor/Outdoor ratio	Indoor concentrations ($\mu g/m^3$)	Outdoor concentrations ($\mu g/m^3$)	Indoor/Outdoor ratio
$N = 72$	Panel 1 Mean	58 ± 125	20 ± 21	3.0	62 ± 125	24 ± 21	2.5
	Panel 1 Median	13	13	1.1	18	17	1.0
$N = 55$	Panel 2 Mean	67 ± 145	17 ± 13	2.8	74 ± 146	26 ± 18	2.9
	Panel 2 Median	20	13	1.6	25	19	1.5
$N = 53$	Panel 3 Mean	37 ± 87	10 ± 5	2.9	41 ± 87	16 ± 7	2.2
	Panel 3 Median	19	10	1.9	22	15	1.5

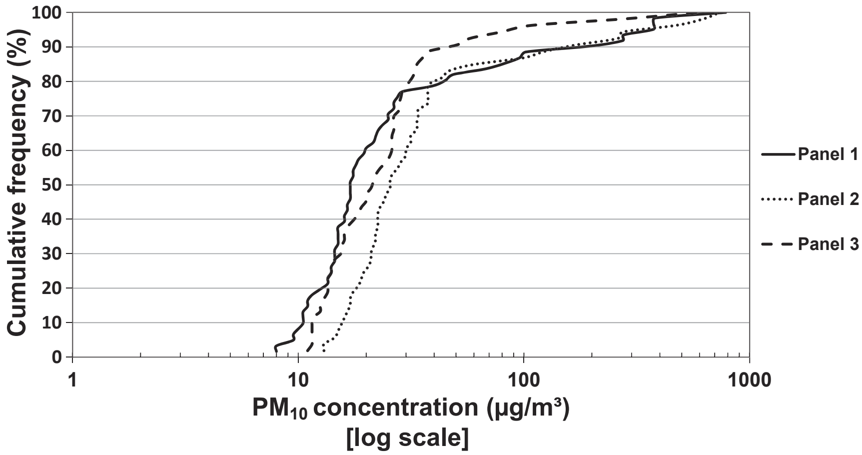

Fig. 1 Cumulative frequency plot of PM_10 from Panel 1 (solid), Panel 2 (dot), and Panel 3 (dash)

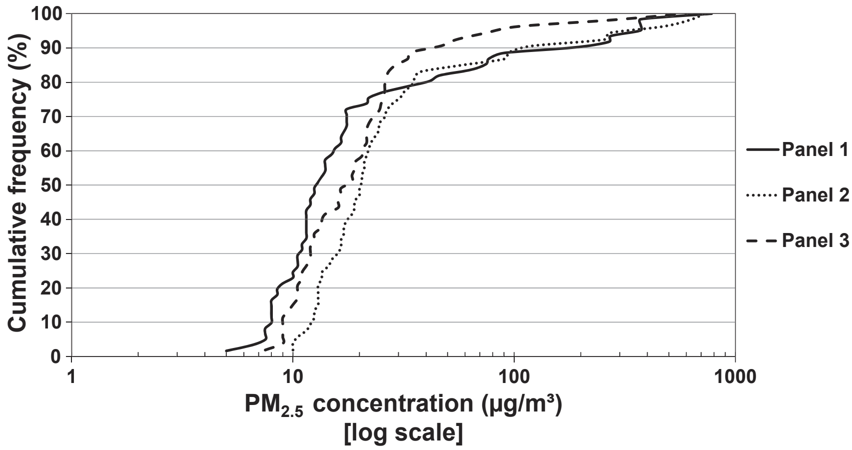

Fig. 2 Cumulative frequency plot of PM_2.5 from Panel 1 (solid), Panel 2 (dot), and Panel 3 (dash)

$PM_{2.5}$ $t = 6.592$, $P < 0.001$, I/O PM_{10} $t = 6.957$, $P < 0.001$). However, there was no significant change in the short term when smoking was added as a covariate.

In the long term (between Panels 1 and 3), the resident's length of stay, resident's age, and whether the resident smoked were statistically significant covariates. Contrasting to the short-term changes, as a resident's length of stay increased, a decrease in long-term $PM_{2.5}$ and PM_{10} concentrations was identified ($PM_{2.5}$ $t = -1.865$, $P = 0.065$; PM_{10} $t = -1.897$, $P = 0.061$). This change was not reflected in the indoor/outdoor ratios. When compared to the increasing age of a resident, both long-term PM concentrations and indoor/outdoor ratios decreased ($PM_{2.5}$ $t = -2.214$, $P = 0.029$; PM_{10} $t = -2.151$, $P = 0.034$ and I/O $PM_{2.5}$ $t = -2.151$, $P = 0.034$; I/O PM_{10} $t = -1.929$, $P = 0.057$, respectively). Finally, units occupied by residents who smoke had higher PM levels than units with non-smoking residents ($PM_{2.5}$ $t = 6.186$, $P < 0.001$; PM_{10} $t = 6.161$, $P < 0.001$). The higher PM concentrations measured in units with smokers have a significant decrease compared with non-smokers ($PM_{2.5}$ $t = -3.078$, $P < 0.001$; PM_{10} $t = -3.059$, $P < 0.003$).

Table 4 Means and medians for $PM_{2.5}$ concentrations and indoor/outdoor ratios for all three panels, separated by smoking units and non-smoking units: Panel 1 ($N = 16$, $N = 56$) from 2010, Panel 2 ($N = 9$, $N = 44$) from 2011, and Panel 3 ($N = 11$, $N = 42$) from 2012

	Smoking $PM_{2.5}$			Non-smoking $PM_{2.5}$		
	Indoor concentrations (µg/m^3)	Outdoor concentrations (µg/m^3)	Indoor/Outdoor ratio	Indoor concentrations (µg/m^3)	Outdoor concentrations (µg/m^3)	Indoor/Outdoor ratio
Panel 1 Mean	209 ± 232	24 ± 18	8.5	20 ± 38	19 ± 22	1.4
Panel 1 Median	99	20	4.6	12	12	1
Panel 2 Mean	361 ± 430	28 ± 20	12	22 ± 14	15 ± 11	2.2
Panel 2 Median	257	51	5	19	12	1.6
Panel 3 Mean	82 ± 173	13 ± 6	4.3	25 ± 41	10 ± 5	2.5
Panel 3 Median	25	10	2.5	16	10	1.9

Table 5 Mean and median concentrations of acetone, acetaldehyde, and formaldehyde for each Panel

		Acetone		Acetaldehyde		Formaldehyde	
		Indoor concentrations ± standard deviation (ppb)	Indoor Outdoor Ratio	Indoor concentrations ± standard deviation (ppb)	Indoor/Outdoor Ratio	Indoor concentrations ± standard deviation (ppb)	Indoor/Outdoor Ratio
N = 72	Panel 1 Mean	41 ± 41	8.7	20 ± 9	11	39 ± 11	8.7
	Panel 1 Median	28	8.1	18	9.8	38	7.7
N = 54	Panel 2 Mean	91 ± 45	14	34 ± 17	13	42 ± 13	9.5
	Panel 2 Median	90	11	33	10	43	7.1
N = 55	Panel 3 Mean	52 ± 42	11	20 ± 7	10	27 ± 7	7.1
	Panel 3 Median	39	9.7	20	9.1	26	6.8

Carbonyl measurements

Table 5 summarizes acetone, acetaldehyde, and formaldehyde concentrations and indoor/outdoor ratios for each panel. We also illustrate the cumulative frequencies of the formaldehyde and acetaldehyde data in Figures 3 and 4. Figure 3 also includes reference lines for the most recent California 8-h Reference Exposure Level (REL), the Health Canada 8-h REL, and the California acute REL.

As seen in Figure 3, 100% of samples in all three panels, with levels ranging from 17 to 69 ppb, exceeded the California EPA 8-h REL of 7 ppb. When compared to the CA acute REL standard of 44 ppb, 32% of Panel 1 and 43% of Panel 2 units were above the standard. Additionally, 40% of Panel 1 samples, 56% of Panel 2 samples and only 4% of Panel 3 samples exceeded the Health Canada REL of 40 ppb. However, no unit exceeded the WHO guideline of 80 ppb. These formaldehyde levels are comparable or higher than those reported for US buildings and homes. Hun et al., (2010) reported a mean and median formaldehyde concentration of 17 ppb in 179 US residences. Offermann (2009) determined a median of 29 ppb formaldehyde in new homes, and Hodgson and Levin (2003) reported a median formaldehyde level of 17 ppb, with a 95 percentile of 61 ppb. Similar residential formaldehyde levels have been reported in other countries, with a mean of 18 ppb in the UK (n = 833, 1997–1999), 19 ppb in Germany (n = 586, 2003–2006), 33 ppb in Finland, 20 ppb in Austria (n = 160), and 25 ppb in Japan (n = 1181, 2005), and a median of 16 ppb in France (n = 554, 2003–2005) and 24 ppb in Canada (n = 96, 2005) (WHO, 2010). By contrast, very high levels have been reported in recently remodeled Chinese homes, with a mean of 190 ppb (n = 6000, 1999–2006) (WHO, 2010), and in trailers supplied by the US Federal Emergency Management Agency (FEMA) to shelter evacuees from Hurricanes Katrina and Rita in 2005, with a mean formaldehyde concentration of 77 ppb (n = 519) (Murphy et al., 2013).

All measured acetaldehyde levels, reported in Figure 4, were below the health-based exposure levels recommended by the California EPA (8-h REL = 160 ppb and 1-h REL = 260 ppb). Acetone levels measured in this study do not pose any health hazards, as the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) is 250 ppm as a time-weighted average for up to 10-h work shift over a 40-h work week (NIOSH, 1994). Acetone levels are included in this report, even though levels are far below health guidelines, to illustrate the behavior of a common indoor VOC generated by sources predominantly related to human activities.

As can be seen in Table 5, long-term changes were notably different from those of the short term for formaldehyde. While there was no change in the short term, there is a significant decrease in the long term

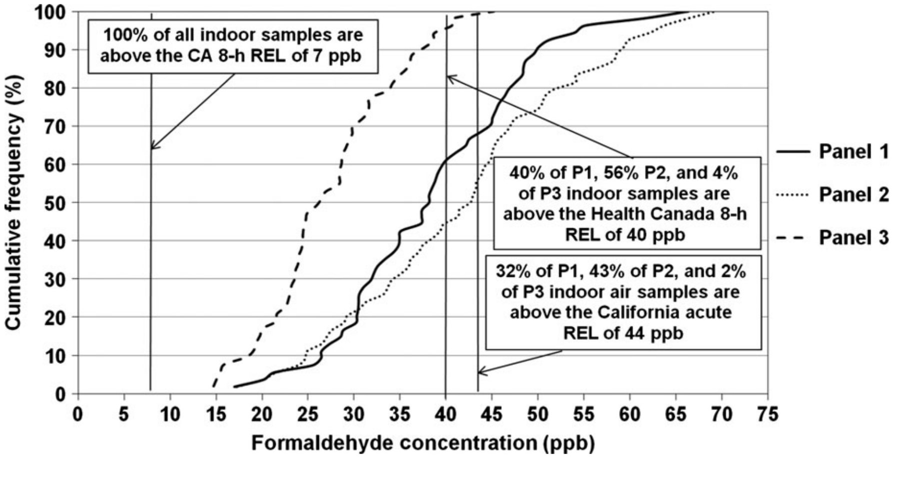

Fig. 3 Cumulative frequency plot of formaldehyde concentrations from Panel 1 (solid), Panel 2 (dot), and Panel 3 (dash)

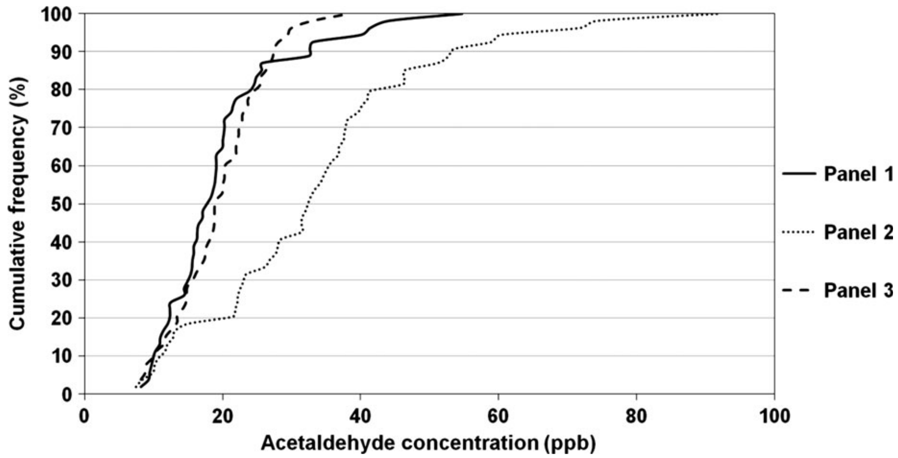

Fig. 4 Cumulative frequency plot of acetaldehyde concentrations from Panel 1 (solid), Panel 2 (dot), and Panel 3 (dash)

($t = -6.376$, $P < 0.001$). This decrease held after controlling for most of the mediating building characteristics (orientation, wing, floor) and other covariates. While older residents had higher formaldehyde concentrations in their apartments, there was no change between Panels 1 and 3.

Interestingly, acetaldehyde and acetone did not follow the same trends as formaldehyde. In contrast, both acetone and acetaldehyde had a statistically significant increase in the short term ($t = 5.928$, $P < 0.001$ and $t = 4.924$, $P < 0.001$, respectively), even after controlling for mediating factors. Additionally, residents who have lived longer at the residence or began using odor-masking products had a higher increase in acetaldehyde concentrations in their homes ($t = 2.180$, $P = 0.031$ and $t = 1.934$, $P = 0.056$, respectively) while those who stopped using indoor insecticide saw a decrease ($t = -2.483$, $P = 0.015$). In the long term, neither chemical experienced a change from panel 1, although acetaldehyde concentrations were higher in units where residents indicated they smoked ($t = -5.290$, $P < 0.001$).

Correspondence between improvements in air quality and reported health

Given the relatively brief scope of this study and lack of a control group, we did not expect to find definite changes in health conditions after the retrofit, particularly among the more serious medical and health diagnoses. Nonetheless, we did examine whether the significant decrease in formaldehyde levels in the long-term measurements also resulted in improved health conditions. For example, an index of respiratory conditions, an index of quality of life/health, emotional distress, and number of hours sleeping during the night are conditions that may be responsive to improved indoor air quality.

As shown in Table 6, differences between individual unit formaldehyde concentrations are associated with self-reported health conditions, particularly in the short term. Using fixed-effects regression of data between Panels 1 and 2, changes in formaldehyde concentrations were correlated with residents' reported quality of life/health and reduction in emotional distress. That is, as the formaldehyde levels in one's apartment improved (i.e. declined in concentration levels), residents expressed greater satisfaction with their quality of life/health and less emotional distress. Between Panels 1 and 3, formaldehyde change correlated with reduced emotional distress scores, but only at marginal statistical significance possibly because all formaldehyde concentrations showed a significant decrease in Panel 3. These findings between formaldehyde reductions and emotional distress improvements are suggestive only. The larger study (Ahrentzen et al., 2013) noted correspondence between emotional improvements and other environmental improvements (e.g. temperature) and physiological factors (e.g. functional limitations). Multivariate modeling to examine interrelationships between these variables was not conducted because of the small sample size. However, given the prominent improvement in emotional distress in the larger study, future research with larger sample sizes

Table 6 Fixed-effects regression of formaldehyde change in unit and resident reported emotional distress and life/health quality, both short term and long term

	Short term				Long term			
	Quality of health/life		Emotional distress		Quality of health/life		Emotional distress	
	t	*P*-value	*t*	*P*-value	*t*	*P*-value	*t*	*P*-value
Formaldehyde level in unit	2.624	<0.01	−3.912	<0.001	1.257	n.s.	−1.781	<0.08

should examine the role of multiple environmental factors in improving mental health of older adults. There were no significant correlations between formaldehyde changes and sleep or respiratory conditions.

Conclusions

The research presented here reports key indoor air quality parameters, including PM levels and carbonyl concentrations, for a low-income senior apartment complex before and after an energy efficiency retrofit. The air quality sampling was combined with a detailed health questionnaire and educational material on 'green' and healthy homes. The questionnaire was used to garner information on the personal habits and general health of residents. The educational booklet was designed specifically for the residents at the apartment complex and was distributed prior to the Panel 3 data collection (Ahrentzen et al., 2013).

Although it was expected to have a short-term increase in PM concentrations after the retrofit, this was only statistically apparent with two covariates: length of stay for the occupant and the use of odor-masking products. In general, smokers had higher PM concentrations in all three panels, but no short-term change and a slight decrease in the long term. In the long term, a decrease in PM concentrations occurred in units with residents who had lived longer at the apartment complex.

The Panel 1 and Panel 2 formaldehyde levels measured in this study were comparable or higher than other US buildings and homes, as described in the literature. Panel 3 concentrations, however, showed a significant decrease with only 4% of units exceeding the Health Canada 8-h REL of 40 ppb and virtually none exceeding the California acute REL of 44 ppb. The units tested here are much smaller than the reported literature studies, so increased surface-to-volume ratios could be a factor in the increased concentrations. The significant decrease in formaldehyde levels in Panel 3 is most likely a result of the replacement of building materials and furnishings during the retrofit. This is supported by the fact that only formaldehyde, but not acetaldehyde and acetone (which are measured simultaneously with the same method), showed a significant reduction in concentration. Changes in ventilation would have affected all three carbonyls similarly. Other factors, such as variations in the use of insecticide, were also not correlated with long-term changes in carbonyl levels.

While both acetone and acetaldehyde concentrations experienced an increase in the short term, long-term concentrations were unchanged and well below any defined risk levels.

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