Self-Reported Health Outcomes Associated With Green-Renovated Public Housing Among Primarily Elderly Residents

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Objectives: Assess the benefits of green renovation on self-reported health of primarily elderly residents of a low-income public housing apartment building. **Design and Setting:** Using questions from the Medicare Health Outcomes Survey, we interviewed residents at baseline and 1 year after green renovation of their 101-unit building in Mankato, Minnesota, comparing self-reported mental and physical health outcomes of 2 sets of residents (all-ages: median, 66 years, n = 40; elder: median, 72 years, n=22) with outcomes for 2 same-aged low-income Minnesota comparison groups taken from Medicare Health Outcomes Survey participants (n=40 and 572, respectively). **Participants:** Study group: Mankato apartment building residents. **Interventions:** Green renovation including building envelope restoration; new heating, electrical, and ventilation systems; air sealing; new insulation and exterior cladding; window replacement; Energy-Star fixtures and appliances; asbestos and mold abatement; apartment gut retrofits; low volatile organic chemical and moisture-resistant materials; exercise enhancements; and indoor no-smoking policy. **Main Outcome Measures:** Self-reported health status including Activities of Daily Living and Veteran's Rand 12 (VR-12) survey results; housing condition visual assessment; indoor environmental sampling; and building performance testing. **Results:** The all-ages study group's mental health improved significantly more than the comparison group's mental health on the basis of mean number of good mental health days in the past month ($P = .026$) and mean VR-12 mental component score ($P = .023$). Sixteen percent fewer all-ages study group people versus 8% more comparison group people reported falls ($P = .055$). The elder study group's 9% improvement in general physical health was not statistically significantly better than the elder comparison group's decline (6%) ($P = 0.094$). Significantly fewer people in the all-ages group reported smoke in their apartments because of tobacco products (20% vs 0%, $P = .005$), likely reflecting the new no-smoking policy. **Conclusions:** Green healthy housing renovation may result in improved mental and general physical health, prevented falls, and reduced exposure to tobacco smoke.

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The Veterans RAND 12-Item Health Survey was developed from the Veterans RAND 36-Item Health Survey, which was developed and modified from the original RAND version of the 36-Item Health Survey version 1.0 (also known as the "MOS SF-36"). We complied with the uses of the Rand 36-Item Health Survey listed in http://www.rand.org/health/surveys/sf36item/permission.html.

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Housing affects health directly and indirectly,[1] with substantial burdens of housing-related diseases and injuries.[2] The effectiveness of housing interventions in reducing exposure to physical, chemical, and biological agents has been reviewed elsewhere.[3-6] Low-income households are more likely to encounter environmental health and safety hazards in their homes and communities and are disproportionately affected by environmental diseases.[7,8] In 2009, 40% of households with people aged 65 years and older versus 36% of other households had housing cost burdens (expenditures on housing and utilities exceeding 30% of household income), and 9% of older households versus 3% of others had physically inadequate housing.[9] Thirty-one percent of residents in federally assisted housing are aged 62 years or older and 35% have a disability.[10] Many older Americans have little financial cushion to find suitable housing to meet age-related needs,[10] yet little research on the influence of healthy housing on elder health has been completed.

According to the Department of Health and Human Services' Administration on Aging, persons aged 65 years or older, numbering 39.6 million in 2009 and representing 12.9% of Americans, are expected to grow to 72.1 million by 2030.[11] Per capita health care costs are increasing and at the same time, the number of older Americans is increasing, with low-income older Americans incurring higher health care costs than those with higher incomes.[9] If green and healthy housing renovation leads to elder health improvements, health care costs might decrease, and elders could enjoy a higher quality of life in their homes for a longer period.

While the definition of "green" construction is fluid, different green rating systems, including Enterprise Green Communities Criteria[12] and Leadership in Energy and Environmental Design (LEED),[13] require environmentally responsible and resource-efficient construction practices. These rating systems differ, in that Enterprise requires several health-related specifications, but LEED generally provides a certain number of optional points for health items.

Several studies have found health improvements following new green construction or green renovation; however, these studies focused on children or the general population, not elders.[14-18] Many studies evaluating the impact of housing design on older residents tend to focus on physical safety, such as fall prevention.[19-23] At least 1 study evaluated the impact of home repair on health-related elder quality of life.[24]

The current study investigated the impact of green low-income housing renovation not just on physical safety but also on the physical and mental health of primarily elder residents, evaluating whether self-reported physical and mental health of study residents changed from baseline to 1-year postrenovation and whether these changes differed from changes in a comparable Minnesota population over the same time period.

Methods

The Chesapeake Research Review Institutional Review Board approved this study prior to any data collection, and informed consent was obtained from all study participants. We collected self-reported health status data via interview and conducted air sampling and building performance tests to see whether the renovation met Enterprise Green Community and LEED design standards and improved indoor environmental quality.

Study building description

The study apartment building is a 7-story low-income public housing building built in the early 1970s in Mankato, Minnesota, with 101 units arranged in a rectangular block around an open atrium. Prerenovation, the building had major water infiltration deficiencies, with windows that had leaked since the building was built; little insulation; degraded exterior concrete wall panels; and a failing wastewater collection system. The building had individual through-wall air conditioners, an exhaust-only ventilation system, and no mechanical fresh air ventilation into apartments. Southwest Minnesota Housing Partnership oversaw the building renovation to meet Enterprise Green Communities Criteria,[12] LEED[13] specifications and current codes, as well as life safety standards and accessibility requirements of the Americans With Disabilities Act. Residents gave crucial input in the overall redesign. One building quarter (eg, each of 4 corners) was renovated in each of 4 phases.

Study group recruitment and enrollment

During baseline stage 1 (May-July 2010), we enrolled 53 residents living in 52 of the 72 apartments remaining occupied just before first building quarter construction began in August 2010. On average, baseline stage 1 participants had lived in the building for 9 years (1.7-28 years) prior to their baseline visit. Once the first quarter was renovated, second quarter residents were relocated to the newly renovated first quarter and so on until

the building was fully renovated. No study enrollment occurred during renovation. In April 2012, after full renovation was complete except for remaining ventilation work, property management began moving new tenants into the final building quarter. We conducted baseline stage 2 recruitment from April-September 2012, enrolling 13 new tenants within 60 days of move-in (average, 22 days) to yield 66 participants with baseline data. At 1 year postintervention, 43 of these 66 participants remained in residence. Between August 2013 and October 2013, we collected 1-year postrenovation data for 40 of these participants, comprising the study data set. We analyzed 2 study groups: an "all-ages" group of all participants regardless of age (median, 66 years; n = 40) and a subset, "elder" study group, 65 years or older at baseline (median, 72 years; n = 22).

Comparison group identification

We compared study group health outcomes with comparison groups drawn from a limited data set of 2010 and 2012 MN Medicare Health Outcomes Survey (HOS) data.[25] To create the HOS comparison groups (called the "all-ages HOS group" and "elder HOS group"), we created a preliminary HOS data set of Minnesota residents with household income less than $30 , with at least 90% of follow-up HOS completed. For each HOS participant (n = 1953) and study group participant (n = 40), we classified race/ethnicity as "Non-Hispanic white" yes or no. For each study group participant, we selected HOS comparison group participants of the same age and gender, yielding a minimum of 1 HOS and 26 HOS matches, respectively, for each study group participant in the all-ages and elder study groups. We sorted these HOS participants first by similarities to study group income, then by race/ethnicity, and finally by highest percentage of HOS follow-up interview completed. We selected the first HOS participant for the all-ages study group (n = 40) and the first 26 participants for the HOS elder group (n = 572). One-year follow-up visits averaged 34 months postbaseline (14-40 months) for the study group versus 25 months (22-27 months) for the HOS comparison group.

Health interview

We interviewed residents using a form adapted from 3 published survey tools. We used physical health and mental health questions from the US Centers for Disease Control and Prevention's National Health Interview Survey[26] and the Centers for Medicare & Medicaid Services' HOS,[27] and housing condition questions from the National Survey of Lead and Allergens in Housing.[28]

Health Outcomes Survey questions included 2 summary tools, the Veterans RAND 12-Item Health Survey (VR-12) and Limitations in Activities of Daily Living (ADLs). The VR-12 uses answers to 12 questions to calculate a physical component score and a mental component score, assessing health-related quality of life over time including general health perceptions, physical functioning, role limitations due to physical and emotional problems, bodily pain, energy-fatigue, social functioning, and mental health.[25,29-32] Scores range from 0 to 100 (lowest to highest quality of life). Because all study group participants had valid data for all VR-12 components, no imputation was needed. The Centers for Medicare & Medicaid Services used the Modified Regression Estimate for imputation of missing data and scores to calculate VR-12 scores for HOS group people who had missing data for some VR-12 score components.[31]

Activities of Daily Living are 6 common daily tasks (bathing, dressing, eating, getting in or out of chairs, toileting, and walking) needed for personal self-care and independent living.[25,33] We categorized people as having no limitations in any of the 6 ADLs versus having at least 1 ADL limitation.

Structural interventions

The renovation included

- building envelope improvements, stabilizing and restoring the primary concrete structure;
- heating, electrical, and ventilation system replacement: central geothermal heat pump feeding a water loop to apartment heat pumps;
- new fresh air apartment and building ventilation supplied by 2 rooftop units with maximum efficiency reporting value (MERV) 13 filters (above ASHRAE [American Society of Heating, Refrigeration, and Air-Conditioning Engineers] 62.1's minimum MERV 6 requirement[34]), with apartment air continuously exhausted via bathroom fans from powered roof ventilators;
- new insulation, air sealing, and exterior cladding systems;
- window replacement with double-paned, Energy Star windows;
- new gas ranges with recirculating hoods, outside-exhausted bathroom fans and dryers, and Energy Star light fixtures;
- asbestos tile and mold abatement;
- unit-by-unit gut retrofit;
- use of low volatile organic chemical paints, sealants, and adhesives; green label carpet; moisture-resistant tub/shower enclosure materials;
- lead-safe work practices;
- common interior and immediate outdoor area renovation, including exercise enhancements for those

with a disability and elderly residents (fitness center, walking track, enlarged lobby);
- additional community seating areas; and
- no-smoking policy prohibiting smoking in any indoor area including apartments and restricting smoking to a designated outdoor area away from building entrances and windows.

Building performance

In a convenience subset of 21 enrolled nonsmoking units distributed vertically throughout the building, we installed Onset HOBO U12 temperature (T) and relative humidity (RH) data loggers and Telaire 7001 CO_2 monitors for approximately 2 months prerenovation, removing them just prior to construction. We reinstalled the data loggers immediately postrenovation (September 2012, after ventilation system renovation was done) through 1 year postrenovation (September 2013). Data were downloaded quarterly at 13-minute intervals (~40 430 data points/year), and hourly averages (8760 data points/year) were calculated using HOBOware Pro software (Onset Corporation, Bourne, Massachusetts). To understand the impact of the renovation on indoor moisture levels, we used hourly T/RH data and local weather data to analyze the outdoor-to-indoor dew point differential.

At immediate postrenovation, we tested the primary ventilation systems in the same 21 units to verify fresh air delivery, measure apartment bathroom exhaust air flow rate, and test interstitial pressures between units and corridor, units and outdoors, and between units, under controlled closed conditions. We measured energy use, analyzing pre- and postrenovation utility bills.

Statistical analyses

For all statistical analyses, we defined marginal significance as $0.05 \leq P < .1$ and significance as $P < .05$.

Within-cohort analyses

For dichotomous (yes/no) variables, we used the Cochran-Mantel-Haenzel test to test that the percent yes was different at baseline versus 1 year postrenovation. For continuous outcomes, we used repeated measures models to test that means changed from baseline to 1-year follow-up. We present model-based least squares means that control for the correlation between baseline and 1-year follow-up.

Between-cohort analyses

We conducted statistical tests that the study groups and HOS comparison groups were similar at baseline. For continuous variables (eg, age), we used a 2-sample t test to determine whether study group means were different from comparison group means. For ordinal variables (eg, highest level of school completed, annual income), we used the Cochran-Mantel-Haenzel test to determine whether mean scores were different for study group versus comparison group. For dichotomous variables (eg, yes/no), we used Fisher exact test to determine whether the percent "yes" was different for study versus comparison group.

For the dichotomous (yes/no) variables, we used weighted least squares methods to test that the change in percent "yes" from baseline to follow-up was different for the study versus the comparison groups. The weighted least squares test was not possible if the change was 0% for either cohort. Because of the statistical complexities and assumptions required to model ordinal outcomes, we converted ordinal variables to yes/no outcomes prior to statistically comparing changes in the study versus comparison groups. For continuous outcomes, we used repeated measures models to evaluate whether changes in the mean from baseline to 1-year follow-up were different for the study group versus comparison group. We present model-based least squares means that control for the correlation between baseline and 1-year follow-up.

Building performance data analysis (RH, dew point, and CO_2)

We conducted a paired t test to test that prerenovation versus postrenovation means were significantly different.

Results

Demographics

Most residents in the all-ages group (n = 40) were non-Hispanic white (95%) females (70%), with a median baseline age of 66 years, low annual incomes (92% below $20 000/year), and with either a high school or some college education (82%) (Table 1). Elder study participants had similar demographic characteristics, except the median baseline age was 72 years. Neither the all-ages study group nor the elder study group differed significantly from its respective HOS comparison groups on the basis of gender, age, education, race, and income (P values in Table 1).

Health Outcomes: All-Ages Group

The baseline mental health status was similar for both groups; however, the all-ages study group's mental health improved over the follow-up period while the

TABLE 1 ● Baseline Resident Characteristics: Study Groups and HOS Comparison Groups

Characteristic	All-Ages Study Group N = 40	All-Ages HOS Group N = 40	*P*	Elder Study Group N = 22	Elder HOS Group N = 572	*P*
Age, y			1.0[a] (matched)			1.0[a] (matched)
Minimum	33	33		66	66	
Mean	63	63		72	72	
Median	66	66		72	72	
Maximum	86	86		86	86	
Highest-level of school completed (n, %)[b]			.379[c]			.710[c]
Less than high school	2 (5%)	1 (2.5%)		2 (9.5%)	46 (8%)	
Some high school	2 (5%)	8 (20%)		2 (9.5%)	77 (13.5%)	
High school graduate/GED	18 (46%)	18 (45%)		9 (43%)	301 (53%)	
Some college	14 (36%)	9 (22.5%)		7 (33%)	113 (20%)	
College graduate	3 (8%)	4 (10%)		1 (5%)	16 (3%)	
More than 4-year degree	0	0		0	19 (3%)	
Race, n (%)			1.0[d]			.267[d]
Non-Hispanic White	38 (95%)	38 (95%)		21 (95.5)	501 (88%)	
Non-Hispanic Black	0	0		0	17 (3%)	
Hispanic	1 (2.5%)	0		1 (4.5)	6 (1%)	
Other race	1 (2.5%)	2 (5%)		0	48 (8%)	
Female gender, n (%)	28 (70%)	28 (70%)	1.0[e] (matched)	19 (86%)	494 (86%)	1.0[e] (matched)
Annual income, n (%)[b,f]			.959[d]			.609[d]
<$5000	4 (10%)	3 (7.5%)		2 (9%)	21 (4%)	
$5000-$9999	9 (23%)	12 (30%)		2 (9%)	97 (17%)	
$10 000-$19 999	23 (59%)	21 (52.5%)		15 (68%)	348 (61%)	
$20 000-$29 999	3 (8%)	4 (10%)		3 (14%)	106 (19%)	

[a]Two-sample *t* test that mean age is different for study versus Health Outcomes Survey (HOS).
[b]For all-ages study group, data are missing for 1 person; N = 39.
[c]Cochran-Mantel-Haenzel (CMH) mean score test that the mean scores are different for study and HOS.
[d]CMH test that % Non-Hispanic white is different for study versus HOS.
[e]CMH test that % female is different for study versus HOS.
[f]For study groups, if baseline income was missing, income reported at 1-year postrenovation was used.

all-ages HOS group worsened on the basis of both the mean number of good mental health days in the past month ($P = .026$) and the mean VR-12 mental component score ($P = .023$) (Table 2).

Baseline physical health for both groups was also similar, with both reporting high percentages of overweight or obesity and problems with balance, walking, and shortness of breath. Sixteen percent (16%) fewer all-ages participants versus 8% more HOS comparison group reported falls at 1-year follow-up versus baseline ($P = .055$). Other physical health changes were not significantly different, with neither group experiencing significant changes in either the mean VR-12 physical component score or the mean number of good physical health days.

Health Outcomes—Elder Group

Nine percent (9%) more elder study participants versus 6% fewer elder HOS participants reported being in excellent, very good, or good physical health at 1-year follow-up versus baseline, with the elder study group's improvement marginally significantly better than the elder HOS group's decline ($P = .094$). Both the elder groups experienced a significant increase in the percentage of people with one or more ADL limitations; however, the elder study group's change was significantly worse than that of the elder HOS group ($P = .021$). Difficulty walking was the primary contributor to the worsening of the ADL picture. Other elder physical health parameters did not substantially change over the study period.

Based on the mean number of good mental health days in the past 30 days and the mean VR-12 mental component score, the mental health of both the elder study group and the elder HOS group was good and did not significantly change between baseline and 1-year follow-up ($P = .605$ and .745, respectively) (Table 3).

Housing Condition

Housing condition data were collected only for the all-ages study group. Between baseline and 1 year

TABLE 2 ● Changes in Physical and Mental Health From Baseline to 1-Year Follow-up for the All-Ages Study and HOS Comparison Groups[a]

	All-Ages Study Group					All-Ages HOS Comparison Group					
Outcome	N	Baseline, % or Mean	1-Year Post, % or Mean	Change	*P*	N	Base-line, % or Mean	1-Year Post, % or Mean	Change	*P*	Study Versus HOS, *P*
Physical health and safety											
% people who fell in past 12 mo	38	42%	26%	− 16%	.134[b]	38	21%	29%	8%	.257[b]	**.055[c]**
% people with excellent/good health (vs fair/poor health)	40	62%	70%	8%	.317[b]	40	72%	70%	− 2%	.705[b]	.314[c]
% people with any limitation in ADL	39	23%	51%	28%	**.002[b]**	39	31%	44%	13%	**.096[b]**	.196[c]
Mean VR-12 PCS	40	42.9	41.8	−1.1	.578[d]	40	41.7	41.4	−0.3	.797[d]	.737[d]
Mean no. of good physical health days in past month	40	24.7	26.1	1.4	.366[d]	40	24.3	25.0	0.7	.546[d]	.704[d]
% people overweight or obese	30	90%	83%	− 7%	.157[b]	30	73%	70%	− 3%	.705[b]	.739[c]
% people with chest pain or pressure when resting or exercising	40	13%	10%	− 3%	.655[b]	40	30%	25%	− 5%	.480[b]	.781[c]
% people with balance or walking problem	38	32%	39%	8%	.405[b]	38	29%	37%	8%	.317[b]	NA[e]
% people with shortness of breath during various activities[f]	40	38%	45%	8%	.405[b]	40	45%	50%	5%	.480[b]	0.827[c]
Mental health											
Mean no. of good mental health days in past month[g]	40	25.7	27.3	1.6	**.066[d]**	40	26.5	25.1	−1.5	.167[d]	**.026[d]**
Mean VR-12 MCS	40	55.4	57.4	1.9	.159[d]	40	52.7	49.9	−2.8	**.071[d]**	**.023[d]**

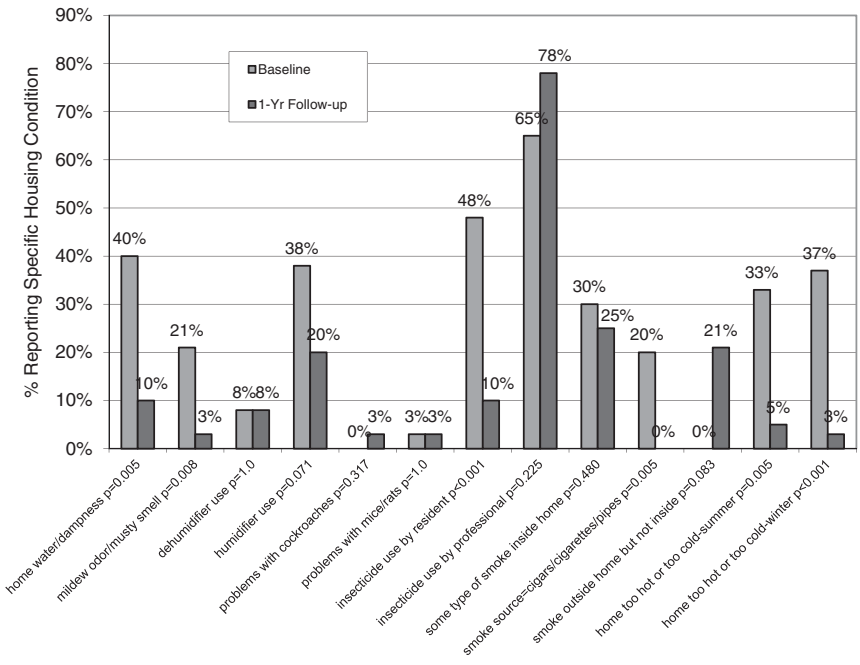
Abbreviations: ADL, activity of daily living; HOS, Health Outcomes Survey; VR-12 MCS, Veterans RAND 12-Item Health Survey mental component score; VR-12 PCS, Veterans RAND 12-Item Health Survey physical component score.
[a]Bold values indicate either marginally significant ($0.05 \leq P < 0.1$) or significant ($P < 0.05$).
[b]CMH test that the percent "yes" changes from baseline to 1-year follow-up within each cohort.
[c]Weighted least squares that the change in percent "yes" from baseline to 1-year postrenovation is different for all-ages study versus all-ages HOS.
[d] Repeated measures model was used to test that, within each cohort and between cohorts, the change in means from baseline to 1 year postrenovation is different.
[e]NA indicates not applicable. Weighted least squares test could not be done because the all-ages study group had the same change (3%) from baseline to 1 year postrenovation as the all-ages HOS group.
[f]During any 1 of 4 activities: when lying down flat, sitting or resting, walking less than 1 block, or climbing 1 flight of stairs.
[g]Based on the question: "Now, thinking about your mental health, which includes stress, depression, and problems with emotions, for how many days during the past 30 days was your mental health not good?"

TABLE 3 ● Changes in Physical and Mental Health From Baseline to 1-Year Follow-up for the Elder Study and HOS Comparison Groups (≥65 Years)[a]

	Elder Study Group					Elder HOS Comparison Group					
Outcome	N	Baseline, % or Mean	1-Year Post, % or Mean	Change	*P*	N	Base-line, % or Mean	1-Year Post, % or Mean	Change	*P*	Study Versus HOS, *P*
Physical health and safety											
% people who fell in past 12 mo	22	36%	32%	−5%	.739[b]	566	28%	28%	0%	1.000[b]	.742[d]
% people with excellent/good health (vs fair/poor health)	22	73%	82%	9%	.317[b]	565	69%	63%	−6%	**<.001[b]**	**.094[d]**
% people with any limitation in ADL	22	23%	55%	32%	**.008[b]**	537	41%	45%	4%	**.024[b]**	**.021[d]**
Mean no. of good physical health days in past month	22	25.6	26.5	0.9	.729[d]	526	22.9	22.2	−0.7	**.099[d]**	.526[e]
Mean VR-12 PCS	22	43.7	41.6	−2.1	.503[d]	572	36.9	36.1	−0.7	**.064[d]**	.669[e]
% people overweight or obese	17	88%	76%	−12%	.157[b]	429	72%	73%	2%	.354[d]	.114[d]
% people with chest pain or pressure when resting or exercising	22	0%	9%	9%	.157[b]	569	33%	34%	2%	.445[b]	.266[d]
% people with balance or walking problem	22	27%	36%	9%	.480[b]	561	40%	41%	1%	.577[b]	.537[d]
% people with shortness of breath during various activities[e]	22	27%	45%	18%	.102[b]	571	58%	62%	5%	**.023[b]**	.234[d]
Mental health											
Mean no. of good days in past month based on mental health[f]	22	28.6	28.1	−0.5	.475[d]	539	25.7	25.6	−0.1	.786[d]	.605[e]
Mean VR-12 MCS	22	59.6	59.5	−0.1	.936[d]	572	51.3	50.8	−0.5	.238[d]	.745[e]

Abbreviations: ADL, activity of daily living; HOS, Health Outcomes Survey; VR-12 MCS, Veterans RAND 12-Item Health Survey mental component score; VR-12 PCS, Veterans RAND 12-Item Health Survey physical component score.
[a]Bold values indicate either marginally significant ($0.05 \leq P < 0.1$) or significant ($P < 0.05$).
[b]Cochran-Mantel-Haenzel test that the percent "yes" changes from baseline to 1-year follow-up within each cohort.
[c]Weighted least squares that the change in percent "yes" from baseline to 1-year postrenovation is different for elder study versus elder HOS.
[d]Repeated measure model was used to test that, within each cohort and between cohorts, the change in means from baseline to 1-year follow-up is different.
[e]During any 1 of 4 activities: when lying down flat, sitting or resting, walking less than 1 block, or climbing 1 flight of stairs.
[f]Based on the question: "Now, thinking about your mental health, which includes stress, depression, and problems with emotions, for how many days during the past 30 days was your mental health not good?"

FIGURE ● Changes in Specific Housing Conditions Baseline Versus 1-Year Follow-up, Based on Interview[a,b]



[a]n = 40, except for mildew odor (n = 39), professional insecticide use (n = 37), smoke outside but not inside (n = 14), and home comfort in winter (n = 38). [b]Cochran-Mantel-Haenzel test that the percent "yes" changes from baseline to 1-year follow-up.

postrenovation, significantly fewer people reported home water or dampness issues (40% vs 10%; $P = .005$) or mildew or musty smells (21% vs 3%; $P = .008$) (Figure). Resident insecticide use decreased significantly ($P < .001$). Significantly fewer people at 1-year follow-up reported smoke in apartments because of cigars, cigarettes, or pipes (20% vs 0%; $P = .005$), likely a reflection of the new no-smoking policy. At 1-year follow-up, residents reported that the most common source of smoke came either from their neighbor's apartments or from electronic cigarette vapor (0% at baseline vs 10%; $P = .046$). Of the people who smoke (n = 14), marginally significantly more reported smoking outside but not inside homes (0% vs 21%; $P = .083$).

Participants reported significantly more frequent use of both kitchen and bathroom exhaust fans ($P = .011$ and $P < .001$, respectively).

Building Performance

Postrenovation average winter RH was below the 30% lower design limit, while average summer RH was just slightly above the 50% upper design limit. The majority of hours above 50% RH occurred in June-August, with average postrenovation summer RH within the design goal of 30% to 50% only 37% of the time. Over the summer monitoring periods, the mean prerenovation outdoor versus indoor dew point difference of 11 exceeded the postrenovation difference of 2 ($P < .001$), suggesting a stronger connection between indoor and outdoor conditions than expected postrenovation, possibly due to the designed introduction of fresh air into the building, which may not have been adequately dehumidified. The mean postrenovation summer CO_2 concentration was significantly less than the mean prerenovation level ($P < .001$), indicating that fresh air introduction improved apartment air quality.

All tested 1-bedroom apartments met the ASHRAE 20-cubic feet per minute (cfm) design criterion[35] for mechanically delivered fresh air, with a mean flow rate of 53 cfm (range, 20-92 cfm) (Table 4), and 85% met the more recent, stringent ASHRAE 30-cfm standard.[36] Eighteen of 21 apartment bathroom fans tested (86%) met the ASHRAE 25-cfm standard,[37] with only 1 failing by more than 10%. With the fan wall switch on, the mean flow rate increased to 64 cfm (range, 40-84 cfm).

The building ventilation and exhaust systems were designed to maintain pressure balances controlling air movement and odor migration between adjacent apartments and between common areas and apartments. Deviations from design were minimal (Table 4).

After renovation, building energy use decreased by 44%. Prerenovation, the building's mean annual energy use was 127 kilo-British thermal units per square foot per year (kBtu/sf-y). While the 1-year postrenovation energy use, 71.5 kBtu/sf-y, exceeded the 63.5 kBtu/sf-y design target,[38] the 44% improvement marked a

TABLE 4 ● Building Performance Results[a]

Environmental Monitoring Parameter	Prerenovation			Postrenovation			Design Criterion	Pre Versus Post, *P*[b]
	Minimum	Mean	Maximum	Minimum	Mean	Maximum		
Relative humidity (RH) (%)								
Winter % RH[c]	NA	NA	NA	3	18	48	30%-50%	NA
Summer % RH[c]	24	45	79	33	53	80	30%-50%	**<.001**
Total % RH	NA	NA	NA	3	33	80	30%-50%	NA
% hours RH between 30% and 50% in summer	20%	78%	99%	14%	37%	73%		**<.001**
Dew point difference (indoor-outdoor)								
Winter	NA	NA	NA	−60	−13	24	NA	NA
Summer	−12	11	37	−12	2	24	NA	**<.001**
Annual	NA	NA	NA	−60	−8	30	NA	NA
CO_2								
Winter concentration (ppm)[c]	NA	NA	NA	106	647	2499	≤1000	NA
Summer concentration (ppm)[c]	396	813	2499	310	553	2499	≤1000	**<.001**
Annual concentration (ppm)	NA	NA	NA	106	611	2499	≤1000	NA
% hours CO_2 <1000 ppm in summer	25%	81%	100%	89%	98%	100%		**.002**
Ventilation Parameter								**N (%) Units Outside Design**
Fresh air delivery to one-bedroom units (cfm) (n = 20)				20	53	92	20[d]	0 (0%)
							30[e]	3 (15%)
Apt exhaust testing, PRV On/EF Off (cfm) (n = 21)				21	29	38	25[f]	2 (10%)
Apt Exhaust Testing, PRV On/EF On (cfm) (n = 21)				40	64	84	25[f]	2 (10%)
Interstitial pressure between units ("wc") (n = 21)				−0.01	0	0.01	0[g]	8 (38%)
Interstitial pressure units wrt hallway (inches wc) (n = 21)				−0.05	−0.01	0.01	Negative[g]	9 (43%)
Interstitial pressure units wrt outside (inches wc) (n = 21)				−0.01	0.02	0.05	Positive[g]	1 (5%)

Abbreviations: cfm, cubic feet per minute; EF, exhaust fans; NA, not applicable because prerenovation monitoring was conducted only during summer months; ppm, parts per million; PRV, powered roof ventilators; wc, inches of water column; wrt, with respect to.

[a]Bold values indicate either marginally significant ($0.05 \leq P < 0.1$) or significant ($P < 0.05$).

[b]Paired *t* test that prerenovation mean was significantly different from postrenovation mean.

[c]Meteorological winter: December-February; meteorological summer: June-August.

[d]From American Society of Heating, Refrigerating, and Air Conditioning Engineers.[35]

[e]From American Society of Heating, Refrigerating, and Air Conditioning Engineers.[36]

[f]From American Society of Heating, Refrigerating, and Air Conditioning Engineers.[37]

[g]Design specification.

substantial accomplishment given the addition of fresh air to units and improvements in exhaust air flow.

Discussion

Our findings support the hypothesis that the physical and mental health of the primarily elderly residents and the residents with a disability improved following the green renovation of their homes. After the green renovation, only 10% of participants reported water and dampness issues and only 3% reported mildew or musty smells. By comparison, a national survey showed that 38% of low-income Midwest residents reported water or dampness issues, while 20% reported mildew odors or musty smells.[39] Postrenovation, both winter and summer average RH values fell below the 70% level of concern for mold propagation.[40]

While the Hawthorne effect[41] may be a concern, a recent, similar study of green renovation and the elderly in Phoenix, Arizona,[42] also found fall reductions and mental health improvements. At 1-year follow-up, falls were reduced by 6%, and 75% of Phoenix participants felt "much better" or "somewhat better" when asked how the renovation affected their emotions. Many mentioned that the renovation made their apartments cleaner, brighter, or more open, and a quarter specifically noted that the kitchen renovation made them feel better.

In our study, innovations designed to give the elderly residents and the residents with a disability access to indoor ponds and gardens, sitting areas on different floors to socialize, and walkable outdoor areas may have contributed to the observed mental health improvements. A recent article noted that people thrive in communities designed to be walkable, disabled-accessible, and sustainable.[43] Other articles discuss the link between the perceived ability to "stay put," and older people feeling their everyday lives are meaningful and their environment is safe.[44,45] On the contrary, we reported that the unexpectedly large increase in study participants, particularly the elderly, reporting any limitation in ADLs (elder study group 32% increase vs HOS comparison group 4% increase), was primarily due to an increase in walking problems, without special equipment or help from another person, over the study period. While our data could not explain this unusual finding, study building residents may have noticed walking problems more postrenovation because the renovation created more indoor and outdoor walking opportunities. While we did not formally collect data on disability status, anecdotal information indicated that more than half of the residents were those with a disability and possibly needed more mechanical assistance over the study period. In both the study and the HOS comparison groups, the percentage of people reporting at least 1 ADL limitation at baseline and follow-up (values in Table 3) was substantially higher than the general 2010 US population (12%).[46] While the HOS group was demographically comparable with the study group, we do not know how the HOS group's disability status compares with study participants. Both the study group and HOS group's increase in ADL limitations over time differs from other trend studies, indicating fewer older US adults reporting ADL impairments over time.[47,48] At least 1 other study found an increase in basic ADL disabilities over a 5-year period.[49] Future elder studies should collect data on disability status and use of mechanical assistance to move around their homes.

Despite the ADL findings, the general physical health of elderly study participants marginally improved compared with health declines found in the HOS elder comparison group, a striking finding given the small sample size of study participants aged 65 years or older (n = 22). We had expected difficulties in discerning definitive physical health impacts, especially for an elderly population in generally poor health at baseline and an inherent expectation of health decline over time.

This study had some limitations. We did not have sufficient sample size to control for season in the data analysis; therefore, we could not evaluate the potential effects of season on self-reported health outcomes. While we assumed the 2 groups had similar medical insurance, access to care, and costs, collecting such data was beyond the scope of this project. Future studies should gather such data to evaluate longer-term health implications of green renovation on the elderly. While we cannot know the type and condition of HOS comparison group homes, we surmise that HOS comparison group homes were likely older, with deferred maintenance. A recent study estimated that almost 75% of homeowners and renters aged 50 years and older remain in their homes until they die.[50] According to a 2008 survey from the American Senior Housing Association, nearly 25% of elders have not made a home improvement in 10 years.[51] Approximately 40% of both older (aged ≥65 years) owner and renter households have housing problems.[9]

Other recent studies not targeted to the elderly also suggest that green housing design improves physical health. Newly built, green, energy-efficient Canadian homes yielded improved throat irritation, cough, fatigue, and irritability.[14] Another green construction study targeting asthmatic Seattle children showed significant improvements in asthma outcomes.[15] A Minnesota green renovation study demonstrated significant improvements in the percentage of adults reporting good or excellent health, as well as in chronic

bronchitis, asthma, sinusitis, and hypertension.[16] A study of new green construction in Chicago public housing showed that self-reported general health and several other physical and mental health outcomes were significantly better in the green study group than in the control group.[17] Green-rehabilitated low-income housing in Washington, District of Columbia, resulted in significant adult general health improvement.[18]

We included several HOS questions about respiratory health verbatim from the Medicare HOS,[25] generally phrased as "Has a doctor ever told you that you had. .. ?" Respondents gave conflicting answers to these types of questions at the 2 time periods. The number of people answering "yes" to these questions at 1-year postrenovation should logically be the same or higher than the number at baseline; however, both our study and Centers for Medicare & Medicaid Services HOS data sets found the numbers sometimes illogically decreased, suggesting that this phrasing is confusing to respondents or respondents have poor memory about their health details. Longitudinal national surveys such as HOS should consider rephrasing these questions so that researchers can discern an impact on respiratory conditions over time, especially important for housing intervention studies that include ventilation modifications potentially having a substantial impact on respiratory health.

Although we could not quantitatively evaluate the renovation's impact on respiratory health, we surmise from the data that residents were exposed to less tobacco smoke postrenovation. Participants reported substantially less smoking inside their apartments, and units were air-sealed, perhaps reducing exposure of nonsmoking residents to secondhand smoke. Several residents who smoked stated that they decreased their daily smoking because of the new policy, likely also contributing to the change in smoking inside units, the perception that others are still smoking in their apartments, and the increase in smoking outside but not inside. Management noted that no evictions were necessary due to the change in smoking policy, and the 2 people who voluntarily moved out rather than follow the new policy were reportedly able to find new housing without assistance, indicating that no-smoking policies can be feasible parts of green renovations.

To observe a more substantial impact on elder resident's physical health, structural interventions should perhaps be combined with home visitation programs, which have been shown to be effective in reducing nursing home admissions,[52,53] preserving autonomy,[54] and reducing mortality[45] but may not have affected limitations in ADLs.[45] A recent pilot of Johns Hopkins "Community Aging in Place-Better Living in Elders" (CAPABLE) study showed promising results, suggesting that multicomponent interventions may reduce disability and increase mobility, functionality, and capacity to age in place.[24] The CAPABLE structural interventions, however, do not include large-scale ventilation system interventions. A study combining an elder visitation program with major structural improvements could yield clearer positive elderly health changes. Future studies should document whether participants in major structural intervention studies routinely received visits from nurses, occupational therapists, and so forth.

Conclusions

Green and healthy housing renovation greatly improved air movement, mechanically providing fresh air directly to each apartment in a controlled manner, thus limiting undesirable air movement and improving energy efficiency. Green renovation has a positive effect on self-reported mental health, physical health, and fall outcomes for residents. Including no-smoking policies in green renovation may lead to less exposure of nonsmoking residents to secondhand smoke. The impact of green renovation on ADL limitations for elderly residents requires further research. The design stage of green renovation should consider the specific needs of residents, especially those of the elderly and persons with a disability.

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