Authors

Elizabeth J Carlton, Kelsey Barton, Prateek Man Shrestha, Jamie Humphrey, Lee S Newman, John L Adgate, Elisabeth Root, and Shelly Miller

Relationships between home ventilation rates and respiratory health in the Colorado Home Energy Efficiency and Respiratory Health (CHEER) study

Elizabeth J. Carlton[1], Kelsey Barton[1], Prateek Man Shrestha[2], Jamie Humphrey[2], Lee S. Newman[1,3], John L. Adgate[1], Elisabeth Root[4], Shelly Miller[2]

[1]Department of Environmental and Occupational Health, Colorado School of Public Health, University of Colorado, Anschutz Medical Campus, 13001 E 17th Place B119, Aurora, CO

[2]Department of Mechanical Engineering, University of Colorado, 427 UCB, Boulder, CO 80309-0427

[3]Division of Pulmonary Science and Critical Care Medicine, Department of Medicine, School of Medicine, University of Colorado, Anschutz Medical Campus, Aurora, CO

[4]Department of Geography and Division of Epidemiology, The Ohio State University, 1036 Derby Hall, 154 North Oval Mall, Columbus, OH, 43210.

*Address correspondence to E.J. Carlton, Colorado School of Public Health, 13001 E 17th Place B119, Aurora, CO 80045. Tel: (303) 724-7947. E-mail: elizabeth.carlton@ucdenver.edu

Abstract

Background: As societies adopt green building practices to reduce energy expenditures and emissions that contribute to climate change, it is important to consider how such building design changes influence health. These practices typically focus on reducing air exchange rates between the building interior and the outdoor environment to minimize energy loss, the health effects of which are not well characterized. This study aims to evaluate the relationship between air exchange rates and respiratory health in a multi-ethnic population living in low-income, urban homes.

Methods: The Colorado Home Energy Efficiency and Respiratory Health (CHEER) study is a cross-sectional study that enrolled 302 people in 216 non-smoking, low-income single-family homes, duplexes and town-homes from Colorado's Northern Front Range. A blower door test was conducted and the annual average air exchange rate (AAER) was estimated for each home. Respiratory health was assessed using a structured questionnaire based on standard instruments. We estimated the association between AAER and respiratory symptoms, adjusting for relevant confounders.

Results: Air exchange rates in many homes were high compared to prior studies (median 0.54 air changes per hour, range 0.10, 2.17). Residents in homes with higher AAER were more likely to report chronic cough, asthma and asthma-like symptoms, including taking medication for wheeze, wheeze that limited activities and dry cough at night. Allergic symptoms were not associated with AAER in any models. The association between AAER and asthma-like symptoms was stronger for households located in areas with high potential exposure to traffic related pollutants, but this was not consistent across all health outcomes.

Conclusions: While prior studies have highlighted the potential hazards of low ventilation rates in residences, this study suggests high ventilation rates in single-family homes, duplexes and townhomes in urban areas may also have negative impacts on respiratory health, possibly due to the infiltration of outdoor pollutants.

Key Words: Respiratory Health; Asthma; Urban Health; Ventilation; Air Exchange Rate

Acknowledgements. This article was developed under Assistance Agreement No. RD 83575201 awarded by the U.S. Environmental Protection Agency to Dr. Shelly Miller. It has not been formally reviewed by EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication. We thank Xcel Energy, Boulder Housing Partners, and Loveland Habitat for Humanity with their assistance in recruiting study participants. We also thank Sam Rock, Adam Pittman, Ethan Zerpa, Adam Hahn, Hanadi Salamah, Tess Bloom, Ryan Hourigan, Mohamed Eltarkawe, Olivia Cecil, Jonathan Kohlenberg, Alisen Bol, Adam Hester, Sarah Hong, Alex Mass and Stefano Brunelli for their assistance with field data collection.

Competing financial interests declaration. The authors declare they have no actual or potential competing financial interests.

Introduction

Over the past four decades, policies and programs have promoted energy efficient design and retrofits of residential housing in the United States in an effort to reduce energy expenses and carbon dioxide emissions (e.g., Hens et al. 2001; Schweitzer 2005; Tonn et al. 2018). More than seven million existing homes have participated in energy efficiency programs since the start of U.S. Department of Energy's Weatherization Assistance Program in 1976. Cities and states are increasingly adopting green building policies promoting energy efficient design in the construction of new residential housing. In the US, residential buildings accounted for 22% of primary energy consumption in 2010 (DOE 2011a). In addition to reducing carbon dioxide emissions, energy efficient design and retrofits can reduce energy expenses, freeing up precious financial resources in low-income families. As society moves towards more energy efficient building practices, it is important to consider how such building design changes may impact the health of residents (Institute of Medicine 2011).

Most U.S. homes are ventilated with natural ventilation practices such as open windows and doors, or infiltration, ventilation through unintended openings such as cracks in the building structure. Green building and weatherization practices typically focus on reducing air exchange between the building interior and the outdoor environment to minimize energy use for heating and cooling. Building shells are made more airtight through the use of insulation (e.g. in attics and walls) and air-sealing activities like weather-stripping on doors and windows, foam sealing around electrical and plumbing conduits that penetrate through walls, and installation of energy efficient windows. These measures can reduce building ventilation, typically measured using the air exchange rate: the number of times the total volume of air in the home is replaced per hour.

Changes to ventilation rates in residential buildings may have implications for health for two reasons. First, ventilation has long been recognized as a key component of good indoor air quality (Nazaroff 2013). In fact, weatherization contractors and new building codes require installation of mechanical ventilation when home ventilation rates fall below a minimum threshold (US DOE 2014). Low ventilation rates can lead to unintended health consequences including increased exposure to indoor pollutants because of less dilution of indoor air and build-up of moisture leading to mold and microbial overgrowth. Second, the average American often spends more than 80% of their time indoors. To the extent that hazards are present in the home, there is potential for long-term exposure.

There is growing evidence that low air exchange rates in residential buildings may have adverse health consequences. Low ventilation rates have been associated with respiratory infections in infants (Kovesi et al. 2007), as well as asthma and allergic symptoms in adults (Wang et al. 2017) and children (Bornehag et al. 2005). Low air exchange rates can lead to increased concentrations of common indoor pollutants such as radon, nitrogen dioxides (NO_x) from cooking with natural gas appliances, volatile organic compounds (VOCs) from consumer product use, and particulate matter ($PM_{2.5}$) from cooking, smoking, and cleaning (e.g., Francisco et al. 2017; Oie et al. 1999; Pigg et al. 2018). These indoor pollutants can lead to adverse health outcomes ranging from asthma exacerbations to cancer (Institute of Medicine 2011). Low ventilation rates may also lead to a build-up of moisture which can promote the growth of mold and other microbes that cause allergic and irritant symptoms (Emenius et al. 2004; Hagerhed-Engman et al. 2009). Recent reviews of the literature have found evidence that low air exchange rates in residential buildings may increase the risk of asthma, allergic symptoms, and respiratory infections (Fisk 2018; Sundell et al. 2011). However, much of the evidence cited in these reviews is from studies conducted in Nordic countries where air exchange rates are low and not representative of U.S. housing stock (e.g., Bornehag et al. 2005; Emenius et al. 2004; Oie et al. 1999; Wang et al. 2017). Few of these studies have accounted for outdoor pollutants, which may confound or modify relationships between ventilation rates and respiratory health.

Conversely, high air exchange rates may also have deleterious health consequences. High air exchange rates can increase the infiltration of common outdoor pollutants, such as $PM_{2.5}$, NO_x, and ozone, which have been linked to an array of health outcomes (WHO 2016). Pollutants from outdoor sources can account for a substantial fraction of pollutants inside the home (Meng et al. 2009), and their concentrations are higher in homes with higher ventilation rates (Hodas et al. 2012; Meng et al. 2005). Additional research is necessary to understand the impact of home ventilation on respiratory health, especially in the U.S.

The Colorado Home Energy Efficiency and Respiratory health (CHEER) study was designed to assess the association between ventilation rates, indoor air quality, and respiratory health in low-income, urban households. This cross-sectional study used an objective measure of building ventilation rates and focused on populations with traditionally high burdens of respiratory illness: low-income, urban residents. The current study aims to evaluate associations between air exchange rates and self-reported respiratory symptoms.

Methods

Study population

Recruiting methods were designed to enroll homes with a range of ventilation rates across the Northern Front Range of Colorado. CHEER participants were recruited from low-income, non-smoking, households from the cities of Denver, Aurora, Boulder, Loveland, and Fort Collins (Figure 1) over 18 months, from October 15, 2015 to April 15, 2017. Households were recruited through a local utility company and agencies that provide housing for low-income homes: Xcel Energy, Boulder Housing Partners, and Loveland Habitat for Humanity. Xcel Energy sent recruiting material to all homes that qualified for the low-income energy assistance program (LEAP) from 2011 to 2015 in target zip codes including homes that were weatherized through the weatherization assistance program and those that were not. Loveland Habitat for Humanity and Boulder Housing Partners, both of which have adopted green building practices for new home construction, sent recruiting materials to all of their clients. Mail recruiting was supplemented by direct outreach at community events and in target communities in our target areas. Most households were recruited via mail (209 of 216 households). All recruiting materials provided to eligible households were written at a fifth grade reading level and provided in English and Spanish.

For a household to be eligible for enrollment in CHEER, it had to meet four eligibility criteria. First, the residence must be a single-family home or a duplex or townhome with no direct air exchange vents in between each unit such that heating and cooling can be achieved in each unit independent of adjacent units. Second, households were required to be low-income, as defined by the participating agency. Income eligibility differed across the partner agencies, but all used thresholds below the U.S. Department of Housing and Urban Development's (HUD) definition of low income (LEAP: household income <165% of the federal poverty level; Loveland Habitat for Humanity and Boulder Housing Authority: $\leq$60% of the median income for the county). Third, all residents in the home must be reported non-smokers. Finally, household residents must have lived in the home for at least 6 months.

Upon enrollment, a three-person study team conducted a two-hour home visit to assess building and household characteristics, building ventilation rates, and the respiratory health of all participating residents. This study protocol was approved and authorized by the University of Colorado Boulder Institutional Review Board (Protocol 14-0734). All adult participants provided written informed consent. All children provided assent and their parents or guardians provided written, informed permission for them to participate in this study. Upon completion of the home visit, the head of household was provided a $25 grocery store gift card, and information about their home, the respiratory health of all participating residents, and local resources that serve low-income populations.

Air exchange rates

A multi-point depressurization blower door test was conducted in each home to measure the air tightness and air leakage of the building envelope for each home (Sherman and Dickerhoff 1998). Blower door tests were conducted on an exterior door of each household (Minneapolis Blower Door Model 3, TECTITE 4.0 software, The Energy Conservatory, Minneapolis, MN). The depressurization version of the blower door test was selected so as to provide additional information to the participants regarding areas of significant leakage existing in the building. Prior to initiation of the test, all combustion devices were turned off, the presence of mechanical ventilation systems were noted, ashes (if any) were cleared from fireplaces and fireplace flue dampers shut, and all exterior doors and windows were closed. An air infiltration model (Sherman and Modera 1986; Sherman 1987) was used to estimate the annual average air exchange rate (AAER) from the air leakage measurements based on the geographical location of the test being conducted, wind shielding effects, and height of building. AAERs for the few homes (n=11) that had been fitted with continuous mechanical ventilation units were adjusted by adding an effective additional flow rate introduced by the mechanical ventilation system to the airflow rate measured with a blower door test according to a study from Palmiter and Bond (Palmiter and Bond 1991).

Respiratory Symptoms Survey

All consenting household residents 8 years and older were interviewed by trained research staff who were blind to the air exchange rate of the home about respiratory symptoms in the past 12 months using a structured questionnaire derived from standard survey instruments. To ensure both the interviewer and participant were blind to exposure status, residents were provided the results of the blower door test after respiratory questionnaires were completed, and research team members administering health questionnaires were not involved with measurement of air exchange rates. Participants were asked about the frequency and severity of chronic respiratory symptoms using questions from the American Thoracic Society DLD-78 (Ferris 1978). Allergic symptoms (hay fever, sneezing and itchy/runny eyes without a cold, eczema), and asthma-like symptoms including wheeze and dry cough at night were assessed using questions from the International Study of Asthma and Allergies in Childhood (Asher et al. 1995; ISAAC Steering Committee 1998). Current asthma diagnosis, the severity of asthma-like and allergic symptoms, and healthcare utilization were also collected, using questions from the National Health and Nutrition Examination Survey (Centers for Disease Control and Prevention 2012). Parents were asked to report symptoms for children.

Basic demographic information was collected from each participant and smoking history was assessed via a questionnaire administered to all participants over age 13 using a standard survey instrument (Centers for Disease Control and Prevention 2012).

Household Characteristics

Observations that could indicate poor indoor air quality were recorded during the walkthrough surveys; these were chosen based on concerns for health of the occupants and included conditions such as the presence of visible mold, dampness on walls or floors, and presence of a gas stove. Residents were also queried about ventilation practices including opening windows and the use of exhaust fans.

Statistical Analysis

The relationships between household AAER and respiratory symptoms were evaluated using logistic regression models. Generalized estimating equations (GEE) were used to fit the logistic model to account for potential dependence among individuals within the same household. All GEE regression models assumed an exchangeable correlation structure among individuals within the same household, calculating robust variance estimates (Zeger et al. 1988). We restricted our analysis to respiratory symptoms reported by at least 10% of the population and defined each outcome as a binary variable. AAER was modeled as a continuous variable. For each respiratory outcome, we estimated the odds ratio (OR) and 95% confidence interval (CI) for a one-unit change in AAER. Models were fit separately for each respiratory outcome.

In order to evaluate evidence for linear exposure-response relationships, separate models were fit by defining quartiles of AAER and modeling this as a categorical variable. Here, the OR was estimated for each outcome relative to the reference group, which was the lowest AAER quartile. Tests for trend were conducted by modeling the categorical AAER quartile variable as ordinal and examining the p-value of the parameter estimate.

For each outcome of interest, both crude and adjusted ORs were estimated. Models were adjusted for variables known to be associated with respiratory symptoms including sex, age (including both age and age^2 to allow for non-linearities), race/ethnicity, smoking status, socio-economic status, and indoor nitrogen dioxide (NO_2) exposure. A person was classified as a prior smoker if they reported smoking at least 100 cigarettes over their lifetime, ever regularly smoking a pipe (>12 oz. in their lifetime) or cigar (>1 cigar per week for at least one year), and they did not currently smoke cigarettes, pipes or cigars. Socio-economic status was classified based on the educational attainment of the head of the household. The presence of a gas stove was used as a surrogate for indoor NO_2 exposure as studies have found that homes with gas stoves have greater NO_2 concentrations compared to homes with electric stoves, and that NO_2 exposure increases asthma severity and symptoms (e.g., Basu and Samet 1999; Belanger et al. 2013; Garrett et al. 1998). Models were additionally adjusted for region, defined based on political boundaries and landmarks that divide communities (e.g., interstates and major roadways). Four regions were delineated: Aurora, West Denver, North/Central Denver, and Boulder/Loveland/Fort Collins.

We estimated a second set of adjusted ORs to account for potential confounding by outdoor air pollutants. These models included the aforementioned confounders as well as two measures of traffic-related air pollution (TRAP): household distance to major road and annual average traffic-related nitrogen oxide (NO_x) concentrations in the neighborhood (defined by census block). Distance to the nearest major road was defined for each household using a proximity model, where a major road was defined as a road with annual average daily traffic (AADT) of greater than 10,000 (Carlsen et al. 2015; Rose et al. 2009; Schikowski et al. 2005). The measure was dichotomized at 200 meters of a major road based on evidence that TRAP drops to background levels at between 100 and 200 meters from a roadway, depending on the pollutant and meteorological conditions (Karner et al. 2010). Census block estimates for NO_x, a proxy for overall TRAP in a neighborhood, were developed using Community Line Source Model (C-Line), Version 3.0, a reduced-form dispersion modeling program developed at University of North Carolina's Institute for the Environment in conjunction with the U.S. Environmental Protection Agency (Barzyk et al. 2015). The model uses emissions factors derived from the Multi-scale motor Vehicle and equipment Emission System (MOVES), road network and traffic activity data from the Federal Highway Administration, and meteorological data (including wind speed, direction and ambient temperature) from the National Weather Service to estimate TRAP at fine spatial scales. C-LINE was run for our study area for the year 2015, generating average NOx concentrations by census block. Census blocks above the maximum value that can be estimated using C-LINE (200 ppb) were assigned the maximum value (this applied to 3% of households).

Sensitivity analyses were conducted to evaluate the stability of our results when 1) excluding the 11 homes with mechanical ventilation, 2) excluding the 33 duplexes and townhomes, and 3) excluding the seven homes that were built as energy efficient homes ("built green"). Additional sensitivity analyses were conducted to evaluate the relationship between AAER and respiratory symptoms excluding homes from the Boulder/Loveland/Fort Collins region, as this region generally has lower population density and participants from this area were the most demographically distinct from residents in other regions. In light of our findings, a post-hoc sensitivity analysis was conducted to evaluate the potential role of dampness and mold as a confounder, adjusting models for the presence of visible mold and or dampness on walls or floors observed during the home visit.

Supplemental analyses examined evidence that associations between ventilation rates and respiratory symptoms were due to infiltration of outdoor pollutants in leaky homes. High air exchange rates increase the infiltration of outdoor pollutants (Hodas et al. 2012; Meng et al. 2005; Sarnat et al. 2013). If infiltration of outdoor pollutants is causing respiratory symptoms, we expect to see a stronger relationship between AAER and respiratory symptoms in areas with higher concentrations of outdoor pollutants compared to homes located in less polluted areas. To test this, we conducted a stratified analysis, estimating the relationship between AAER and respiratory symptoms for homes in areas with potentially high levels of TRAP and homes in areas where the ambient concentrations of traffic-related pollutants were suspected to be lower. A home was classified as being in a high outdoor pollution area if it was located within 200 meters of a major road and/or if the mean annual NO_x concentrations in the census block, estimated from the CLINE models, described above, were above the 75th percentile (86 ppb) for our study population.

Results

Respiratory symptom questionnaires were administered to 302 individuals in 216 households where home ventilation rates were measured. Households were drawn from cities in Colorado's Northern Front Range (Figure 1). Most (68%) reported spending an average of 15 hours or more in their home each day (Table 1). Participants were predominantly female (67%), older (mean age 54) and ethnically diverse (including 41% non-Hispanic white, 34% Hispanic, 14% non-Hispanic black). The sample includes 115 LEAP-eligible homes that were weatherized through the Weatherization Assistance Program, 94 LEAP-eligible homes that were not weatherized and 7 homes that were built green (Table 2).

The estimated annual AAER ranged from 0.10 to 2.17 air changes per hour (ACH). The median and mean were 0.54 and 0.64 ACH, respectively. Mean and median AAER was lowest for homes that were built green, and highest for non-weatherized homes although the differences were small and the distribution of AAER for all home types overlapped considerably (Figure 2). We found that 33% of weatherized homes, 20% of non-weatherized homes and 57% of built green homes had AAER values in the lowest quartile (0.10 to 0.42 ACH). The full range of AAER values were observed in both non-weatherized and weatherized homes (range 0.16 to 1.66 and 0.25 to 2.17 ACH in weatherized and non-weatherized homes, respectively). AAER did not exceed 0.57 ACH in built green homes.

Participants reported a range of respiratory and allergic symptoms (Table 3). Chronic cough was reported by 17% of participants. One or more allergic symptoms were reported by 40% of participants. Current asthma was reported by 11% of participants, and 40% of participants reported asthma-like symptoms in the past year including wheeze (22%) or dry cough at night without a cold or chest infection (26%).

Residents in homes with higher AAER were more likely to report chronic cough, asthma, and asthma-like symptoms (Table 4 and Figure 3). Specifically, cough, taking medication for wheeze,

wheeze that limited activities, dry cough at night, and having a current asthma diagnosis were associated with higher AAER in adjusted models. There were considerable differences in the odds ratios in the adjusted vs. unadjusted models. The adjusted odds ratios were robust to reductions in the set of variables used to control for confounding. The association between AAER and asthma, as well as asthma-like symptoms, was stronger in models that adjusted for traffic-related air pollutants, although there is considerable uncertainty around the point estimates. Any wheeze in the past 12 months was also positively associated with higher AAER, although this may be due to chance. A one-unit change in AAER was associated with a 5.03 fold increase in the odds of taking medication for wheezing in the past year (95% confidence interval: 1.83, 13.87) and a 5.44 fold increase in the odds of having a current asthma diagnosis (95% CI: 1.58, 18.76).

Models that included quartiles of AAER generally provided evidence for a positive, linear association between AAER and chronic cough, asthma and asthma-like symptoms – including taking medication for wheeze and dry cough at night (Figure 3 and Supplemental Material, Table S1).

Allergic symptoms were not associated with AAER in any models.

Sensitivity analyses limiting the analysis to the 205 homes without mechanical ventilation, the 183 single family homes, the 206 homes recruited through the low-income energy assistance program that were not built green, and the 182 homes in the Denver/Aurora region did not meaningfully change the results (Supplementary Material, Table S2), nor did adjusting for mold and dampness in the home (Supplementary Material, Table S3). The association between AAER and asthma as well as asthma-like symptoms were modestly larger when the sample was restricted to homes without mechanical ventilation and to homes in the Denver/Aurora region.

The associations between AAER and some asthma-like symptoms were stronger for households located in areas with higher potential exposures to traffic-related air pollution (Table 5, Figure 4,

Table S4). We observed a stronger association between AAER and wheezing and dry cough at night when we limited our analysis to households located near major roads or in census blocks with high average NOx concentrations, compared to households with lower potential TRAP exposures, but there is considerable uncertainty around these estimates. The association between AAER and taking medication for wheezing was stronger for homes with poor outdoor air quality when AAER was modeled in quartiles but not when modeled as a continuous variable. The inverse pattern was seen for asthma: the association between AAER and current asthma was stronger in areas with lower potential TRAP exposure, compared to areas with higher TRAP exposures.

Discussion

Research to date has provided evidence that that *low* ventilation rates have adverse effects on respiratory health (Fisk 2018; Sundell et al. 2011), likely due to increased concentrations of indoor pollutants. Our study suggests that some low-income, urban homes have high ventilation rates, and these high ventilation rates may also have negative impacts on respiratory health, possibly due to the infiltration of outdoor pollutants. Here we review plausible explanations for our study findings, as well as implications for policy and future research.

Key finding 1: air exchange rates in our study population were generally high. The air exchange rates in our study population were higher than in many studies showing associations between low ventilation rates and adverse respiratory health outcomes (e.g., Fisk 2018; Sundell et al. 2011). The aforementioned studies have primarily been conducted in Nordic countries where building ventilation rates are typically lower than what we observed in our study population. The mean ventilation rates in two recent Swedish studies were 0.36 ACH (Bornehag et al. 2005; Wang et al. 2017) compared to 0.49 ACH in our study homes. In fact, only 17% of homes in our study had ACH below the 0.36 ACH mean value of the two Swedish studies. This distribution of air exchange rates in our study population leaves us ill-powered to evaluate the associations between very low ventilation and respiratory health, but it does draw attention to the fact that some low-income urban residents are living in homes with high air exchange rates. Notably, mechanical ventilation systems were rare, present in just 5% of homes. The people with high air exchange rates in our population were living in homes with considerable infiltration through the building structure.

The air exchange rates observed in our study have been observed by others in urban US housing stock in similar climates. Past studies in U.S. urban populations have found ventilation rates similar to those of our study population (Isaacs et al. 2013; Murray and Burmaster 1995). One study measured air exchange rates in over 2,800 U.S. homes across the country and the region including Colorado, and estimated a mean AAER of 0.55, median of 0.40, and a range of 0.04 to 5.49 – similar to our population (Murray and Burmaster 1995). A study of 126 homes in Michigan found median weeklong air exchange rates of 0.57 ACH (Du et al. 2012). Recent estimates of air exchange rates for census tracts based on the same LBNL model we used to interpret our blower door data suggest air exchange rates in regions with similar climate as Colorado are the same or higher than what we observed in our study population: the mean (median) AERs ranged from 0.75 (0.74) to 0.88 (0.84) for Michigan and from 0.64 (0.61) to 0.92 (0.90) for New Jersey, depending on season (Baxter et al. 2017). High air exchange rates lead to high energy expenditures, an important consideration for many low-income families. Given that high air exchange rates are not uncommon, it is important to document the potential impacts of high ventilation rates on human health.

Key finding 2. High AAERs are associated with adverse respiratory outcomes, possibly due to the infiltration of outdoor pollutants. Residents in homes with the highest ventilation rates were most likely to report chronic cough, asthma-like symptoms, and to have a current asthma diagnosis. The associations were strong and, in most cases, suggestive of an exposure-response relationship. A one-unit increase in AAER was associated with a 5.1-fold increase in the odds of taking medication for wheeze, a 2.3-fold increase in the odds of having a dry cough at night, a 5.9 fold increase in the odds of having a current asthma diagnosis, and a 4.2-fold increase in the odds of reporting chronic cough. Moreover, associations between air exchange rates and some respiratory symptoms were stronger in homes with higher potential exposures to TRAP and weaker in less polluted areas. If infiltration of outdoor pollutants into the home environment is causing respiratory morbidity, we expect the association between high ventilation rates and adverse respiratory outcomes to be weakest in areas with very low outdoor pollution levels and strongest in areas with very high outdoor pollution levels – this is consistent with what we observed. The associations between ventilation rates and asthma, asthma-like symptoms, and chronic cough were stronger when we limited our study population to the Denver/Aurora region, where population density, traffic density, and TRAP levels are typically higher than in the northern study cities (Boulder, Loveland, and Fort Collins). Similarly, associations between ventilation rates and some asthma-like symptoms including dry cough at night and wheezing were stronger in homes with higher potential exposures to TRAP as defined by neighborhood NO_x concentrations and proximity to a major road, but this pattern was not consistent across all health endpoints associated with high ventilation rates. Notably, as all of the homes in our study were in urban areas, we lacked a comparison group of homes with very low TRAP exposures.

We think the most plausible explanation for these findings is that *high* ventilation rates lead to the infiltration of outdoor air pollutants into the home environment, increasing indoor exposure to outdoor pollutants such as $PM_{2.5}$, NO_x, and ozone, which have been linked to an array of health outcomes (WHO 2016). High air exchange rates can increase the rate at which outdoor pollutants enter the home, leading to indoor concentrations of classically outdoor pollutants at levels approaching outdoor concentrations (Hodas et al. 2012; Meng et al. 2009). This can lead to prolonged exposure to such pollutants as people spend a considerable amount of time at home—in our study, 68% of participants reported spending at least 15 hours per day in their home. If true, the infiltration of outdoor pollutants into leaky homes may be an important cause of respiratory morbidity in low-income, urban U.S. populations.

Our findings are consistent with several intervention studies which have documented improvements in occupant respiratory health after interventions that target tightening of the building shell through measures including installation of more energy efficient windows, improving insulation and sealing around doors. Notably, the aforementioned studies included urban populations where infiltration of outdoor pollutants may be a key source of air contaminants in leaky homes. However, such interventions have also included asthma education (Breysse et al. 2014), repairs and or installation of ventilation systems (Colton et al. 2014), or have targeted populations where home temperatures are unusually low (Howden-Chapman et al. 2007), making it difficult to generalize from their results and determine the extent to which changes in ventilation rates alone drive health impacts.

Alternative explanations for our observed associations between high ventilation rates and respiratory outcomes include residual confounding due to poverty and/or poor housing quality. In general, the homes with the highest ventilation rates were older and were more likely to have visible mold, and the head of household was least likely to have a college degree. It is possible that homes with high ventilation rates are the homes in the worst repair overall, serving as the housing of last resort for the poorest populations in our study, in which issues such as mold that could lead to adverse respiratory health outcomes. Homes with high ventilation rates may also have poor temperature control, leading to low indoor temperatures, which have been shown to negatively impact respiratory health (Howden-Chapman et al. 2007). To account for potential confounding by poverty, we restricted to low-income households and we adjusted for head of household educational attainment in our models, recognizing that even within low-income populations, socioeconomic status is variable. We additionally evaluated the sensitivity of our results to adjustment for mold and dampness – this adjustment did not meaningfully alter our estimates. Nonetheless, it is possible that socio-economic status and housing quality may not have been fully eliminated as potential confounders. Ultimately, confidence in our study findings would be heightened by replication of our findings in other contexts.

Policy implications. Our findings suggest that energy efficiency measures that tighten the building shell may reduce respiratory morbidity in low-income homes in urban areas, particularly in regions where outdoor air pollutant concentrations are high, provided that indoor sources of pollution can be addressed. Efforts to reduce ventilation must also consider the potential risks of concentrating indoor pollution sources, such as mold and tobacco smoke. Optimal ventilation rates may be those that reduce the concentration of indoor pollutants and protect against the infiltration of outdoor pollutants (Nazaroff 2013). In areas where outdoor pollution concentrations are high, and during high pollution events such as wildfires, efforts to reduce building ventilation rates reduce personal exposures to outdoor pollutants and ultimately protect respiratory health.

Our findings and the work of others also suggest that policies to reduce outdoor pollution may lead to improvements in indoor air quality, reducing personal exposures to harmful outdoor pollutants that are generated by mobile and point sources. Urban, low-income communities such as those included in our study, have some of the highest rates of respiratory morbidity in the U.S. and residents are often exposed to high levels of outdoor pollutants (e.g., Ash and Fetter 2004; Maantay 2007). Residents in high-pollution communities that also live in homes with high air exchange rates may face added risks of respiratory morbidity.

Notably, many of the homes in our study population had been weatherized, but AAERs were similar in weatherized and non-weatherized homes. This suggests not all weatherization strategies will meaningfully lower ventilation rates in existing buildings, a topic we explore in-depth in a separate analysis.

Limitations. We chose to estimate an annual average measure of air exchange rates using a well-established air infiltration model that accounts for seasonal weather patterns and home characteristics. This allowed us to compare exposure and respiratory symptoms assessed over the same 12-month time period. Air exchange rates can vary considerably by season, especially in climates where people cool with open windows in the summer and with heating in the winter such as in Colorado. Murray and Burmaster reported for Colorado that the highest mean AERs were measured during the summer (1.31) and lowest in the fall (0.35); spring and winter were 0.52 and 0.57 respectively (Murray and Burmaster 1995). We also found evidence that window opening varies seasonally. It is possible that acute respiratory symptoms, such as asthma exacerbations, are more closely related to a season-specific air exchange rate and/or occupant behavior such as opening of windows, which may warrant further investigation.

Our health outcome measures, while assessed using well-recognized respiratory survey instruments, were ultimately self-reported health data. We do not think that exposure status biased reporting of symptoms as residents and technicians collecting respiratory health data were not informed of the results of their blower door test until after questionnaires were administered. It is possible that some participants did not live in their home for the full 12-month period over which we asked about respiratory symptoms as our inclusion criteria required residents had lived in their home for at least 6 months. To the extent this occurred, we expect this exposure misclassification to be nondifferential, biasing estimates towards the null. Our assessment of outdoor air pollution as both a confounder and effect modifier was limited to consideration of traffic-related air pollution. This study employed a cross-sectional design and thus we were unable to assess how changes in AAER within a home, due, for example to weatherization, impacted respiratory symptoms. We did not adjust for weatherization status, because weatherization is designed to reduce ventilation rates and it is inappropriate to adjust for variables on the causal pathway. However, it is possible that weatherization impacts respiratory health through other pathways (e.g. thermal comfort, volatile organic compound concentrations (Noris et al. 2013)) which we do not account for in this analysis. We did not recruit households using statistical sampling and there may have been some selection bias due to our recruiting methods. By design, our study populations had low exposure to a key source of indoor pollution, secondhand tobacco smoke (SHS) as we excluded homes with active smokers. It is unclear how our findings generalize to homes with smokers. We limited our focus to respiratory outcomes and did not consider other health outcomes that might be affected by building ventilation rates. Finally, we had few homes with low ventilation rates, and thus were unable to evaluate the impacts of very low AAER on respiratory health within our study population.

Conclusions

Our study found that in low-income, urban homes, high ventilation rates are associated with increases in chronic cough, asthma and asthma-like symptoms. This association is likely due to the infiltration of outdoor air pollutants from traffic-related sources into the home, leading to higher personal exposures to classically outdoor air pollutants and adverse impacts on respiratory health. Our study also showed that many of the residents in our study lived in homes with high ventilation rates, which may lead to considerable energy expenditures in a low-income population. Residents in high pollution areas may be good candidates for effective energy efficiency measures that reduce ventilation rates, or that provide ventilation with pollutant-free air using filtration, provided that indoor sources of pollution can also be addressed. Moreover, policies to improve outdoor air quality have the potential to improve indoor air quality, with implications for respiratory health.

References

Ash M, Fetter TR. 2004. Who lives on the wrong side of the environmental tracks? Evidence from the EPA's risk-screening environmental indicators model. Social Science Quarterly 85:441-462.

Asher MI, Keil U, Anderson HR, Beasley R, Crane J, Martinez F, et al. 1995. International Study of Asthma and Allergies in Childhood (ISAAC): rationale and methods. Eur Respir J 8:483-491.

Barzyk TM, Isakov V, Arunachalam S, Venkatram A, Cook R, Naess B. 2015. A near-road modeling system for community-scale assessments of traffic-related air pollution in the United States. Environ Modell Softw 66:46-56.

Basu R, Samet JM. 1999. A review of the epidemiological evidence on health effects of nitrogen dioxide exposure from gas stoves. Journal of Environmental Medicine 1:173-187.

Baxter LK, Stallings C, Smith L, Burke J. 2017. Probabilistic Estimation of residential air exchange rates for population-based human exposure modeling. J Expo Sci Environ Epidemiol 27:227-234.

Belanger K, Holford TR, Gent JF, Hill ME, Kezik JM, Leaderer BP. 2013. Household levels of nitrogen dioxide and pediatric asthma severity. Epidemiology 24:320-330.

Bornehag CG, Sundell J, Hagerhed-Engman L, Sigsgaard T. 2005. Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. Indoor Air 15:275-280.

Breysse J, Dixon S, Gregory J, Philby M, Jacobs DE, Krieger J. 2014. Effect of weatherization combined with community health worker in-home education on asthma control. Am J Public Health 104:e57-64.

Carlsen HK, Modig L, Levinsson A, Kim JL, Toren K, Nyberg F, et al. 2015. Exposure to traffic and lung function in adults: a general population cohort study. BMJ open 5:e007624.

Centers for Disease Control and Prevention. 2012. National Health and Nutrition Examination Survey Questionnaire, 2011-2012. Available: https://wwwn.cdc.gov/nchs/nhanes/continuousnhanes/questionnaires.aspx?BeginYear=2011 [accessed 1/22/2015 2015].

Colton MD, MacNaughton P, Vallarino J, Kane J, Bennett-Fripp M, Spengler JD, et al. 2014. Indoor air quality in green vs conventional multifamily low-income housing. Environ Sci Technol 48:7833-7841.

DOE. 2011a. Buildings Energy Data Book

Du L, Batterman S, Godwin C, Chin JY, Parker E, Breen M, et al. 2012. Air change rates and interzonal flows in residences, and the need for multi-zone models for exposure and health analyses. Int J Environ Res Public Health 9:4639-4661.

Emenius G, Svartengren M, Korsgaard J, Nordvall L, Pershagen G, Wickman M. 2004. Building characteristics, indoor air quality and recurrent wheezing in very young children (BAMSE). Indoor Air 14:34-42.

Ferris BG. 1978. Epidemiology Standardization Project. Am Rev Respir Dis 118:1-120.

Fisk WJ. 2018. How home ventilation rates affect health: a literature review. Indoor Air.

Francisco PW, Jacobs DE, Targos L, Dixon SL, Breysse J, Rose W, et al. 2017. Ventilation, indoor air quality, and health in homes undergoing weatherization. Indoor Air 27:463-477.

Garrett MH, Hooper MA, Hooper BM, Abramson MJ. 1998. Respiratory symptoms in children and indoor exposure to nitrogen dioxide and gas stoves. Am J Respir Crit Care Med 158:891-895.

Hagerhed-Engman L, Sigsgaard T, Samuelson I, Sundell J, Janson S, Bornehag CG. 2009. Low home ventilation rate in combination with moldy odor from the building structure increase the risk for allergic symptoms in children. Indoor Air 19:184-192.

Hens H, Verbeeck G, Verdonck B. 2001. Impact of energy efficiency measures on the CO2 emissions in the residential sector, a large scale analysis. Energ Buildings 33:275-281.

Hodas N, Meng Q, Lunden MM, Rich DQ, Ozkaynak H, Baxter LK, et al. 2012. Variability in the fraction of ambient fine particulate matter found indoors and observed heterogeneity in health effect estimates. J Expo Sci Environ Epidemiol 22:448-454.

Howden-Chapman P, Matheson A, Crane J, Viggers H, Cunningham M, Blakely T, et al. 2007. Effect of insulating existing houses on health inequality: cluster randomised study in the community. BMJ 334:460.

Institute of Medicine. 2011. Climate Change, the Indoor Environment, and Health. Washington, DC.

ISAAC Steering Committee. 1998. Worldwide variation in prevalence of symptoms of asthma, allergic rhinoconjunctivitis, and atopic eczema: ISAAC. The International Study of Asthma and Allergies in Childhood (ISAAC) Steering Committee. Lancet 351:1225-1232.

Isaacs K, Burke J, Smith L, Williams R. 2013. Identifying housing and meteorological conditions influencing residential air exchange rates in the DEARS and RIOPA studies: development of distributions for human exposure modeling. J Expo Sci Environ Epidemiol 23:248-258.

Karner AA, Eisinger DS, Niemeier DA. 2010. Near-roadway air quality: synthesizing the findings from real-world data. Environ Sci Technol 44:5334-5344.

Kovesi T, Gilbert NL, Stocco C, Fugler D, Dales RE, Guay M, et al. 2007. Indoor air quality and the risk of lower respiratory tract infections in young Canadian Inuit children. CMAJ 177:155-160.

Maantay J. 2007. Asthma and air pollution in the Bronx: methodological and data considerations in using GIS for environmental justice and health research. Health Place 13:32-56.

Meng QY, Turpin BJ, Korn L, Weisel CP, Morandi M, Colome S, et al. 2005. Influence of ambient (outdoor) sources on residential indoor and personal PM2.5 concentrations: analyses of RIOPA data. J Expo Anal Environ Epidemiol 15:17-28.

Meng QY, Spector D, Colome S, Turpin B. 2009. Determinants of indoor and personal exposure to PM2.5 of indoor and outdoor origin during the RIOPA study. Atmos Environ 43:5750-5758.

Murray DM, Burmaster DE. 1995. Residential air exchange rates in the United States: empirical and estimated parametric distributions by season and climatic region. Risk Analysis 15:459-465.

Nazaroff WW. 2013. Four principles for achieving good indoor air quality. Indoor Air 23:353-356.

Noris F, Adamkiewicz G, Delp WW, Hotchi T, Russell M, Singer BC, et al. 2013. Indoor environmental quality benefits of apartment energy retrofits. Build Environ 68:170-178.

Oie L, Nafstad P, Botten G, Magnus P, Jaakkola JK. 1999. Ventilation in homes and bronchial obstruction in young children. Epidemiology 10:294-299.

Palmiter L, Bond T. Interactions of mechanical ventilation and natural infiltration. In: Proceedings of the 12th Annual AIVC Conference on Air Movement and Ventilation Control within Buildings, 1991. Ottawa, Canada.

Pigg S, Cautley D, Francisco PW. 2018. Impacts of weatherization on indoor air quality: A field study of 514 homes. Indoor Air 28:307-317.

Rose N, Cowie C, Gillett R, Marks GB. 2009. Weighted road density: A simple way of assigning traffic-related air pollution exposure. Atmos Environ 43:5009-5014.

Sarnat JA, Sarnat SE, Flanders WD, Chang HH, Mulholland J, Baxter L, et al. 2013. Spatiotemporally resolved air exchange rate as a modifier of acute air pollution-related morbidity in Atlanta. J Expo Sci Environ Epidemiol 23:606-615.

Schikowski T, Sugiri D, Ranft U, Gehring U, Heinrich J, Wichmann HE, et al. 2005. Long-term air pollution exposure and living close to busy roads are associated with COPD in women. Respiratory Research 6:152-152.

Schweitzer M. 2005. Estimating the national effects of the US Department of Energy's Weatherization Assistance Program with state-level data: a metaevaluation using studies from 1993 to 2005. Oak Ridge, TN.

Sherman M, Dickerhoff D. 1998. Airtightness of U.S. dwellings.

Sherman MH, Modera MP. 1986. Comparison of measured and predicted infiltration using the LBL infiltration model. In: Measured air leakage of buildings:ASTM International.

Sherman MH. 1987. Estimation of Infiltration from Leakage and Climate Indicators. Energ Buildings 10:81-86.

Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, Grimsrud DT, et al. 2011. Ventilation rates and health: multidisciplinary review of the scientific literature. Indoor Air 21:191-204.

Tonn B, Rose E, Hawkins B. 2018. Evaluation of the US department of energy’s weatherization assistance program: Impact results. . Energy Policy 118.

US DOE. 2014. ASHRAE Standard 62.2. Ventilation and acceptable indoor air quality in low-rise residential buildings

Wang J, Engvall K, Smedje G, Nilsson H, Norback D. 2017. Current wheeze, asthma, respiratory infections, and rhinitis among adults in relation to inspection data and indoor measurements in single-family houses in Sweden-The BETSI study. Indoor Air 27:725-736.

WHO. 2016. Ambient air pollution: A global assessment of exposure and burden of disease. Geneva.

Zeger SL, Liang KY, Albert PS. 1988. Models for longitudinal data: a generalized estimating equation approach. Biometrics 44:1049-1060.

Table 1. Characteristics of the 302 participants in the CHEER study, by quartiles of home ventilation rates.

Characteristics	Total N=302 (%)	Annual average air exchange rate			
		Low N= 77 (%)	Moderate N=77 (%)	High N= 76 (%)	Very High N=72 (%)
Region					
Aurora	57 (18.9)	13 (16.9)	23 (29.9)	14 (18.4)	7 (9.7)
Boulder/Ft. Collins	47 (15.6)	22 (28.6)	8 (10.4)	13 (17.1)	4 (5.6)
West Denver	112 (37.1)	16 (20.8)	22 (28.6)	33 (43.4)	41 (56.9)
North/Central Denver	86 (28.5)	26 (33.8)	24 (31.2)	16 (21.1)	20 (27.8)
Sex					
Female	203 (67.2)	53 (68.8)	44 (57.1)	56 (73.7)	50 (69.4)
Male	99 (32.8)	24 (31.2)	33 (42.9)	20 (26.3)	22 (30.6)
Age (years)					
8 to 13	18 (6.0)	5 (6.5)	4 (5.2)	4 (5.3)	5 (6.9)
14 to 18	11 (3.6)	2 (2.6)	5 (6.5)	1 (1.3)	3 (4.2)
19 to 35	25 (8.3)	1 (1.3)	13 (16.9)	6 (7.9)	5 (6.9)
36 to 50	66 (21.9)	16 (20.8)	18 (23.4)	18 (23.7)	14 (19.4)
51 to 65	91 (30.1)	20 (26.0)	21 (27.3)	25 (32.9)	25 (34.7)
> 65	91 (30.1)	33 (42.9)	16 (20.8)	22 (28.9)	20 (27.8)
Race/Ethnicity					
Non-Hispanic White	123 (40.7)	43 (55.8)	29 (37.7)	29 (38.2)	22 (30.6)
Hispanic	102 (33.8)	16 (20.8)	27 (35.1)	28 (36.8)	31 (43.1)
Non-Hispanic Asian	16 (5.3)	6 (7.8)	5 (6.5)	5 (6.6)	0 (0.0)
Non-Hispanic Black	43 (14.2)	11 (14.3)	11 (14.3)	8 (10.5)	13 (18.1)
Non-Hispanic Other	18 (6.0)	1 (1.3)	5 (6.5)	6 (7.9)	6 (8.3)
Educational attainment of head of household					
Did not complete high school	33 (10.9)	1 (1.3)	14 (18.2)	6 (7.9)	12 (16.7)
Completed high school	108 (35.9)	21 (27.3)	24 (31.2)	31 (40.8)	32 (44.4)
Some College	60 (19.9)	17 (22.1)	15 (19.5)	15 (19.7)	13 (18.1)
Bachelor's Degree or Higher	100 (33.1)	38 (49.4)	23 (29.9)	24 (31.6)	15 (20.8)
Missing	1 (0.3)	0 (0.0)	1 (1.3)	0 (0.0)	0 (0.0)
Smoking history					
Never smoked	174 (57.6)	45 (58.4)	51 (66.2)	44 (57.9)	34 (47.2)(47.2)
Past smoker	121 (40.1)	30 (39.0)	25 (32.5)	31 (40.8)	35 (48.6)
Missing	7 (2.3)	2 (2.6)	1 (1.3)	1 (1.3)	3 (4.2)
Average time spent at home					
<10 hours per day	8 (2.6)	1 (1.3)	4 (5.2)	0 (0.0)	3 (4.2)
10 – 14 hours per day	90 (29.8)	16 (20.8)	28 (36.4)	27 (35.5)	19 (26.4)
15 – 19 hours per day	87 (28.8)	26 (33.8)	17 (22.1)	21 (27.6)	23 (31.9)
20+ hours per day	117 (38.7)	34 (44.2)	28 (36.4)	28 (36.8)	27 (37.5)

The annual average air exchange rate was classified into quartiles where low is 0.1 to 0.42 air changes per hour (ACH); moderate is 0.43 to 0.52 ACH; high is 0.53 to 0.77 ACH and very high is 0.79 to 2.17 ACH.

Table 2. Characteristics of 216 homes in the CHEER study, by quartiles of home ventilation rate.

Characteristics	Total N=216 (%)	Annual average air exchange rate			
		Low N= 61 (%)	Moderate N=46 (%)	High N= 56 (%)	Very High N=53 (%)
Region					
Aurora	44 (20.4)	11 (18.0)	14 (30.4)	13 (23.2)	6 (11.3)
Boulder/Ft. Collins	31 (14.4)	15 (24.6)	6 (13.0)	7 (12.5)	3 (5.7)
West Denver	81 (37.5)	14 (23.0)	15 (32.6)	22 (39.3)	30 (56.6)
North/Central Denver	60 (27.8)	21 (34.4)	11 (23.9)	14 (25.0)	14 (26.4)
Year Built					
Average (SD)	1959 (26.2)	1971 (24.1)	1964 (23.9)	1958 (22.9)	1940 (24.1)

Gas Stove					
Present	81 (37.5)	20 (32.8)	12 (26.1)	19 (33.9)	30 (56.6)
Not Present	134 (62.0)	41 (67.2)	34 (73.9)	36 (64.3)	23 (43.4)
Missing	1 (0.5)	0 (0.0)	0 (0.0)	1 (1.8)	0 (0.0)
Proximity of home to major road(s)					
Within 200 meters	82 (38.0)	23 (37.7)	15 (32.6)	17 (30.4)	27 (50.9)
> 200 meters	134 (62.0)	38 (62.3)	31 (67.4)	39 (69.6)	26 (49.1)
Mechanical Ventilation					
Present	11 (5.1)	3 (4.9)	5 (10.9)	3 (5.4)	0 (0.0)
Not Present	205 (94.9)	58 (95.1)	41 (89.1)	53 (94.6)	53 (100.0)
Home Type					
Single Family	183 (84.7)	55 (90.2)	41 (89.1)	46 (82.1)	41 (77.4)
Duplex/Townhome	33 (15.3)	6 (9.8)	5 (10.9)	10 (17.9)	12 (22.6)
Visible Mold					
Present	68 (31.5)	15 (24.6)	16 (34.8)	16 (28.6)	21 (39.6)
Not Present	148 (68.5)	46 (75.4)	30 (65.2)	40 (71.4)	32 (60.4)
Dampness on floors or walls					
Present	47 (21.8)	8 (13.1)	12 (26.1)	11 (19.6)	16 (30.2)
Not Present	169 (78.2)	53 (86.9)	34 (73.9)	45 (80.4)	37 (69.8)
Weatherization Status					
Weatherized	115 (53.2)	38 (62.3)	24 (52.2)	26 (46.4)	27 (50.9)
Not Weatherized	94 (43.5)	19 (31.1)	21 (45.7)	28 (50.0)	26 (49.1)
Built Green	7 (3.2)	4 (6.6)	1 (2.2)	2 (3.6)	0 (0.0)
Household Ventilation Practices-Summer					
Open windows or doors	140 (64.8)	44 (72.1)	33 (71.7)	34 (60.7)	29 (54.7)
Other	58 (26.9)	14 (23.0)	8 (17.4)	18 (32.1)	18 (34.0)
Missing	18 (8.3)	3 (4.9)	5 (10.9)	4 (7.1)	6 (11.3)
Household Ventilation Practices-Winter					
Open windows or doors	31 (14.4)	6 (9.8)	5 (10.9)	12 (21.4)	8 (15.1)
Other	167 (77.3)	52 (85.2)	36 (78.3)	40 (71.4)	39 (73.6)
Missing	18 (8.3)	3 (4.9)	5 (10.9)	4 (7.1)	6 (11.3)

The annual average air exchange rate was classified into quartiles where low is 0.1 to 0.42 air changes per hour (ACH); moderate is 0.43 to 0.52 ACH; high is 0.53 to 0.77 ACH and very high is 0.79 to 2.17 ACH.

Table 3. Participant reported respiratory and allergic symptoms in the past 12 months.

Symptom	N[a]	Total No. (%)
Chronic Respiratory Symptoms		
Cough (usually)	302	52 (17.2)
Cough 4 times a day, 4 or more days a week	301	27 (9.0)
Phlegm (usually)	302	77 (25.5)
Phlegm 2 times a day, 4 or more days a week	302	42 (13.9)
Allergy Symptoms		
Episode of hay fever	299	80 (26.5)
Allergic rhinoconjunctivitis[b]	299	74 (24.5)
Eczema[c]	300	20 (6.7)
Asthma and asthma-like symptoms		
Wheezing or whistling in the chest	301	65 (21.6)
Wheezing during or after exercise	300	29 (9.6)
Wheezing disturbed sleep	301	29 (9.7)
Visited doctor or ER for wheezing	301	24 (8.0)
Took medication for wheezing	301	36 (12.0)
Wheezing limited activities	300	33 (11.0)
Dry cough at night[d]	301	78 (25.9)
Dry cough lasted 14 days or more	300	28 (9.3)
Currently have asthma	300	33 (11.0)
Asthma attack	300	14 (4.7)
Visited ER or urgent care for asthma	300	4 (1.3)

[a] Some participants did not answer all questions.

[b] Defined as sneezing or runny or blocked nose without a cold or the flu, accompanied by itchy, watery eyes.

[c] Defined as an itchy rash coming and going for at least 6 of the past 12 months affecting the folds of the elbows, behind the knees, in front of the ankles, under the buttocks, or around the neck, ears or eyes.

[d] Not associated with a cold or chest infection.

Table 4. The association between the annual average air exchange rate and participant reported respiratory symptoms in the past 12 months.

	Unadjusted		Adjustment 1[a]		Adjustment 2[b]	
	OR	(95% CI)	OR	(95% CI)	OR	(95% CI)
Chronic Respiratory Symptoms (n=292)						
Cough	2.39	(1.07, 5.33)	3.98	(1.64, 9.66)	4.25	(1.66, 10.91)
Phlegm	1.26	(0.55, 2.91)	1.19	(0.48, 2.90)	1.07	(0.43, 2.62)
Chronic phlegm	1.53	(0.55, 4.25)	1.29	(0.44, 3.80)	1.38	(0.44, 4.37)
Allergy Symptoms (n=289)						
Hay fever	0.84	(0.40, 1.75)	1.00	(0.45, 2.22)	1.06	(0.46, 2.44)
Allergic rhinoconjunctivitis	0.94	(0.46, 1.93)	0.99	(0.44, 2.20)	1.07	(0.47, 2.44)
Asthma and asthma-like symptoms (n=291)						
Wheeze	1.34	(0.65, 2.74)	1.67	(0.77, 3.62)	1.95	(0.87, 4.42)
Took medications for wheeze	1.73	(0.73, 4.07)	2.78	(1.17, 6.63)	5.03	(1.83, 13.87)
Wheezing limited activities[c]	2.03	(0.89, 4.66)	2.39	(1.09, 5.27)	3.05	(1.23, 7.57)
Dry cough at night	1.79	(0.90, 3.56)	2.03	(0.86, 4.81)	2.31	(1.04, 5.13)
Asthma	1.85	(0.70, 4.86)	3.14	(1.12, 8.80)	5.44	(1.58, 18.76)

OR – odds ratio; CI – confidence interval.

Home ventilation was quantified as annual average air exchange rate and modeled as a continuous variable. Models were fit separately for each respiratory outcome and include all individuals with complete confounder data.

[a] Models adjusted for region, sex, age (age + age^2), race (non-Hispanic white vs. other), educational attainment of the head of the household (at least some college vs. high school or less), past smoking, and the presence of a gas stove in the home.

[b] Models adjusted for all confounders in adjustment 1 plus living within 200 meters of a major road and average annual NO_x concentration in the census block.

[c] n=290 people

Table 5. The association between annual average air exchange rate and participant reported respiratory symptoms in the past 12 months, estimated separately for households located in areas with higher and lower outdoor concentrations of traffic-related air pollution (TRAP).

	Low TRAP[a]		High TRAP[a]	
	OR	(95% CI)	OR	(95% CI)
Chronic Respiratory Symptoms				
Cough	5.53	(0.82, 37.22)	3.28	(1.13, 9.47)
Allergy Symptoms				
Hay fever	1.02	(0.18, 5.82)	0.87	(0.33, 2.30)
Allergic rhinoconjunctivitis	1.42	(0.24, 8.30)	0.80	(0.31, 2.03)
Asthma and asthma-like symptoms				
Wheeze	1.56	(0.32, 7.66)	2.16	(0.79, 5.92)
Took medications for wheeze	5.92	(0.85, 41.32)	4.45	(0.91, 21.91)
Dry cough at night	1.06	(0.17, 6.59)	2.11	(0.83, 5.34)
Asthma	8.29	(0.84, 81.87)	2.91	(0.69, 12.29)

TRAP - traffic-related air pollution; OR – odds ratio; CI – confidence interval.

Sample includes 152 residents in 109 households located in areas with higher potential exposure to TRAP, and 140 residents in 104 homes located in areas with lower potential exposure to TRAP.

Models were fit separately for each respiratory outcome and adjusted for region, sex, age (age + age^2), race (non-Hispanic white vs. other), educational attainment of the head of the household (at least some college vs. high school or less), past smoking, and the presence of a gas stove in the home. Models could not be fit for phlegm and wheezing that limited activities due to small cell sizes.

[a] A home was defined as being in an area with high TRAP concentrations if it was located within 200 m of a major road or in a census block where annual average NO_x was greater than the 75th percentile value for our study population (83 ppb).

Figure 1: Map of study area. Roads shown are Colorado highways and major roads with greater than 10,000 annual average daily traffic (AADT), which we define as major roads.

Figure 2. The distribution of annual average air exchange rates for 216 low-income households in Colorado.

ACH – Air changes per hour

Figure 3. Odds ratios (circles) and 95% confidence intervals (capped lines) for select participant reported respiratory symptoms by quartiles of the annual average air exchange rate. The odds ratio for each quartile is plotted at the median value of each quartile and estimated using the first quartile as the reference group. All models are adjusted for region, sex, age (age + age^2), race (non-Hispanic white vs. other), educational attainment of the head of the household (at least some college vs. high school or less), past smoking, the presence of a gas stove in the home, home location within 200 meters of a major road, and average annual NOx concentration in the census block. Grey lines indicate quartile boundaries.

Figure 4. Odds ratios (circles) and 95% confidence intervals (capped lines) for select self-reported respiratory symptoms by quartiles of annual average air exchange rate, estimated separately for homes located in areas with higher (light blue) and lower (dark blue) traffic related air pollution (TRAP) concentrations. Homes in areas with high TRAP concentrations are defined as those located within 200 meters of a major road, or in a census block where annual average traffic related NO_x concentration, as determined by the Community Line Source Model, exceeded the 75th percentile value for our study population. Sample includes 152 residents in 109 homes located in high TRAP areas, and 140 residents in 104 homes in low TRAP areas. All models are adjusted for region, sex, age (age + age^2), race (non-Hispanic white vs. other), educational attainment, past smoking, and the presence of a gas stove in the home. Grey lines indicate quartile boundaries.