A Section 508–conformant HTML version of this article is available at https://doi.org/10.1289/EHP11179.

Household Air Pollution and Adult Lung Function Change, Respiratory Disease, and Mortality across Eleven Low- and Middle-Income Countries from the PURE Study

Ying Wang,[1] MyLinh Duong,[2] Michael Brauer,[3] Sumathy Rangarajan,[4] Antonio Dans,[5] Fernando Lanas,[6] Patricio Lopez-Jaramillo,[7] Thandi Puoane,[8] Karen Yeates,[9] Jephat Chifamba,[10] Rita Yusuf,[11] Zhiguang Liu,[12] Yang Li,[13] Lap Ah Tse,[14] Deepa Mohan,[15] Rajeev Gupta,[16] Sanjeev Nair,[17] PVM Lakshmi,[18] Romaina Iqbal,[19] Taniya Anto,[20] Salim Yusuf,[4] and Perry Hystad[1]

[1]College of Public Health and Human Sciences, Oregon State University, Corvallis, Oregon, USA
[2]Department of Medicine, McMaster University, Hamilton, Ontario, Canada
[3]School of Population and Public Health, University of British Columbia, Vancouver, British Columbia, Canada
[4]Population Health Research Institute, Hamilton Health Sciences, McMaster University, Hamilton, Ontario, Canada
[5]University of the Philippines, Ermita, Manila, Philippines
[6]Universidad de La Frontera, Francisco Salazar, Temuco, Chile
[7]Universidad de Santander (UDES), Bucaramanga, Colombia
[8]School of Public Health, University of the Western Cape, Cape Town, South Africa
[9]Department of Medicine, Queen's University, Kingston, Ontario, Canada
[10]Department of Biomedical Sciences, University of Zimbabwe, Harare, Zimbabwe
[11]School of Life Sciences, Independent University, Dhaka, Bangladesh
[12]Department of Pharmacy, Beijing Anzhen Hospital, Capital Medical University, Beijing, China
[13]Medical Research and Biometrics Center, National Clinical Research Center for Cardiovascular Diseases, Fuwai Hospital, National Center for Cardiovascular Diseases, Peking Union Medical College and Chinese Academy of Medical Sciences, Beijing, China
[14]Jockey Club School of Public Health and Primary Care, Chinese University of Hong Kong, Hong Kong, China
[15]Madras Diabetes Research Foundation, Chennai, India
[16]Eternal Heart Care Centre & Research Institute, Jaipur, India
[17]Health Action By People, Government Medical College, Trivandrum, India
[18]Post Graduate Institute of Medical Education and Research, Chandigarh, India
[19]Department of Community Health Science, Aga Khan University Hospital, Karachi, Pakistan
[20]Department of Physiology, St. John's Medical College, Bangalore, India

Background: Globally, household air pollution (HAP) is a major environmental hazard that affects respiratory health. However, few studies have examined associations between HAP and lung function decline and respiratory disease and mortality.

Methods: We used data from the Prospective Urban and Rural Epidemiology study and examined adults residing in 240 rural communities in 11 low- and middle-income countries where HAP from cooking with solid fuels is common. Spirometry was conducted for 28,574 individuals at baseline and 12,489 individuals during follow-up (mean of 8 y between spirometry measures). In cross-sectional analyses, we compared lung function measurements [forced expiratory volume in 1 s (FEV_1), forced vital capacity (FVC), and FEV_1/FVC ratio] in those who used solid fuels for cooking in comparison with clean fuels. Using repeated measurements of lung function, we examined the percent change in lung function measures per year, comparing individuals by baseline fuel type and individuals who used solid fuels at baseline but switched to clean fuels during follow-up. We also examined associations with prospective health events (any respiratory diseases, respiratory disease hospitalizations, and all-cause mortality).

Results: In adjusted cross-sectional models, use of solid fuel in comparison with clean fuels was associated with lower FEV_1 of −17.5 mL (95% CI: −32.7, −2.3) and FVC of −14.4 mL (95% CI: −32.0, 3.2), but not FEV_1/FVC. In longitudinal analyses, individuals who switched from solid fuels to clean cooking fuels during follow-up ($n = 3{,}901$, 46% of those using solid fuel at baseline), showed no differences in the annual rate of change in FEV_1 or FVC, but had small improvements in FEV_1/FVC change (0.2% per year, 95% CI: 0.03, 0.3). Individuals who switched from solid to clean fuels had a decreased hazard ratio for respiratory events of 0.76 (95% CI: 0.57, 1.00) in comparison with persistent solid fuel users, which was not attenuated by lung function measures.

Conclusion: We observed modest associations between HAP exposure and lung function, lung function change, and respiratory disease and mortality. https://doi.org/10.1289/EHP11179

Introduction

Approximately 3 billion people worldwide are exposed to household air pollution (HAP) from cooking or heating with solid fuels, such as wood, coal, dung, and crop residues, with most living in low- and middle-income countries (LMICs).[1] Current evidence suggests that HAP is associated with acute respiratory infection, chronic obstructive pulmonary disease (COPD), lung cancer, tuberculosis, cerebrovascular disease, ischemic heart disease, respiratory and cardiovascular mortality.[2]

Lung function is an important predictors of overall health and longevity, with indices such as forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) being strongly associated with adverse cardiopulmonary outcomes, and overall mortality.[3,4] Although evidence suggests that HAP is associated with lower lung function in children,[5,6] the findings in adults have not been consistent. For example, the Burden of Obstructive Lung Disease (BOLD) study examined 18,554 adults from 23 countries with postbronchodilator spirometry measurements and did not observe strong associations between solid fuels use for cooking or heating with airflow obstruction.[7] On the other hand, a study of 12,396 adults in 13 low-income countries observed an elevated odds ratio (OR) of 1.41 (95% CI: 1.18, 1.68) for airflow obstruction in

Address correspondence to Perry Hystad, Oregon State University, 2520 SW Campus Way, Corvallis, OR 97331 USA. Email: perry.hystad@oregonstate.edu

Supplemental Material is available online (https://doi.org/10.1289/EHP11179).
The authors declare they have nothing to disclose.
Received 27 February 2022; Revised 16 March 2023; Accepted 20 March 2023; Published 26 April 2023.

Note to readers with disabilities: *EHP* strives to ensure that all journal content is accessible to all readers. However, some figures and Supplemental Material published in *EHP* articles may not conform to 508 standards due to the complexity of the information being presented. If you need assistance accessing journal content, please contact ehpsubmissions@niehs.nih.gov. Our staff will work with you to assess and meet your accessibility needs within 3 working days.

individuals using solid fuels in comparison with clean fuels for cooking.[8] Other cross-sectional studies with smaller sample sizes have also reported inconsistent results.[9–12]

The impact of switching from solid to clean fuels, and whether this leads to improved lung function outcomes (e.g., slowing of adult lung function decline), is unknown but key to informing policy considerations. To our knowledge, no observational study has examined natural household fuel switching and associated impacts on lung function change or respiratory disease. Although it is challenging to conduct interventions or randomized controlled trials (RCT) to examine the long-term impact of HAP exposure, a few studies have reported changes in HAP exposures and lung function. An intervention study of 996 individuals in China observed that transitioning to clean fuels or improved ventilation was associated with reduced lung function decline and COPD risk.[13] A RCT in Guatemala among 504 women age 15–50 y, comparing traditional open fires to improved chimney woodstoves for 18 months, observed reductions in respiratory symptoms but not lung function decline.[14] Another RCT among 552 Mexican women found that individuals using improved stoves had lower FEV_1 decline (31 mL) in comparison with traditional open-fire stove use (62 mL) over a 1-y follow-up.[15] The follow-up in these RCT studies were relatively short, and data incorporating the complex mechanisms linking HAP to lung function and respiratory events over longer-term follow-up are needed.

The Prospective Urban and Rural Epidemiology (PURE) study is an ongoing international multicenter study that has enrolled adults from rural and urban communities across 31 high-, middle-, and low-income countries. The study has collected comprehensive baseline data at the individual and household levels, as well as follow-up data, including repeated lung function measurements and respiratory events. The aim of this study is to examine the associations between adult lung function, follow-up lung function change, and respiratory events and mortality with long-term HAP exposure, and the effect of switching from solid to clean fuels during follow-up.

Methods

PURE Cohort

The PURE cohort began enrolling adults (age 35–70 y) in 2003 and recruited new participants each subsequent year in 31 low-, middle-, and high-income countries. Details of the PURE cohort study are provided elsewhere.[16,17] Here, we used a subset of the overall PURE study. To ensure valid comparisons between individuals who were exposed and not exposed to HAP, we restricted our analyses to communities where at least 10% of participants used solid fuels primarily for cooking at baseline ($n = 77{,}439$), and further restricted to rural communities ($n = 32{,}666$) because rural and urban communities have very different solid fuel use rates as well as differences in socioeconomic status (SES) and environmental factors. Urban/rural status was determined by local investigators when establishing the original PURE cohort based on set guidelines (i.e., rural communities should correspond to small villages at least 50 km from the closest city). The resulting sample for this analysis included 240 rural communities from 11 developing countries according to World Bank criteria at the time of recruitment: 5 low-income countries (Bangladesh, India, Pakistan, Tanzania, and Zimbabwe), 3 lower middle-income countries (China, Colombia, and the Philippines), and 3 upper middle-income countries (Brazil, Chile, and South Africa). Spirometry was collected using standardized protocols, which were available for these 32,666 individuals at baseline and 12,489 individuals during follow-up. PURE cohort follow-up is ongoing, and lung function measurements and event data included in these analyses were collected up to the end of 2019. At the time of these analyses, 12,489 individuals (of the 32,666 with baseline measures) had repeated lung function measures. This number is a function of where the PURE cohort was first established and the current stage of follow-up. Some individuals had three repeated lung function measures, and we chose the most recent follow-up values as the repeated lung function value for analysis. Among those with follow-up measures, information on cooking-fuel type change and respiratory events was also recorded via face-to-face surveys conducted by local study staff. The mean [standard deviation (SD)] time between baseline and follow-up spirometry was 8.0 (3.6) y, providing a long-term follow-up period to assess the associations between HAP, changes in lung function, and respiratory disease.

HAP Exposure

HAP exposure was defined as self-reported primary cooking fuel in response to the question: "What is the primary fuel used for cooking at your home?" Eight fuel types were gathered and recoded into two categories: solid fuels (i.e., coal, wood, charcoal, agriculture/crop, animal dung, and shrub/grass) and clean fuels (i.e., electricity and gas). Cooking with kerosene was excluded due to small numbers ($<2\%$). Secondary exploratory analyses examining associations between lung function and each specific fuel type. During follow-up, an additional questionnaire was implemented that asked the same questions about cooking fuels, which allowed us to examine changes in cooking-fuel types. Among individuals with repeated spirometry measures, we focused specifically on individuals who used solid fuels at baseline but who switched to clean fuels during follow-up and compared those with individuals who continued to use solid fuels through follow-up. We believe this is the most relevant policy scenario, because policies and interventions seek to transition homes from dirty fuels to clean fuels. In sensitivity analyses, we also examined the small number of individuals ($<5\%$) who switched from clean fuels at baseline to solid fuels during follow-up.

Lung Function Outcomes

Lung function was measured with portable spirometers (MicroGP; MicroMedical) at baseline by trained staff following a standardized protocol that aligns with the 2005 American Thoracic Society guidelines for standardization of spirometry.[18] We did not measure postbronchodilator lung function in the PURE cohort. Participants were coached before attempting forced expiratory maneuvers while standing and wearing a noseclip. Maneuvers were observed to ensure maximal effort without coughing for >6 s. Participants were allowed up to eight attempts, participants with two or more FEV_1 and FVC measurements within 100 mL were included, and the highest values were selected for analysis. The quality of spirometry data has previously been validated and showed strong agreement with FEV_1 values acquired from hospital-based pulmonary laboratories in 531 randomly selected participants,[19] as well as with mortality outcomes.[3] Our main outcomes of interest include the highest acceptable FEV_1, FVC, and the ratio of FEV_1/FVC.

During follow-up, lung function was measured with a new portable spirometer (EasyOne Ndd) that has built-in quality checks, messaging, and spirographs to enable high-quality measurements. This spirometry has been well validated[20] and is commonly used in large epidemiological studies. We conducted a study with an extensive comparison between the two spirometers in 4,603 adults from 628 communities in 18 countries in PURE and found high correlations and small mean differences between measurements, demonstrating that the data provide accurate trends in serial lung function measurements over time.[21]

To examine the long-term effect of HAP on lung function change, we examined the associations between HAP and the decline in FEV_1, FVC, and FEV_1/FVC ratio among individuals with repeated lung function measures. Yearly percent decline was calculated as follows:

$$FEV_{1\%\,\text{decline over years}} = \left[\frac{(FEV_1\text{follow}_{\text{up}} - FEV_1\text{baseline})}{FEV_1\text{baseline}} \times (100\%)\right] / \text{years between spirometry measures.}$$

Changes in lung function between the follow-up and the baseline spirometry measures were divided by the baseline spirometry measure to get a percentage change, which was further divided by the number of years between the baseline and the follow-up visits (because this time period varied by participant). The final change metric can therefore be interpreted as the average percentage change in lung function per year between baseline and follow-up measures.

Respiratory Events and Mortality

Detailed documentation of follow-up protocols and event adjudication in PURE are available.[17,22] Briefly, the follow-up period for this analysis was conducted using data collected between 2003 and the end of 2019, with face-to-face or telephone interviews conducted for all individuals every 3 y. The mean (SD) of follow-up for the event analysis was 11.0 (2.4) y. Lung function measures occurred at some of these follow-up contacts, but not all. To determine a probable diagnosis of an event, information was collected on prior medical illness, hospital records where available, and medically certified cause of death or verbal autopsies where medical information was not available.[23] The primary outcomes in this analysis include: *a*) composite of all respiratory disease events, including nonfatal or fatal tuberculosis (TB), COPD, pneumonia, asthma, or other respiratory diseases; *b*) hospitalization due to respiratory disease (including TB, COPD, pneumonia, asthma, or other respiratory diseases); and *c*) all-cause mortality. We did not separately examine respiratory mortality or specific respiratory diseases due to power limitations.

Statistical Analyses

Baseline lung function analysis. We examined cross-sectional associations between solid fuel for cooking, in comparison with clean fuels, and FEV_1, FVC, and ratio of FEV_1/FVC using linear mixed effect models. Covariates included in models were selected *a priori*. The base model (Model 1) included age (continuous), sex (male, female), height (continuous), and geographic center to account for unmeasured differences by geographic location. Community was treated as a random intercept to account for the hierarchical study design in PURE and clustering of individuals within communities. The term "center" represents a large geographic area, such as a small country or state in a large country (e.g., China has 10 centers to capture distinct geographic regions). Community corresponds to a small village in rural areas. The inclusion of geographic centers as a fixed effect and community as a random intercept controls for unmeasured factors at these levels that may confound the relationship between HAP and respiratory disease. Model 2 (adjusted model) includes additional covariates: body mass index (BMI; continuous, kilograms per square meter), smoking status (former, current, or never smoker), baseline respiratory conditions (including asthma, COPD, or TB), SES factors including education (less than or equal to primary, secondary, higher than trade/college) and household wealth index (poor, middle-class, or rich; index created from household assets and categorized into country-specific tertiles),[24] elevation, and ambient particulate matter (PM) with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$), defined by community annual average $PM_{2.5}$ concentrations derived using a Bayesian model that integrates $PM_{2.5}$ ground monitor measurements, satellite retrievals of aerosol optical depth, and chemical transport models at ~ 11 km resolution.[25] We conducted full case analyses for all models and removed individuals with missing data.

Change in Lung Function Analysis

We examined lung function change (average percentage change in lung function per year between baseline and follow-up measures) using two exposure measures. The first is the baseline fuel type (solid vs. clean fuels) used for cooking. The second is individuals who used solid fuels at baseline but switched to clean fuels during follow-up, in comparison with individuals who continued to use solid fuels. We used the same linear mixed effect models and covariates as in the cross-sectional analysis.

Prospective Analyses of Respiratory Events

We used Cox-proportional hazards models to examine the associations between HAP and the first documented respiratory event, respiratory hospitalization and all-cause mortality adjusting for the same variables in the baseline HAP and lung function models above. Person-years of follow-up were calculated from study enrollment to the date of the first respiratory event, hospitalization, or death, or the most recent follow-up date. The proportional hazards assumption was assessed visually and with interaction terms for time and HAP exposure metrics, with no substantial departures from the proportional hazards assumption observed. We first examined associations between HAP and each outcome in the base (Model 1) and adjusted (Model 2) models. We then included lung function measures (FEV_1 and the percent change in FEV_1 during follow-up) as covariates in a third Cox-proportional hazards model (Model 2 plus lung function measures) and compared model estimates for our HAP exposures and respiratory disease, hospitalizations, and all-cause mortality. As with the lung function change analyses, we examined baseline solid fuel use for cooking as well as compared individuals who consistently used solid fuels during follow-up to individuals who used solid fuel at baseline but switched to clean fuels during follow-up.

Sensitivity Analyses

We conducted a number of sensitivity analyses to explore the robustness of our models. We conducted exploratory analyses of models stratified by age group (≥55, <55), sex (female, male), household wealth index (tertiles), smoking status (ever, never smokers), respiratory condition (asthma, COPD, or TB) at baseline (yes, no), solid fuel use with chimney (yes, no), and country/region (China; India/Pakistan/Bangladesh/Philippines; South Africa/Tanzania/Zimbabwe; and Brazil/Chile/Colombia). We did not have sufficient sample size to examine models for all countries or centers separately. Next, we examined different model specifications. First, we examined the influence of excluding ambient $PM_{2.5}$ in our models; this approach may capture a component of HAP exposures because HAP emissions contribute to ambient $PM_{2.5}$. Second, we included a variable representing heating with solid fuels, because heating can contribute substantially to HAP. We did not include a heating variable in our main models because most PURE locations do not require routine home heating and locations that did require heating had similar heating fuel types. Third, we included a variable for secondhand smoke exposure and occupational class. We did not include these variables in our main model because of a high level of missingness. Fourth, we examined model results when the household wealth index was removed because this variable is

Table 1. Characteristics of adults with baseline ($n = 28{,}574$) and repeated ($n = 12{,}489$) spirometry measurements stratified by solid or clean fuels used for cooking at baseline in 11 countries during 2003–2019 from the PURE study.

	Baseline lung function			Repeated lung function[b]		
	All participants	Solid fuel	Clean fuel	All participants	Solid fuel	Clean fuel
n (%)	28,574 (100)	19,595 (68.6)	8,979 (31.4)	12,489 (100)	8,421 (67.4)	4,068 (32.6)
Age [x̄ (SD)]	49.6 ± 9.5	49.7 ± 9.6	49.4 ± 9.4	49.4 ± 9.1	49.5 ± 9.2	49.1 ± 8.9
Height [cm (x̄, SD)]	159.3 ± 8.4	159.0 ± 8.4	159.8 ± 8.5	159.0 ± 8.3	158.7 ± 8.2	159.8 ± 8.3
BMI [x̄ (SD)] kg/m^2	24.3 ± 4.5	23.8 ± 4.2	25.4 ± 4.7	24.4 ± 4.4	24.0 ± 4.3	25.4 ± 4.6
Sex						
Female	16,731 (58.6)	11,500 (58.7)	5,231 (58.3)	7,757 (61.3)	5,173 (61.4)	2,482 (61.0)
Male	11,843 (41.5)	8,095 (41.3)	3,748 (41.7)	4,889 (38.7)	3,248 (38.6)	1,586 (39.0)
Education [*n* (%)]						
≤Primary	16,128 (56.4)	11,627 (59.3)	4,501 (50.1)	7,412 (58.6)	5,259 (62.5)	2,050 (50.4)
Secondary	11,505 (40.3)	7,473 (38.1)	4,032 (44.9)	4,923 (38.9)	3,019 (35.8)	1,856 (45.6)
≥Trade/college	941 (3.3)	495 (2.5)	446 (5.0)	311 (2.5)	143 (1.7)	162 (4.0)
Home wealth index [*n* (%)]						
T1 (low)	14,601 (51.1)	11,502 (58.7)	3,099 (34.5)	6,708 (53.0)	5,094 (60.5)	1,560 (38.3)
T2 (moderate)	9,889 (34.6)	6,285 (32.1)	3,604 (40.1)	4,258 (33.7)	2,623 (31.1)	1,569 (38.6)
T3 (high)	4,084 (14.3)	1,808 (9.2)	2,276 (25.4)	1,680 (13.3)	704 (8.4)	939 (23.1)
Smoking [*n* (%)]						
Former	1,820 (6.4)	1,103 (5.6)	717 (8.0)	719 (5.7)	452 (5.4)	257 (6.3)
Current	7,059 (24.7)	4,933 (25.2)	2,126 (23.7)	2,865 (22.7)	1,880 (22.3)	946 (23.3)
Never	19,695 (68.9)	13,559 (69.2)	6,136 (68.3)	9,062 (71.6)	6,089 (72.3)	2,865 (70.4)
Respiratory conditions [*n* (%)][a]						
Yes	1,254 (4.4)	952 (4.9)	302 (3.4)	504 (4.0)	375 (4.5)	119 (2.9)
No	27,320 (95.6)	18,643 (95.1)	8,677 (96.6)	12,142 (96.0)	8,046 (95.5)	3,949 (97.1)
Ambient $PM_{2.5}$ (x̄ ± SD) $\mu g/m^3$	54.0 ± 23.7	56.4 ± 22.0	48.7 ± 26.2	55.5 ± 24.2	57.2 ± 22.4	52.5 ± 27.1
FEV_1 (x̄ ± SD) ml	2,260.3 ± 704.6	2,251.1 ± 705.8	2,280.5 ± 701.6	2,026.3 ± 676.7	2,021.0 ± 677.9	2,036.9 ± 674.2
FVC (x̄ ± SD) ml	2,671.1 ± 865.0	2,654.9 ± 854.2	2,706.3 ± 887.1	2,561.4 ± 837.7	2,556.7 ± 845.4	2,571.6 ± 821.6
FEV_1/FVC (x̄ ± SD) %	85.6 ± 11.2	85.8 ± 11.2	85.5 ± 11.2	80.0 ± 12.9	79.8.3 ± 12.8	80.1 ± 13.3

Note: BMI, body mass index; COPD, chronic obstructive pulmonary disease; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; PURE, Prospective Urban and Rural Epidemiology; Ref, reference; SD, standard deviation; TB, tuberculosis.
[a]Respiratory conditions at baseline, including asthma, COPD, or TB.
[b]Repeated spirometry measures taken a mean of 8.0 y apart.

correlated with the use of solid fuels for cooking. Fifth, we examined how model results changed when the variable for baseline respiratory disease was removed, because baseline disease may be related to HAP exposures. Sixth, we examined how model results changed when we removed the center variable, allowing comparisons across centers, and when including community as a fixed effect, rather than a random effect, which tested how sensitive our models are to potential unmeasured geographic confounding. Finally, we examined associations between individuals ($n = 690$) switching from clean to solid fuels during follow-up and lung function change.

Results

Population Characteristics

Within the PURE cohort, there were 32,666 individuals living in rural communities where >10% of participants used solid fuel for cooking at baseline. We excluded 4,092 (12.5%) individuals with missing or low-quality lung function data or missing covariates. Our final sample included 28,574 individuals from 240 rural communities across 25 centers (regions) in 11 developing countries enrolled from 2003 to 2015. Table 1 summarizes characteristics of the 28,574 participants according to self-reported solid fuel and clean fuel use at baseline. Approximately 69% of individuals primarily used solid fuels for cooking. Of those using solid fuels, 62% were from China, 16% from South Asia (Bangladesh, India, and Pakistan), and 22% from other countries (Brazil, Chile, Colombia, the Philippines, South Africa, Tanzania, and Zimbabwe). Population characteristics were similar between solid or clean fuel users in mean age (49.7 vs. 49.4 y), height (159.0 vs. 159.8 cm), sex (58.7% vs. 58.3% female), and current smoking status (25.2% vs. 23.7%). Solid fuel users had slightly lower BMI (23.8 vs. 25.4 kg/m^2), higher ambient $PM_{2.5}$ (56.4 vs. 48.7 $\mu g/m^3$), and higher prevalence of low education (59.3% vs. 50.1%), low household wealth index (58.7% vs. 34.5%), and chronic respiratory conditions (4.9% vs. 3.4%), in comparison with clean fuel users. The overall mean (SD) lung function values at baseline were 2,260 (704.6) mL for FEV_1, 2,671 (865.0) mL for FVC, and 85.6% (11.2) for the FEV_1/FVC ratio.

When restricted to individuals with repeated lung function measures ($n = 12{,}489$), we observed similar patterns in baseline characteristics between solid and clean fuel users. During follow-up, 3,901 individuals (46% of individuals using solid fuel at baseline) switched from cooking with solid fuels to clean fuels. A small number of individuals ($n = 690$) reported shifting from clean to solid fuel during follow-up. The mean (SD) time between baseline and follow-up spirometry was 8.0 (3.6) y. The mean change in FEV_1 was −30.2 (89.6) mL/y (−0.95%/y), FVC −24.9 (120) mL/y (−0.40 %/y), and the FEV_1/FVC ratio −0.45 (2.7) %/y in our repeated lung function analyses. Among individuals with repeated lung function measures, the overall mean values at baseline were 2,255 (670) mL for FEV_1, 2,698 (842) mL for FVC, and 84.8 (11.6) % for the FEV_1/FVC ratio.

Cross-Sectional Associations between Baseline Cooking Fuels and Lung Function

In baseline models, solid fuel users had lower FEV_1 (−23.8 mL; 95% CI: −38.7, −8.9), FVC (−13.1 mL; 95% CI: −30.4, 4.1), and FEV_1/FVC ratio (−0.4; 95% CI: −0.6, −0.1), in comparison with clean fuel users (Table 2). When adjusting for additional individual, household, and community covariates, the associations were attenuated for FEV_1 to −17.5 mL (95% CI: −32.7, −2.3), FVC −14.4 mL (95% CI: −32.0, 3.2) and FEV_1/FVC ratio −0.10% (95% CI: −0.0, 0.2). We also examined associations across specific solid fuel types and observed larger associations between lung function measures with charcoal and shrub/grass, in comparison with electricity or gas, but with wide confidence intervals for all estimates.

Table 2. Cross-sectional associations between solid fuels used for cooking, in comparison with clean fuels, and lung function for 28,574 individuals at baseline in the PURE study (2003–2019).

	n (%)	FEV_1 β (95% CI)	FVC mL β (95% CI)	FEV_1/FVC % β (95% CI)
Base model[a]				
Clean cooking fuels	8,979 (31.4)	Ref	Ref	Ref
Solid cooking fuels	19,595 (68.6)	−23.8 (−38.7, −8.9)	−13.1 (−30.4, 4.1)	−0.4 (−0.6, −0.1)
Coal	5,995	−17.3 (−45.3, 10.7)	−22.8 (−55.3, 9.7)	0.1 (−0.4, 0.6)
Charcoal	589	−43.0 (−109.9, 23.9)	−43.8 (−120.3, 32.7)	−0.2 (−1.4, 1.1)
Wood	6,768	−22.1 (−43.8, −0.4)	−4.6 (−29.2, 19.9)	−0.5 (−0.9, −0.04)
Agriculture	4,332	−20.4 (−45.6, 4.9)	−5.2 (−34.5, 24.2)	−0.5 (−1.0, −0.02)
Animal dung	684	−10.7 (−67.7, 46.2)	−5.7 (−71.3, 59.9)	0.3 (−0.8, 1.4)
Shrub	1,227	−47.3 (−90.5, −4.1)	−50.7 (−100.1, −1.2)	−0.4 (−1.2, 0.4)
Adjusted model[b]				
Clean cooking fuels	8,979 (31.4)	Ref	Ref	Ref
Solid cooking fuels	19,595 (68.6)	−17.5 (−32.7, −2.3)	−14.4 (−32.0, 3.2)	−0.1 (−0.4, 0.2)
Coal	5,995	−17.4 (−45.3, 10.5)	−28.0 (−60.6, 4.5)	0.2 (−0.3, 0.8)
Charcoal	589	−44.7 (−110.9, 21.4)	−54.1 (−130.2, 22.0)	0.2 (−1.1, 1.4)
Wood	6,768	−8.9 (−31.3, 13.4)	−1.5 (−27.0, 23.9)	−0.1 (−0.5, 0.4)
Agriculture	4,332	−15.8 (−40.9, 9.4)	−4.6 (−34.0, 24.8)	−0.4 (−0.8, 0.1)
Animal dung	684	−3.5 (−59.6, 52.6)	−6.7 (−71.7, 58.3)	0.6 (−0.5, 1.7)
Shrub	1,227	−39.0 (−81.7, 3.7)	−45.8 (−95.1, 3.5)	−0.3 (−1.1, 0.6)

Note: Independent models for all fuels combined as well as for each specific fuel type used for cooking. BMI, body mass index; CI, confidence interval; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; PURE, Prospective Urban and Rural Epidemiology; Ref, reference.
[a]Base model: age, sex, height, geographic center, random intercept for community.
[b]Adjusted model: age, sex, height, geographic center, random intercept for community, BMI, smoking status, baseline respiratory conditions, education, household wealth index, elevation, and outdoor $PM_{2.5}$.

Longitudinal Analysis of Cooking Fuels and Change in Lung Function

We compared the annual lung function change between individuals with solid fuel use ($n = 8{,}421$) vs. clean fuel use ($n = 4{,}068$) at baseline and among those individuals who switched from solid to clean cooking fuels during follow-up ($n = 3{,}901$) in comparison with individuals who persistently used solid fuels ($n = 4{,}520$) (Table 3). We observed no differences in the rate of annual lung function change in FEV_1, FVC, or FEV_1/FVC between solid fuel users vs. clean fuel users at baseline. For the 3,901 individuals who switched to clean fuels during follow-up, in comparison with individuals persistently using solid fuels ($n = 4{,}520$), we observed no differences in the rate of change in the FEV_1 or FVC, but a small reduction in the decline rate of FEV_1/FVC ratio by 0.2% per year (95% CI: 0.03, 0.3).

Prospective Analyses of Respiratory Events

During a mean (SD) of 11.0 (2.4) y of follow-up, 541 respiratory events, including 263 respiratory hospitalizations, were recorded. Respiratory events comprised nonfatal and fatal cases of TB (80), COPD (146), pneumonia (203), asthma (108), and other respiratory diseases (4). There were only 22 respiratory deaths out of the 406 total deaths recorded. Associations between HAP exposure with clinical events are summarized in Table 4. In the adjusted models, solid fuel use at baseline, in comparison with clean fuels, was associated with a hazard ratio (HR) of 1.19 (95% CI: 0.92, 1.54) for all respiratory events, 1.17 (95% CI: 0.81, 1.68) for respiratory hospitalizations, and 1.22 (95% CI: 0.93, 1.60) for all-cause mortality. Individuals who switched from solid to clean fuels, in comparison with individuals who persistently used solid fuels, had an adjusted HR of 0.76 (95% CI: 0.57, 1.00) for all respiratory events, 0.71 (95% CI: 0.48, 1.06) for respiratory hospitalizations, and 0.85 (95% CI: 0.62, 1.17) for all-cause mortality. When lung function was added to the adjusted models of baseline solid fuel use and fuel switching, the estimates for HAP exposures remained largely unchanged.

Sensitivity Analyses

We conducted stratified analyses by key individual, household, and geographic variables (see Tables S1 and S2). For cross-sectional associations of solid fuel use for cooking and lung function measured at baseline, we observed the largest differences for FVC and country/region. Models stratified by region demonstrated consistent results, except for South America (Brazil, Chile, Colombia). Here, we observed inverse associations between solid fuel use for cooking and FEV_1 and FVC. In our analyses using repeated measurements of lung function and the percent change in lung function per year, we observed the largest differences for the percent decline of the FEV_1/FVC ratio by year for age and education level. Individuals ≥55 y of age who switched from solid to clean cooking fuels during follow-up, in comparison with individuals who persistently used solid fuels, had a FEV_1/FVC % per year decline of 0.3 (95% CI: 0.04, 0.6) in comparison with 0.1 (95% CI: −0.1, 0.3) for individuals <55 y of age. Individuals with no or primary-level education had a FEV_1/FVC % per year decline of 0.3 (95% CI: 0.04, 0.65) in comparison with 0.1 (95% CI: −0.1, 0.3) for individuals who had a secondary level or higher level of education. We also examined associations for individuals who changed from clean to solid cooking fuels during follow-up ($n = 691$), in comparison with individuals who persistently used clean fuels during follow-up ($n = 3{,}377$), with lung function change (Table S3) and did not observe any associations. Our model results were robust to several other model parameterizations and sensitivity analyses, including: removing ambient $PM_{2.5}$; adding covariates for heating with solid fuels, secondhand smoking exposure, and occupational classification; removing the household wealth index, baseline respiratory symptoms, and the center covariates; and adding in a community covariate in place of the community random intercept (Table S4 and S5).

Discussion

In this large study of HAP across 11 LMIC countries, we observed lower levels of lung function in cross-sectional analyses among individuals who used solid fuels for cooking at baseline in comparison with clean fuels. In longitudinal analyses, we observed that individuals who switched from solid to clean fuels, in comparison with individuals who continued to use solid fuels during follow-up, had small attenuation in the rate of decline of the FEV_1/FVC ratio. In addition, solid fuel use at baseline, in comparison with clean fuels, was associated with increased risk

Table 3. Associations of solid fuel use at baseline and change from solid to clean cooking fuels during follow-up, with lung function change in the PURE study (2003–2019).

	n	ΔFEV_1 %/y β (95% CI)	Δ FVC %/y β (95% CI)	$\Delta FEV_1/FVC$ %/y β (95% CI)
Household fuel use at baseline and change in lung function				
Base model[a]				
Clean cooking fuels	4,068	Ref	Ref	Ref
Solid cooking fuels	8,421	1.3 (−2.8, 5.4)	2.9 (−2.6, 8.5)	−0.1 (−0.2, 0.1)
Adjusted model[b]				
Clean cooking fuels	4,068	Ref	Ref	Ref
Solid cooking fuels	8,421	1.5 (−2.8, 5.8)	2.9 (−2.8, 8.7)	−0.00 (−0.5, 0.4)
Households switching from solid to clean fuels and change in lung function				
Base model[a]				
Persistent solid fuels	4,520	Ref	Ref	Ref
Switched to clean fuels	3,901	0.01 (−0.3, 0.3)	−0.3 (−0.6, 0.1)	0.2 (0.03, 0.3)
Adjusted model[b]				
Persistent solid fuels	4,520	Ref	Ref	Ref
Switched to clean fuels	3,901	−0.05 (−0.4, 0.3)	−0.3 (−0.7, 0.1)	0.2 (0.03, 0.3)

Note: BMI, body mass index; CI, confidence interval; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; PURE, Prospective Urban and Rural Epidemiology; Ref, reference.
[a]Base model: age, sex, height, geographic center, random intercept for community.
[b]Adjusted model: age, sex, height, geographic center, random intercept for community, BMI, smoking status, baseline respiratory conditions, education, household wealth index, elevation, and outdoor $PM_{2.5}$.

of respiratory events, hospitalizations, and all-cause mortality and in comparison with persistent solid fuel users, individuals who switched from solid to clean fuels during follow-up had reduced risk of respiratory events, hospitalizations, and all-cause mortality, which were not mediated through lung function. These results provide new information on how HAP may influence lung function, respiratory disease and mortality.

The literature linking HAP to lung function impairment has reported mixed findings.[7–12] Our cross-sectional findings of lower FEV_1 with solid fuels in comparison with clean fuels aligns with some of the existing research, although we generally observed smaller associations.[10,26,27] For example, a cross-sectional study in Nepal found that adults using biomass fuels had lower FEV_1 by −103 mL (95% CI: −167, −39), FVC by −45 mL (95% CI: −118, 28), and FEV_1/FVC by −2.9% (95% CI: −4.1, −1.6), in comparison with gas users.[26] These estimates are much larger than our current findings of lower FEV_1 of −17.5 mL (95% CI: −32.7, −2.3) in solid fuel vs. clean fuel users. In terms of multicountry studies, two large cross-sectional studies have examined the association between HAP with COPD across multiple country data using spirometry measurements. The first study included 12,396 adults from 13 low-income countries and reported an increased OR of 1.41 (95% CI: 1.18, 1.68) for airflow obstruction ($FEV_1/FVC <70\%$) with solid fuels in comparison with clean fuels for cooking.[8] In the same study, the authors also reported on lower prebronchodilator FEV_1 for all ages with solid fuel use in comparison with clean fuels, which is consistent with our findings. The second study examined 18,554 adults from 23 countries and observed an OR of 1.20 (95%

Table 4. Associations between solid fuel use at baseline and change from solid to clean cooking fuels during follow-up, and respiratory events, hospitalizations, and all-cause mortality in the PURE study (2003–2019).

		All respiratory events		Respiratory hospitalizations		All-cause mortality	
	n	Events	HR (95% CI)	Events	HR (95% CI)	Events	HR (95% CI)
Household fuel use at baseline and respiratory events							
Base model[a]							
Clean cooking fuels	4,068	141	Ref	71	Ref	107	Ref
Solid cooking fuels	8,421	400	1.27 (0.99, 1.63)	192	1.24 (0.87, 1.78)	299	1.27 (0.98, 1.65)
Adjusted model[b]							
Clean cooking fuels	4,068	141	Ref	71	Ref	107	Ref
Solid cooking fuels	8,421	400	1.19 (0.92, 1.54)	192	1.17 (0.81, 1.68)	299	1.22 (0.93, 1.60)
Adjusted model+lung function[c]							
Clean cooking fuels	4,068	141	Ref	71	Ref	107	Ref
Solid cooking fuels	8,421	400	1.18 (0.91, 1.53)	192	1.16 (0.81, 1.67)	299	1.23 (0.94, 1.62)
Households switching from solid to clean fuels and respiratory events							
Base model[a]							
Persistent solid fuels	4,520	271	Ref	130	Ref	162	Ref
Switched to clean fuels	3,901	129	0.74 (0.56, 0.97)	62	0.74 (0.56, 0.97)	137	0.83 (0.60, 1.14)
Adjusted model[b]							
Persistent solid fuels	4,520	271	Ref	130	Ref	162	Ref
Switched to clean fuels	3,901	129	0.76 (0.57, 1.00)	62	0.71 (0.48, 1.06)	137	0.85 (0.62, 1.17)
Adjusted model+lung function[c]							
Persistent solid fuels	4,520	271	Ref	130	Ref	162	Ref
Switched to clean fuels	3,901	129	0.78 (0.60, 1.04)	62	0.71 (0.48, 1.05)	137	0.85 (0.62, 1.17)

Note: BMI, body mass index; CI, confidence interval; FEV_1, forced expiratory volume in 1 second; HR, hazard ratio; PURE, Prospective Urban and Rural Epidemiology; Ref, reference.
[a]Base model: age, sex, height, geographic center, random intercept for community.
[b]Adjusted model: age, sex, height, geographic center, random intercept for community, BMI, smoking status, baseline respiratory conditions, education, household wealth index, elevation and outdoor $PM_{2.5}$.
[c]Adjusted model plus baseline FEV_1 and change in FEV_1 during follow-up.

CI: 0.94, 1.53) in men and 0.88 (95% CI: 0.67, 1.5) in women for airflow obstruction with solid fuels vs. clean fuels use for cooking.[7] Although this study reported on the pattern of spirometric impairment (i.e., airflow obstruction or restriction), the authors did not report on FEV_1 or FVC specifically. In our cross-sectional analyses, we observed neither any clear association between solid fuel use with the FEV_1/FVC ratio nor large differences by sex.

There is a paucity of data on the types of cooking fuels that may be more harmful to health,[7,27] despite the fact that there are quantitative and qualitative differences in the air pollutants arising from the different cooking-fuel types. For example, our previous work in a subsample of 2,541 households in PURE using direct household air quality measurements in kitchens quantified a clear gradient of $PM_{2.5}$ concentration across different fuel types.[28] Although this work supports our use of primary fuel type for cooking as a HAP exposure indicator, the differences in reported findings across studies may in part be related to the differences in air pollution exposures associated with different fuel types, cooking practices, and housing characteristics. These differences may explain the inverse association we observed in South America. Here, cooking with wood is mostly done in enclosed wood stoves with good ventilation, which has much lower associated air pollution exposures than cooking with open-fire stoves. We have documented this in the PURE household monitoring study, where mean 48-h kitchen $PM_{2.5}$ levels were 41 $\mu g/m^3$ in South American PURE communities, in comparison with 318 $\mu g/m^3$ in Africa, 383 $\mu g/m^3$ in Asia, and 140 $\mu g/m^3$ in India.[28] We accounted for these regional differences in the present analyses by including center as a fixed effect variable in our models, which restricted the comparison to the same geographical area and thus minimized HAP exposure misclassification and residual confounding. Although we explored associations by specific fuel types and ventilation status, we had limited power because of small numbers and clustering of fuel types by country and region of the PURE study. Further research that examines measured household and personal air pollution exposure concentrations associated with lung function and respiratory disease is needed.

In the present study, we were able to examine the changes in lung function for 12,489 individuals with repeated spirometry measures over a long time frame (average of 8.0 y between spirometry measures). Given the natural changes in fuel use switching over time in the PURE study,[29] we were able to compare individuals who did and did not switch to clean fuels during follow-up. This is an important comparison because it informs the potential implications of HAP interventions on respiratory health that aim to transition households to cleaner fuel sources. Although we did not observe any differences in the rate of change in FEV_1 or FVC, there was a small attenuation in the decline of the FEV_1/FVC ratio by 0.2% per year (95% CI: 0.03, 0.3) among individuals who switched from solid fuels to clean fuels, in comparison with persistent solid fuel users. This attenuation corresponds to a 2% higher FEV_1/FVC ratio over a 10-y period among people who switched from solid to clean fuels. This association was most robust for individuals over age 55 y and females (both showing a 3% increase over 10 y). This finding is in line with intervention and RCT studies that show evidence of benefits to respiratory health from switching from solid to clean fuels. A RCT in Mexico found that women using improved wood stoves most of the time had a lower FEV_1 decline (31 mL or 1%) in comparison with wood open-fire users (62 mL or 2%) over a 1-y follow-up period.[15] In addition, a prospective intervention study of 996 individuals in China observed that transitioning to clean fuels or improved ventilation reduced decline in FEV_1 of 12 mL/y and 13 mL/y, respectively, in comparison with individuals who had no intervention.[13] Although the effect sizes (2% higher FEV_1/FVC ratio over 10 y) that we observed may be small, they do support policies advocating for switching from solid to clean fuels.

We hypothesized that lung function is an important mediator for the association between HAP exposure with respiratory events, respiratory hospitalizations, and all-cause mortality. We observed increased adjusted HRs of 1.19 (95% CI: 0.92, 1.54) for all respiratory events with solid fuel use at baseline, in comparison with clean fuels, and a HR of 0.76 (95% CI: 0.57, 1.00) for individuals who switched to clean fuels during follow-up, in comparison with individuals continuing to use solid fuels. These results correspond to previous analyses of HAP and health events in a broader sample in the PURE study.[30] When baseline FEV_1 and change in FEV_1 were added to these models, the HAP estimates remained largely unchanged, suggesting that lung function may not be the main pathway linking HAP to respiratory events. Previous studies had shown that biomass fuel exposure was associated with a chronic inflammatory response that leads to pulmonary damage,[31] and a systematic review concluded that inhaled substances such as PM_{10} can trigger local and systemic inflammatory responses, with downstream adverse health impacts, including respiratory and cardiovascular effects.[32] Our results show that although there were small associations between HAP and lung function, these do not explain the overall HAP associations with respiratory events and mortality.

Although there are a number of strengths to our study, which include the large sample size, diverse populations, comprehensive adjustment for many covariates, repeated lung function measures, and longitudinal follow-up of incident events, there are also some important limitations. First, we used solid fuels as an indicator of potential air pollution exposure, rather than direct air pollution measurements, such as $PM_{2.5}$ concentrations. In addition, we lacked detailed information on secondary fuels used for cooking. Although it is not feasible to conduct measurements for such a large population, we have conducted 2,541 household measurements in PURE that demonstrate large differences in $PM_{2.5}$ concentrations between homes cooking with clean fuels (mean = 45 $\mu g/m^3$ for gas) in comparison with solid fuels (mean = 68 $\mu g/m^3$ for coal, 109 $\mu g/m^3$ for wood, 224 $\mu g/m^3$ for animal dung, and 276 $\mu g/m^3$ for shrub/grass).[28] Another form of possible HAP exposure misclassification is that we did not record information on the date individuals switched fuels during follow-up or the use of fuel stacking. Individuals who switched to clean fuel likely previously used solid fuels for a long time, and overall HAP exposure differences from switching may be minimal for long-term exposures. However, our results indicate that over this follow-up duration, switching from solid to clean fuels resulted in small attenuation of the decline in the FEV_1/FVC ratio. Second, the PURE sample is not representative of specific countries, although the PURE cohort has been validated against national statistics with good agreement.[33] Although we examined a large sample covering different countries and socioeconomic and environmental settings, especially those in developing countries where similar studies have seldom been completed, our HAP prevalence estimates and results should not be interpreted as representing regions or countries. We also limited our population to individuals living in rural communities, given the potential unmeasured confounding factors that could exist between urban and rural settings. Third, we cannot rule out potential unmeasured or residual confounding in our results. However, our study included a large number of individual, household, and community covariates collected through standardized questionnaires and study protocols, which help to better address potential confounding in comparison with previous studies. We also included a community random intercept and geographic regional fixed effect variables to control for potential unmeasured geographic confounding factors. Fourth, although our spirometry data have been extensively validated with clinical and field comparisons, there is likely random error that may reduce our ability to detect associations, especially for lung function change, where we had to rely on the change in FEV_1 and FVC between two measures. Once additional follow-up spirometry data are collected in PURE, there will be sufficient data to examine trajectories, rather than absolute change measures.

Conculsions

Use of solid fuels for cooking was associated with lower baseline FEV_1. Individuals who switched from solid to clean fuels, in comparison with individuals who continued to use solid fuels during follow-up, had small attenuation in the rate of decline of the FEV_1/FVC ratio and reduced risk of respiratory events, hospitalizations, and all-cause mortality. These findings support the potential health benefits of households switching to cleaner cooking energy sources. Future research using direct measures of air pollution exposure, especially in prospective longitudinal studies, is needed to further examine the associations between HAP exposure levels and lung function, respiratory disease, and mortality.

Acknowledgments

The main PURE study and its components are funded by the Population Health Research Institute, the Canadian Institutes of Health Research, and the Heart and Stroke Foundation of Ontario and through unrestricted grants from several pharmaceutical companies [with major contributions from Astra Zeneca (Canada), Sanofi-Aventis (France and Canada), Boehringer Ingelheim (Germany and Canada), Servier, and Glaxo Smith Kline] and additional contributions from Novartis and King Pharma. The PURE-AIR study is funded by Canadian Institutes for Health Research (CIHR; grant 136893) and by the Office of the Director, National Institutes of Health (NIH; award DP5OD019850). The content is solely the responsibility of the authors and does not necessarily represent the official views of CIHR or NIH. More details on funding support and PURE institutions are provided in the supplemental material.

References

1. WHO (World Health Organization). The Global Health Observatory. https://www.who.int/data/gho/ [accessed 18 October 2021].
2. Lee KK, Bing R, Kiang J, Bashir S, Spath N, Stelzle D, et al. 2020. Adverse health effects associated with household air pollution: a systematic review, meta-analysis, and burden estimation study. Lancet Glob Health 8(11):e1427–e1434, PMID: 33069303, https://doi.org/10.1016/S2214-109X(20)30343-0.
3. Duong M, Islam S, Rangarajan S, Leong D, Kurmi O, Teo K, et al. 2019. Mortality and cardiovascular and respiratory morbidity in individuals with impaired FEV_1 (PURE): an international, community-based cohort study. Lancet Glob Health 7(5):e613–e623, PMID: 31000131, https://doi.org/10.1016/S2214-109X(19)30070-1.
4. Lange P, Celli B, Agustí A, Boje Jensen G, Divo M, Faner R, et al. 2015. Lung-function trajectories leading to chronic obstructive pulmonary disease. N Engl J Med 373(2):111–122, PMID: 26154786, https://doi.org/10.1056/NEJMoa1411532.
5. Padhi BK, Padhy PK. 2008. Domestic fuels, indoor air pollution, and children's health. Ann N Y Acad Sci 1140:209–217, PMID: 18991919, https://doi.org/10.1196/annals.1454.015.
6. Rinne ST, Rodas EJ, Bender BS, Rinne ML, Simpson JM, Galer-Unti R, et al. 2006. Relationship of pulmonary function among women and children to indoor air pollution from biomass use in rural Ecuador. Respir Med 100(7):1208–1215, PMID: 16318916, https://doi.org/10.1016/j.rmed.2005.10.020.
7. Amaral AFS, Patel J, Kato BS, Obaseki DO, Lawin H, Tan WC, et al. 2018. Airflow obstruction and use of solid fuels for cooking or heating: BOLD results. Am J Respir Crit Care Med 197(5):595–610, PMID: 28895752, https://doi.org/10.1164/rccm.201701-0205OC.
8. Siddharthan T, Grigsby MR, Goodman D, Chowdhury M, Rubinstein A, Irazola V, et al. 2018. Association between household air pollution exposure and chronic obstructive pulmonary disease outcomes in 13 low- and middle-income country settings. Am J Respir Crit Care Med 197(5):611–620, PMID: 29323928, https://doi.org/10.1164/rccm.201709-1861OC.
9. Obaseki DO, Awopeju OF, Awokola BI, Adeniyi BO, Adefuye BO, Ozoh OB, et al. 2017. Domestic solid fuel combustion in an adult population in Nigeria: a cross sectional analysis of association with respiratory symptoms, quality of life and lung function. Respir Med 130:61–68, PMID: 29206635, https://doi.org/10.1016/j.rmed.2017.07.014.
10. Dave M, Ahankari AS, Myles PR, Arokiasamy P, Khobragade P, Mortimer K, et al. 2017. Household air pollution and lung function in Indian adults: a cross-sectional study. Int J Tuberc Lung Dis 21(6):702–704, PMID: 28482966, https://doi.org/10.5588/ijtld.16.0615.
11. Kurti SP, Kurti AN, Emerson SR, Rosenkranz RR, Smith JR, Harms CA, et al. 2016. Household air pollution exposure and influence of lifestyle on respiratory health and lung function in Belizean adults and children: a field study. Int J Environ Res Public Health 13(7):643, PMID: 27367712, https://doi.org/10.3390/ijerph13070643.
12. Devien L, Giovannelli J, Cuny D, Matran R, Amouyel P, Hulo S, et al. 2018. Sources of household air pollution: the association with lung function and respiratory symptoms in middle-aged adult. Environ Res 164:140–148, PMID: 29486345, https://doi.org/10.1016/j.envres.2018.02.016.
13. Zhou Y, Zou Y, Li X, Chen S, Zhao Z, He F, et al. 2014. Lung function and incidence of chronic obstructive pulmonary disease after improved cooking fuels and kitchen ventilation: a 9-year prospective cohort study. PLoS Med 11(3): e1001621, PMID: 24667834, https://doi.org/10.1371/journal.pmed.1001621.
14. Smith-Sivertsen T, Díaz E, Pope D, Lie RT, Díaz A, McCracken J, et al. 2009. Effect of reducing indoor air pollution on women's respiratory symptoms and lung function: the RESPIRE randomized trial, Guatemala. Am J Epidemiol 170(2):211–220, PMID: 19443665, https://doi.org/10.1093/aje/kwp100.
15. Romieu I, Riojas-Rodríguez H, Marrón-Mares AT, Schilmann A, Perez-Padilla R, Masera O. 2009. Improved biomass stove intervention in rural Mexico: impact on the respiratory health of women. Am J Respir Crit Care Med 180(7):649–656, PMID: 19556519, https://doi.org/10.1164/rccm.200810-1556OC.
16. Teo K, Chow CK, Vaz M, Rangarajan S, Yusuf S, PURE Investigators-Writing Group. 2009. The Prospective Urban Rural Epidemiology (PURE) study: examining the impact of societal influences on chronic noncommunicable diseases in low-, middle-, and high-income countries. Am Heart J 158(1):1–7.e1, PMID: 19540385, https://doi.org/10.1016/j.ahj.2009.04.019.
17. Yusuf S, Joseph P, Rangarajan S, Islam S, Mente A, Hystad P, et al. 2020. Modifiable risk factors, cardiovascular disease, and mortality in 155,722 individuals from 21 high-income, middle-income, and low-income countries (PURE): a prospective cohort study. Lancet 395(10226):795–808, PMID: 31492503, https://doi.org/10.1016/S0140-6736(19)32008-2.
18. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, et al. 2005. Standardisation of spirometry. Eur Respir J 26(2):319–338, PMID: 16055882, https://doi.org/10.1183/09031936.05.00034805.
19. Duong M, Islam S, Rangarajan S, Teo K, O'Byrne PM, Schünemann HJ, et al. 2013. Global differences in lung function by region (PURE): an international, community-based prospective study. Lancet Respir Med 1(8):599–609, PMID: 24461663, https://doi.org/10.1016/S2213-2600(13)70164-4.
20. Barr RG, Stemple KJ, Mesia-Vela S, Basner RC, Derk SJ, Henneberger PK, et al. 2008. Reproducibility and validity of a handheld spirometer. Respir Care 53(4):433–441, PMID: 18364054.
21. Duong M, Rangarajan S, Zaman M, Nasir NM, Seron P, Yeates K, et al. 2022. Differences and agreement between two portable hand-held spirometers across diverse community-based populations in the Prospective Urban Rural Epidemiology (PURE) study. PLOS Glob Public Health 2(2):e0000141, PMID: 36962310, https://doi.org/10.1371/journal.pgph.0000141.
22. Yusuf S, Rangarajan S, Koon T, Islam S, Li W, Liu L, et al. 2014. Cardiovascular risk and events in 17 low-, middle-, and high-income countries. N Engl J Med 371:818–827, https://doi.org/10.1056/NEJMoa1311890.
23. Gajalakshmi V, Peto R, Kanaka S, Balasubramanian S. 2002. Verbal autopsy of 48,000 adult deaths attributable to medical causes in Chennai (formerly Madras), India. BMC Public Health 2:7, PMID: 12014994, https://doi.org/10.1186/1471-2458-2-7.
24. Rosengren A, Smyth A, Rangarajan S, Ramasundarahettige C, Bangdiwala SI, AlHabib KF, et al. 2019. Socioeconomic status and risk of cardiovascular disease in 20 low-income, middle-income, and high-income countries: The Prospective Urban Rural Epidemiologic (PURE) study. Lancet Glob Health 7(6): e748–e760, PMID: 31028013, https://doi.org/10.1016/S2214-109X(19)30045-2.
25. Shaddick G, Thomas ML, Amini H, Broday D, Cohen A, Frostad J, et al. 2018. Data integration for the assessment of population exposure to ambient air pollution for global burden of disease assessment. Environ Sci Technol 52(16):9069–9078, PMID: 29957991, https://doi.org/10.1021/acs.est.8b02864.
26. Kurmi OP, Devereux GS, Smith WCS, Semple S, Steiner MFC, Simkhada P, et al. 2013. Reduced lung function due to biomass smoke exposure in young adults in rural Nepal. Eur Respir J 41(1):25–30, PMID: 22556024, https://doi.org/10.1183/09031936.00220511.

27. Li J, Qin C, Lv J, Guo Y, Bian Z, Zhou W, et al. 2019. Solid fuel use and incident COPD in chinese adults: findings from the China Kadoorie Biobank. Environ Health Perspect 127(5):57008, PMID: 31095433, https://doi.org/10.1289/EHP2856.
28. Shupler M, Hystad P, Birch A, Miller-Lionberg D, Jeronimo M, Arku RE, et al. 2020. Household and personal air pollution exposure measurements from 120 communities in eight countries: results from the PURE-AIR study. Lancet Planet Health 4(10):e451–e462, PMID: 33038319, https://doi.org/10.1016/S2542-5196(20)30197-2.
29. Shupler M, Hystad P, Gustafson P, Rangarajan S, Mushtaha M, Jayachtria KG, et al. 2019. Household, community, sub-national and country-level predictors of primary cooking fuel switching in nine countries from the PURE study. Environ Res Lett 14(8):085006, PMID: 33777170, https://doi.org/10.1088/1748-9326/ab2d46.
30. Hystad P, Duong M, Brauer M, Larkin A, Arku R, Kurmi OP, et al. 2019. Health effects of household solid fuel use: findings from 11 countries within the Prospective Urban and Rural Epidemiology study. Environ Health Perspect 127(5):57003, PMID: 31067132, https://doi.org/10.1289/EHP3915.
31. Kurmi OP, Semple S, Simkhada P, Smith WCS, Ayres JG. 2010. COPD and chronic bronchitis risk of indoor air pollution from solid fuel: a systematic review and meta-analysis. Thorax 65(3):221–228, PMID: 20335290, https://doi.org/10.1136/thx.2009.124644.
32. Sinden NJ, Stockley RA. 2010. Systemic inflammation and comorbidity in COPD: a result of "overspill" of inflammatory mediators from the lungs? Review of the evidence. Thorax 65(10):930–936, PMID: 20627907, https://doi.org/10.1136/thx.2009.130260.
33. Corsi DJ, Subramanian SV, Chow CK, McKee M, Chifamba J, Dagenais G, et al. 2013. Prospective Urban Rural Epidemiology (PURE) study: baseline characteristics of the household sample and comparative analyses with national data in 17 countries. Am Heart J 166(4):636–646.e4. PMID: 24093842, https://doi.org/10.1016/j.ahj.2013.04.019.