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ORIGINAL ARTICLE

Lung function in woodsmoke-exposed Guatemalan children following a chimney stove intervention

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ABSTRACT

Rationale Household air pollution (HAP) from solid fuel combustion is a major contributor to the global burden of disease, with considerable impact from respiratory infections in children. The impact of HAP on lung function is unknown.

Objectives The Childhood Exposure to Respirable Particulate Matter (CRECER) prospective cohort study followed Guatemalan children who participated in the Randomised Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) trial of a chimney stove intervention to determine the effect of early childhood HAP exposure on growth of lung function.

Methods RESPIRE households with pregnant women or infant children were randomised to receive a chimney stove at the beginning or at the end of the 18-month trial. During CRECER, a subset of these children, as well as children from households with newly installed stoves, were followed with spirometry beginning at age 5. Biomass smoke exposure was measured using personal carbon monoxide tubes. Two-stage regression models were employed to analyse associations with lung function growth.

Measurements and main results Longitudinal peak expiratory flow (PEF) and FEV₁ data were available for 443 and 437 children, respectively, aged 5–8 (mean follow-up 1.3 years). Decreases in PEF growth of 173 mL/min/year (95% CI –341 to –7) and FEV₁ of 44 mL/year (95% CI –91 to 4) were observed with stove installation at 18 months compared with stove installation at birth in analyses adjusted for multiple covariates. No statistically significant associations were observed between personal HAP exposure and lung function.

Conclusions A significant decrease in PEF growth and a large non-significant decrease in FEV₁ growth were observed with later stove installation. Additional studies including longer follow-up and cleaner stoves or fuels are needed.

INTRODUCTION

Over 2.4 billion people worldwide, most in low-income and middle-income countries, use biomass fuels such as wood, dung and crop residues for cooking. These fuels are typically burned in open fires in poorly ventilated homes, releasing significant quantities of pollutants including particulate matter (PM), carbon monoxide (CO), nitrogen oxides and polycyclic aromatic hydrocarbons.^{1–3} In homes with open fires, indoor concentrations of PM have been found to be 10 or even 100 times

Key messages

What is the key question?

- ▶ Previous studies have shown decreased lung function growth associated with outdoor air pollution, but no longitudinal studies to date have examined the association between household air pollution (HAP) from biomass smoke and childhood lung function.

What is the bottom line?

- ▶ Using follow-up data after a randomised stove intervention trial, longer use of an open fire was associated with a significant decrease in peak expiratory flow rates and a large non-significant decrease in FEV₁.

Why read on?

- ▶ Because HAP from solid fuel combustion is the third greatest contributor to the global burden of disease, it is important to understand the relationship between early-life exposure to HAP and growth of lung function.

higher than maximum levels recommended by WHO guidelines.⁴ Household air pollution (HAP) from solid fuels is estimated to be responsible for 3.5 million premature deaths and 4.3% of disability-adjusted life years lost annually, making it the third greatest contributor to the global burden of disease following high blood pressure and tobacco smoke.⁵

Women who traditionally undertake the majority of household tasks and the young children who accompany them tend to have the highest biomass smoke exposure.^{6–7} Young children are exposed during a critical period of lung development; new alveoli develop and continue to grow in size through adolescence.⁸ Numerous studies have shown increased risks of acute lower respiratory infections associated with biomass smoke exposure.^{7–9–11} Early childhood respiratory infections, along with inflammation and oxidative stress from air pollutant exposure, may affect lung development and predispose children to chronic illnesses such as asthma and COPD later in life.

Outdoor air pollution studies have found increased concentrations of pollutants, including PM, to be associated with decreased lung function growth in children.^{12–16} However, studies of HAP



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and lung function in children have been more limited. Several cross-sectional studies have found associations between biomass use and reduced lung function in children,^{17–22} but they have been limited by their cross-sectional designs and lack of direct exposure assessment, and most could not address important confounders. One longitudinal study in China found a decrease in lung function growth in children living in coal-burning homes compared with those in homes using gas; among coal-using homes, lung function growth was higher in homes with improved ventilation.²³ However, the emissions from coal stoves are somewhat different from those in which biomass is burned. No longitudinal studies have examined the effect of HAP from biomass fuels on lung function in children.

Using longitudinal spirometry data from a cohort of children who participated in the first randomised controlled clinical trial of a chimney stove intervention designed to reduce HAP, this study sought to investigate whether early childhood exposure to biomass smoke was associated with lower lung function growth later in childhood.

METHODS

Study design and participants

In the Randomised Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE), which took place from 2002 to 2004, 534 households in rural Guatemala that cooked exclusively over open fires and included a pregnant woman or young infant were randomised to receive a stove with a chimney to vent emissions to the outdoors (*plancha*) or no intervention. This stove is locally available and was found in pilot studies to be acceptable to the local population and efficacious in reducing indoor pollution levels.²⁴ At the end of the 18-month intervention period, all households in the control group received the chimney stove. The design of the RESPIRE study has been published in detail elsewhere.^{9 25}

The Chronic Respiratory Effects of Early Childhood Exposure to Respirable PM (CRECER) cohort study took place from 2006 to 2009 and included a subset of RESPIRE households, as well as a group of new households. Eligible new households were located in the same region as RESPIRE households, cooked exclusively over open fires, and included one child in the same age range as the RESPIRE children (3–4 years old at the time of enrolment in CRECER), as well as one infant <6 months of age. All new CRECER households received the chimney stove midway through the CRECER study, allowing for a 12–18 month period of observation prior to stove installation. This resulted in three distinct groups with different durations of stove use (table 1): those in the RESPIRE intervention group receiving a stove within 6 months of birth (hereafter Group 1), those in the RESPIRE control group receiving a stove around 18 months of age (Group 2) and those in the new CRECER

group receiving a stove during CRECER, when the study child was around age 5 and their infant sibling was around 18–24 months of age (Group 3).

Biomass smoke exposure

Small passive-diffusion colorimetric tubes were worn by the children for a period of 48-h every 3 months during RESPIRE and every 6 months during CRECER to measure exposure to CO, as described elsewhere.²⁴ As CO measurements from the first 18 months of life were unavailable for new CRECER participants (Group 3) who were enrolled at age 3–4, personal CO measurements from their infant siblings taken prior to stove installation were used as a proxy for these participants' exposure during the first 18 months of life in the exposure–response analyses.

Personal CO exposure correlates well with exposure to fine PM (PM_{2.5}) in this population of wood-fuel users²⁶ and was therefore used as a proxy for PM_{2.5} exposure.

Spirometry

Spirometry was performed beginning at 5 years of age and repeated every 6 months during CRECER follow-up. Using an EasyOne spirometer (ndd Medical Technologies, Inc, Andover, Massachusetts, USA), children performed spirometry guided by a trained physician and following American Thoracic Society performance criteria. Individual curves were graded manually by one of two experienced reviewers blinded to intervention group; only lung function measurements from curves meeting acceptability criteria were included in this analysis. As the children were quite young, reproducible FEV₁ and peak expiratory flow (PEF) measurements from good efforts were retained for analysis even when FVC measurements were not of adequate quality. Per cent predicted lung function was calculated using Global Lung Function Initiative (GLFI) equations.²⁷

Statistical analysis

Linear regression methods were used to analyse whether there were differences in lung function growth based on study group or HAP exposure using a two-stage model. The first stage was a linear regression of lung function variables on age, by subject, generating a separate lung function growth slope for each subject for each spirometric variable. Only children with acceptable spirometry from two or more sessions were included. In the second stage, a regression of the subject-specific growth slopes was conducted on study group, to estimate average lung function growth by study group. Secondary exposure–response analyses using log-transformed mean personal CO measurements from the first 18 months of life were also conducted, to estimate change in lung function growth associated with changes in HAP exposure. All 95% CIs were obtained using a robust estimator.

Sex, height at first spirometry, annual change in height and secondhand smoke exposure were included as a priori confounders in all second-stage models. Other covariates including maternal education, paternal education, asset index and *temazcal* (wood-fuelled sauna bath) use were assessed for inclusion by backwards elimination. Variables were retained in the final model if either their p value was <0.1 or if eliminating them from the model resulted in a change in the β coefficient for the main predictor of >10%. The asset index, used as a marker of socioeconomic status, is a number from 0 to 7 calculated based on possession of any of the following items in a household (each adding 1 point): television, radio, refrigerator, bicycle, motorcycle, automobile or cell phone. Paternal and maternal education

Table 1 Study groups

	Group description	Timing of stove installation
Group 1	RESPIRE intervention households	Within 6 months of birth
Group 2	RESPIRE control households	~18 months, following the conclusion of the RESPIRE trial
Group 3	New CRECER households	~57 months, during the CRECER study

CRECER, Childhood Exposure to Respirable Particulate Matter; RESPIRE, Randomised Exposure Study of Pollution Indoors and Respiratory Effects.

levels were categorised as no formal education, elementary school or greater than elementary school. The *temazcal* is used for bathing and cleaning and has been found to lead to intermittent, high exposures to biomass smoke.^{28, 29} *Temazcal* use was categorised based on whether participants accompanied their parents into the *temazcal* always, sometimes or never. Secondhand smoke exposure was present if any individual in the participant's household was a current smoker. All demographic variables were assessed by questionnaire administered at the beginning of the CRECER study.

Univariate analyses comparing stove groups used χ^2 tests for categorical variables, and analysis of variance for normally distributed continuous variables or their logarithmic transformations, using the Scheffé procedure to assess pairwise differences between groups. Statistical analysis was performed using Stata V.11.2.

Ethical considerations

Both RESPIRE and CRECER protocols were approved by the research ethics committees of the University of California, Berkeley, and the Universidad del Valle in Guatemala prior to study initiation. CRECER was also approved by the research ethics committee at the University of California, San Francisco. Participants were enrolled via oral informed consent, which was conducted by trained local field workers fluent in participants' primary language (Mam). Primary caregivers (typically mothers) provided consent for their participating children.

RESULTS

Five hundred and fifty-seven children were initially enrolled in CRECER, including 194 from each arm of the RESPIRE trial and 169 from new households. Graded spirometry results were available for a total of 506 children, including 175 from Group 1, 180 from Group 2 and 151 from Group 3 (figure 1).

Child and household demographic variables were similar across stove groups (table 2). Average age of first spirometry

across all groups was 5.4 years, and ages ranged from 5 to 8 years during the study period.

The mean number of spirometry sessions per child was 3.6, and 495 children (98%) had two or more spirometry sessions. Average length of follow-up was 1.3 years, and there were 1809 total spirometry sessions among all children. One thousand three hundred and ninety-eight sessions (77%) had at least one acceptable FEV₁ measurement by manual grading criteria; 1306 (72%) had at least one acceptable FVC and FEF_{2.5-7.5} measurement, and 1425 (79%) had at least one acceptable PEF measurement.

Average personal CO exposure concentrations during the first 18 months of life varied across stove groups (table 3). Participants in Group 1 had a mean CO of 1.18 ppm (SD 0.5) following stove installation, which was significantly lower than average CO in Group 2 (1.96 ppm, SD 0.8) and Group 3 (1.67 ppm, SD 0.8) whose measurements were taken prior to stove installation ($p < 0.001$ for both pairwise comparisons). A significant difference was also observed between average exposures in Groups 2 and 3 ($p = 0.001$). For the participants in Group 1, mean baseline CO level prior to stove installation was 2.19 ppm, representing a decrease of 46% ($p < 0.001$) after stove installation. The distributions for personal CO exposure concentrations were positively skewed; their natural log transformations were more normally distributed and were used in all statistical analyses.

Mean FEV₁ at first spirometry was 0.92 L in Group 1, 0.91 L in Group 2 and 0.82 L in Group 3 ($p = 0.19$). Average per cent predicted FEV₁ at first spirometry was 110%, 108% and 104% in Groups 1, 2 and 3, respectively. Baseline measurements and per cent predicted values of FVC, FEF_{2.5-7.5} and PEF were also lower in Group 3 compared with Groups 1 and 2, though none of these differences was statistically significant (table 4).

Average FEV₁ growth was 144 mL/year in Group 1, 100 in Group 2 and 109 in Group 3 ($p = 0.14$), and average FVC growth was 172 mL/year in Group 1, 137 in Group 2 and 146 in Group 3 ($p = 0.43$). Out of 1324 spirometry sessions with

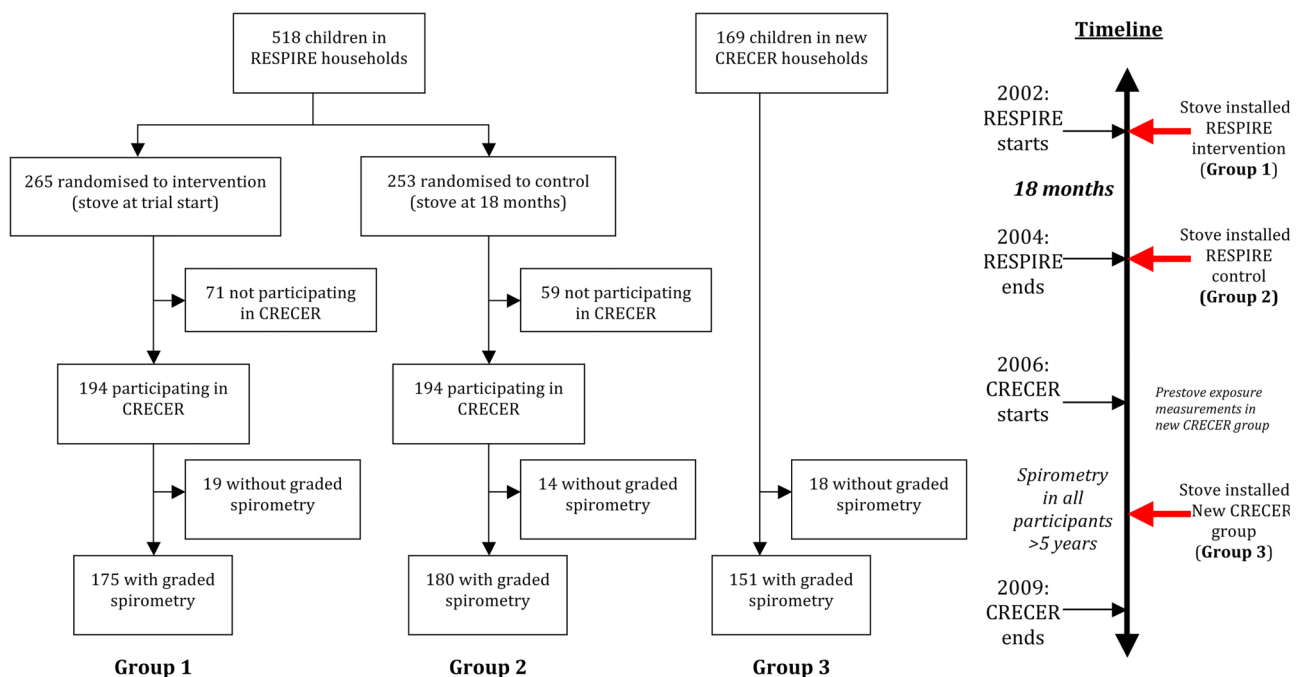


Figure 1 Study diagram and timeline. CRECER, Childhood Exposure to Respirable Particulate Matter; RESPIRE, Randomised Exposure Study of Pollution Indoors and Respiratory Effects.

Table 2 Demographic characteristics by study group

	Group 1 N=175, mean (SD) or n (%)	Group 2 n=180, mean (SD) or n (%)	Group 3 n=151, mean (SD) or n (%)	p Value*
Age at first spirometry	5.3 (0.2)	5.3 (0.2)	5.4 (0.3)	<0.0001
Baseline height (cm)	97 (4.1)	97 (4.2)	98 (4.4)	0.70
Number of spirometry sessions per child	3.8 (1.1)	3.7 (1.1)	3.2 (1.3)	<0.0001
Gender				
Male	85 (49)	88 (49)	72 (48)	0.98
Female	90 (51)	92 (51)	79 (52)	
Maternal education				
None	61 (35)	69 (38)	43 (28)	0.28
Elementary school	107 (61)	108 (60)	106 (70)	
Middle school	4 (2)	1 (1)	1 (1)	
High school	3 (2)	2 (1)	1 (1)	
Paternal education				
None	18 (11)	24 (14)	18 (12)	0.73
Elementary school	126 (76)	123 (71)	107 (71)	
Middle school	8 (5)	6 (3)	7 (5)	
High school	14 (8)	20 (12)	149 (13)	
Unknown	9 (5)	7 (4)	0 (0)	
Asset index (0–7)	1.67 (1.0)	1.72 (1.1)	1.55 (1.0)	0.36
Smoker present in home	13 (7)	22 (12)	14 (9)	0.31
Child use of <i>temazcal</i>				
Always	142 (81)	135 (75)	114 (76)	0.38
Sometimes	123 (13)	31 (17)	230 (20)	
Never	10 (6)	14 (8)	7 (6)	

*Comparing all three groups, using analysis of variance for continuous variables and χ^2 tests for categorical variables.

both acceptable FEV₁ and FVC measurements, only 19 sessions, distributed among 17 children (3.4% of study participants), had FEV₁/FVC ratios <0.7 (table 4).

In the two-stage regression, lower FEV₁, FVC, FEV₁/FVC ratio, FEF_{25–75} and PEF growth rates were observed in Groups 2 and 3 compared with Group 1 (table 5). A statistically significant decrease of 173 mL/min/year in PEF growth rate was seen in Group 2 compared with Group 1 (95% CI –341 to –7; p=0.048). A borderline statistically significant decrease of

Figure 2 An open fire (A) and a study-provided chimney stove (B) in study participants' homes (photo credits: Lisa M Thompson).



Table 3 Average carbon monoxide (CO) exposures during Randomised Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) and Childhood Exposure to Respirable Particulate Matter (CRECER) by study group*

	Group 1, mean (SD)	Group 2, mean (SD)	Group 3, mean (SD)	p Value
Average RESPIRE CO† (ppm)	1.18 (0.5)	1.97 (0.8)	1.66 (0.8)	<0.0001
Average CRECER CO (ppm)	0.88 (0.7)	0.88 (0.5)	1.28 (0.6)	<0.0001

*Shaded boxes indicate measurements taken with stove in place. Unshaded boxes indicate measurements taken prior to stove installation.

†For Group 3 only, the study child's early life exposures were estimated based on CO measurements of their infant sibling, collected prior to stove installation during CRECER in the first 18 months of life.

44 mL/year in FEV₁ growth rate was also seen in Group 2 compared with Group 1 (95% CI –91 to 4; p=0.07).

In the secondary exposure–response analysis, there were no statistically significant associations between personal CO exposure during the first 18 months of life and any lung function variable (table 6). A sensitivity analysis was also conducted adjusting for exposures later in life (during the CRECER study period). There were no significant differences in results compared with the analysis of early life exposures alone.

An additional sensitivity analysis was conducted, restricted to only participants from the two original RESPIRE groups (Groups 1 and 2), excluding participants from the new CRECER group (Group 3). In this analysis with reduced statistical power, although the magnitude of effects was similar to those observed in the full analysis, there were no significant associations between either study group or personal CO exposure and lung function growth.

The final second-stage model used for all adjusted analyses included the following covariates: gender, height at first spirometry, annual change in height, maternal education and second-hand smoke exposure. Paternal education, asset index and *temazcal* use were assessed but excluded from the final model.

DISCUSSION

This study presents longitudinal follow-up data from a cohort of children enrolled in the first randomised controlled clinical trial

Table 4 Baseline spirometry, lung function growth and airflow obstruction by study group

Baseline	Group 1, mean (SD)	Group 2, mean (SD)	Group 3, mean (SD)	p Value
FEV ₁ (L)	0.918 (0.2)	0.911 (0.2)	0.823 (0.2)	0.19
FVC (L)	1.03 (0.2)	1.01 (0.2)	0.87 (0.2)	0.16
FEV ₁ /FVC	0.90 (0.06)	0.90 (0.06)	0.89 (0.06)	0.56
FEF _{25–75} (L)	1.39 (0.4)	1.42 (0.5)	1.28 (0.4)	0.08
PEF (L)	2.27 (0.5)	2.30 (0.6)	2.17 (0.5)	0.22
Per cent predicted lung function at baseline*	Mean (SD)	Mean (SD)	Mean (SD)	
FEV ₁ (%)	110 (20)	108 (19)	104 (16)	0.15
FVC (%)	115 (23)	112 (19)	109 (16)	0.16
FEV ₁ /FVC (%)	95 (6)	96 (6)	95 (6)	0.54
FEF _{25–75} (%)	109 (29)	111 (36)	101 (29)	0.09
Annual change†	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)	
FEV ₁ (mL/year)	144 (114 to 176)	100 (63 to 137)	109 (67 to 152)	0.14
FVC (mL/year)	172 (134 to 209)	137 (96 to 177)	146 (102 to 190)	0.43
FEV ₁ /FVC (%/year)	−0.9 (−2.1 to 0.2)	−1.6 (−2.8 to −0.4)	−1.5 (−3.7 to 0.7)	0.76
FEF _{25–75} (mL/min/year)	116 (31 to 202)	91 (−16 to 198)	89 (−38 to 217)	0.91
PEF (mL/min/year)	405 (298 to 513)	236 (108 to 365)	272 (141 to 402)	0.10
Airflow obstruction	N (%)	N (%)	N (%)	
Children with at least one FEV ₁ /FVC <0.7	6 (3.4)	5 (2.8)	6 (4.0)	0.83

*Using the Global Lung Function Initiative predicted lung function equations; unavailable for PEF.

†Calculations restricted to participants with two or more spirometry sessions.

PEF, peak expiratory flow.

in air pollution history. In addition to the initial randomised design, the RESPIRE and CRECER studies are unique among biomass stove studies in several ways. Unlike many other studies, which either approximated biomass smoke exposure based on fuel or stove type or one-time ambient measurements, RESPIRE and CRECER featured detailed exposure measurements, with longitudinal collection of personal CO exposure. Additionally, in contrast to the cross-sectional nature of previous studies of biomass smoke exposure and children's respiratory health, CRECER is the first to examine the relationship between biomass smoke exposure and longitudinal measurement of lung function in children.

This study identified a statistically significant decrease in PEF growth among children in the RESPIRE control group (Group 2), whose families continued cooking over open fires for their first 18 months of life, compared with children in the RESPIRE intervention group (Group 1), whose households had chimney stoves installed within 6 months of birth (figure 2). However, while PEF measurements at individual time points can provide acute estimates of airflow through the bronchi and possible obstruction, the significance of a decrease in PEF growth over time is less clear. A borderline statistically significant decrease in FEV₁ of 44 mL/year was also seen in Group 2 compared with Group 1. The clinical implications of this finding are more concrete; a difference in FEV₁ growth of 44 mL/year or greater would amount to a large difference in achieved lung function over 20 years of lung growth. Decreased growth of other lung function variables was also seen in both Groups 2 and 3 compared with Group 1, though none reached a level of statistical significance. Exposure–response analyses showed a largely consistent pattern of reductions in lung function associated with increases in biomass smoke exposure during the first 18 months of life (table 6), though none reached a level of statistical significance.

We may have failed to show stronger relationships between biomass smoke exposure and lung function for several reasons.

The first is incomplete exposure reduction. Though biomass smoke exposure was lower following stove installation, there was continued heavy smoke exposure despite the chimney stove; overall, personal exposure reduction associated with the stove was substantially less than the reduction achieved by the stove in measured kitchen levels.^{9 24} The resulting differences in smoke exposure between stove groups may not have been enough to result in large differences in lung function growth. Given the likely non-linear shape of the exposure–response curve for PM and respiratory health outcomes,^{30 31} the lack of exposure heterogeneity may have limited our ability to detect any significant differences in growth of lung function.

Additionally, it is possible that the period of differential biomass smoke exposure in RESPIRE (only 18 months) may not have been long enough to produce a persistent effect on lung function. Any transient effects on pulmonary development may have been compensated for by the time CRECER spirometry began at age 5. A previous study of children who moved from communities with high levels of outdoor air pollution to communities with lower levels of pollution found evidence of increases in previously depressed lung function growth, suggesting that pulmonary damage from pollutants may be reversible over time if exposures are reduced.^{8 32}

Conversely, biomass smoke exposure during infancy may have caused lasting lung damage, but such damage may be subtle and take many years to become apparent. Of note, decreases in lung function growth were relatively similar in Groups 2 and 3, despite different durations of stove use; one possible explanation for this finding could be that the first 1–2 years of life, before either of these groups had stoves installed, might represent a particularly vulnerable period. This study had a relatively limited spirometry follow-up period; it is possible that even more significant differences in lung function would be seen with spirometry follow-up later into childhood and adulthood. The developing lung may be even more susceptible to environmental

Table 5 Changes in annual lung function growth associated with stove group

	FEV ₁ (mL/year), coefficient (95% CI), n=437			FVC (mL/year), coefficient (95% CI), n=407			FEV ₁ /FVC (%/year), coefficient (95% CI), n=407			FEF ₂₅₋₇₅ (mL/min/year), coefficient (95% CI), n=407			PEF (mL/min/year), coefficient (95% CI), n=443		
	B	95% CI	p Value	β	95% CI	p Value	β	95% CI	p Value	β	95% CI	p Value	β	95% CI	p Value
Group 1	<i>Reference group</i>			<i>Reference group</i>			<i>Reference group</i>			<i>Reference group</i>			<i>Reference group</i>		
Group 2															
Unadjusted	-45	-93 to 3	0.065	-35	-90 to 20	0.21	-0.6	-2.3 to 1.1	0.47	-25	-16 to 11	0.72	-170	-337 to -14	0.048
Adjusted*	-44	-91 to 4	0.07	-39	-93 to 16	0.16	-0.6	-2.2 to 1.1	0.52	-23	-158 to 111	0.73	-173	-341 to -7	0.041
Group 3															
Unadjusted	-35	-88 to 17	0.18	-25	-83 to 32	0.39	-0.5	-3.0 to 2.0	0.69	-27	-180 to 126	0.73	-134	-303 to 35	0.12
Adjusted*	-39	-91 to 13	0.14	-36	-94 to 22	0.23	-0.4	-2.9 to 2.2	0.78	-19	-173 to 134	0.80	-137	-303 to 28	0.10

*Final model adjusted for age, gender, baseline height, annual change in height, maternal education and secondhand smoke.

PEF, peak expiratory flow.

Bold = statistical significance p<0.05.

Table 6 Changes in annual lung function growth associated with early life personal carbon monoxide (CO) exposures

	FEV ₁ (mL/year), coefficient (95% CI), n=437			FVC (mL/year), coefficient (95% CI), n=407			FEV ₁ /FVC (%/year), coefficient (95% CI), n=407			FEF ₂₅₋₇₅ (mL/min/year), coefficient (95% CI), n=407			PEF (mL/min/year), coefficient (95% CI), n=443		
	β*	95% CI	p Value	β*	95% CI	p Value	β*	95% CI	p Value	β*	95% CI	p Value	β*	95% CI	p Value
CO during RESPIRE†															
Unadjusted	-2.6	-7.3 to 1.9	0.26	-2.0	-7.0 to 3.0	0.43	-0.02	-0.2 to 0.2	0.82	-1.8	-16 to 12	0.80	-5.7	-21 to 9.5	0.46
Adjusted‡	-2.4	-7.0 to 2.3	0.32	-1.7	-6.8 to 3.5	0.52	-0.04	-0.2 to 0.1	0.68	-2.1	-15 to 11	0.76	-5.6	-21 to 9.4	0.46

*β-Coefficients represent the change in lung function growth for a 10% unit increase in CO.

†For Group 3 only, the study child's early life exposures were estimated based on CO measurements of their infant sibling, collected prior to stove installation during Childhood Exposure to Respirable Particulate Matter in the first 18 months of life.

‡Final model adjusted for age, gender, baseline height, annual change in height, maternal education and secondhand smoke.

PEF, peak expiratory flow; RESPIRE, Randomised Exposure Study of Pollution Indoors and Respiratory Effects.

exposures during the in utero period. While ~50% of the RESPIRE children were recruited during pregnancy, the mean in utero time with chimney stove use was only 40 days.⁹ Thus, the RESPIRE intervention may not have been optimally timed to have the greatest impact on growth of lung function.

Our data provide insight into patterns of biomass smoke exposure in the study population. Exposure levels during the first 18 months of life were lowest in Group 1, as expected, as these households received stoves prior to the initiation of measurements, while households in the other two groups did not. A decrease of 46% in personal exposure levels from baseline was seen in this group following stove installation. Comparisons of early childhood exposures between RESPIRE participants and new CRECER households should be interpreted with some caution; early life exposure estimates for new CRECER household participants were extrapolated from measurements on their younger siblings, as described above. We believe this assumption is valid because the three stove groups were similar with respect to baseline demographics and there is little socioeconomic mobility or change in cooking practices over time in this population.

Biomass smoke exposure levels during the CRECER follow-up period revealed a different pattern. Participants in both RESPIRE groups had lower exposure levels during CRECER than during the first 18 months of life. For the RESPIRE control group (Group 2), this decrease is likely due at least in part to stove installation, which occurred between the two measurement periods. Other factors likely contributed to the decline in both groups; as children grew older, they may have spent less time indoors exposed to higher levels of biomass smoke, or households may have changed their cooking practices to reduce exposure due to their participation in the RESPIRE trial (the Hawthorne effect). Compared with Groups 1 and 2, participants in Group 3 had a significantly higher average personal CO exposure during the CRECER period; this difference is likely attributable to continued cooking over open fires, as the reported exposure measurements for this group were taken prior to stove installation.

Another potential limitation is exposure misclassification based on our use of periodic personal CO measurements as a proxy for cumulative exposure. More detailed exposure data, including ambient measurements, more intensive personal measurements and questionnaire data, were collected on a subset of individuals as part of both RESPIRE and CRECER, but more complex analysis of these data goes beyond the scope of the present study.

Increased risk of asthma morbidity is a well-documented effect of outdoor air pollution,³³ but few studies have examined the effect of biomass smoke exposure on asthma risk, and their results have generally been mixed.^{6 34–37} Even fewer studies have looked specifically at this relationship in children. Though the present study was not designed to specifically examine childhood asthma, there was little clinically apparent airflow obstruction in the lung function testing that was performed. The hygiene hypothesis, which posits that increased early childhood exposure to diverse microbial and environmental antigens—often occurring in rural or lower income settings—decreases risk of atopic disease, offers one possible explanation.³⁸ Genetic factors may also be involved; a study of asthma in Hispanic and non-Hispanic children in the USA found that rates were significantly lower in children of Mexican heritage than in other groups.³⁹

We also sought to compare lung function measurements with predicted reference values based on age, height and gender. The GLFI equations²⁷ include children aged 3 and

older and were used here to calculate predicted lung function. However, these equations appear to underestimate lung function in this population; average per cent predicted FEV₁, FVC and FEF_{25–75} were all >100%. This is consistent with past studies that have found both the GLFI and National Health and Nutrition Examination Survey (NHANES) equations for Mexican-American children to underestimate lung function in cohorts of children in Mexico City.^{10 40} Differences in these studies were attributed to greater sitting height (and therefore lung volume) in Mexican children, as well as higher altitude; similar factors may be at work in this Guatemalan population. Based on this study's findings, the GLFI reference equations may not be optimal for clinical use in this population.

In conclusion, the findings presented here represent the first longitudinal analysis of the relationship between childhood biomass smoke exposure and lung function growth, using follow-up data from a randomised stove intervention featuring detailed exposure measurements. PEF growth was found to be lower in children whose families did not receive a chimney stove until 18 months of life, compared with children who received a stove at birth. Children with longer durations of heavier smoke exposure also had lower FEV₁ growth, though this effect did not reach a level of statistical significance. Further studies involving cleaner stoves or fuels or longer follow-up periods are needed to provide additional insight on this topic.

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