

## ORIGINAL ARTICLE

## Effects of Cooking with Liquefied Petroleum Gas or Biomass on Stunting in Infants

W. Checkley, L.M. Thompson, S.S. Sinharoy, S. Hossen, L.H. Moulton, H.H. Chang, L. Waller, K. Steenland, G. Rosa, A. Mukeshimana, F. Ndagijimana, J.P. McCracken, A. Díaz-Artiga, K. Balakrishnan, S.S. Garg, G. Thangavel, V. Aravindalochanan, S.M. Hartinger, M. Chiang, M.A. Kirby, A.T. Papageorgiou, U. Ramakrishnan, K.N. Williams, L. Nicolaou, M. Johnson, A. Pillarisetti, J. Rosenthal, L.J. Underhill, J. Wang, S. Jabbarzadeh, Y. Chen, V.G. Dávila-Román, L.P. Naeher, E.D. McCollum, J.L. Peel, and T.F. Clasen, for the HAPIN Investigators\*

## ABSTRACT

## BACKGROUND

Household air pollution is associated with stunted growth in infants. Whether the replacement of biomass fuel (e.g., wood, dung, or agricultural crop waste) with liquefied petroleum gas (LPG) for cooking can reduce the risk of stunting is unknown.

## METHODS

We conducted a randomized trial involving 3200 pregnant women 18 to 34 years of age in four low- and middle-income countries. Women at 9 to less than 20 weeks' gestation were randomly assigned to use a free LPG cookstove with continuous free fuel delivery for 18 months (intervention group) or to continue using a biomass cookstove (control group). The length of each infant was measured at 12 months of age, and personal exposures to fine particulate matter (particles with an aerodynamic diameter of  $\leq 2.5 \mu\text{m}$ ) were monitored starting at pregnancy and continuing until the infants were 1 year of age. The primary outcome for which data are presented in the current report — stunting (defined as a length-for-age z score that was more than two standard deviations below the median of a growth standard) at 12 months of age — was one of four primary outcomes of the trial. Intention-to-treat analyses were performed to estimate the relative risk of stunting.

## RESULTS

Adherence to the intervention was high, and the intervention resulted in lower prenatal and postnatal 24-hour personal exposures to fine particulate matter than the control (mean prenatal exposure,  $35.0 \mu\text{g}$  per cubic meter vs.  $103.3 \mu\text{g}$  per cubic meter; mean postnatal exposure,  $37.9 \mu\text{g}$  per cubic meter vs.  $109.2 \mu\text{g}$  per cubic meter). Among 3061 live births, 1171 (76.2%) of the 1536 infants born to women in the intervention group and 1186 (77.8%) of the 1525 infants born to women in the control group had a valid length measurement at 12 months of age. Stunting occurred in 321 of the 1171 infants included in the analysis (27.4%) of the infants born to women in the intervention group and in 299 of the 1186 infants included in the analysis (25.2%) of those born to women in the control group (relative risk, 1.10; 98.75% confidence interval, 0.94 to 1.29;  $P=0.12$ ).

## CONCLUSIONS

An intervention strategy starting in pregnancy and aimed at mitigating household air pollution by replacing biomass fuel with LPG for cooking did not reduce the risk of stunting in infants. (Funded by the National Institutes of Health and the Bill and Melinda Gates Foundation; HAPIN ClinicalTrials.gov number, NCT02944682.)

The authors' full names, academic degrees, and affiliations are listed in the Appendix. Dr. Checkley can be contacted at wcheckl1@jhmi.edu or at the Division of Pulmonary and Critical Care, Johns Hopkins University, 1830 E. Monument St., Ste. 555, Baltimore, MD 21287.

\*A complete list of the HAPIN Investigators is provided in the Supplementary Appendix, available at NEJM.org.

Drs. Checkley and Thompson contributed equally to this article.

This is the *New England Journal of Medicine* version of record, which includes all *Journal* editing and enhancements. The Author Accepted Manuscript, which is the author's version after external peer review and before publication in the *Journal*, is available at PubMed Central.

N Engl J Med 2024;390:44-54.

DOI: 10.1056/NEJMoa2302687

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**H**OUSEHOLD AIR POLLUTION IS A LEADING environmental risk factor in low- and middle-income countries, accounting for an estimated 2.3 million premature deaths and 91.5 million disability-adjusted life years lost in 2019.<sup>1</sup> Household air pollution results from the incomplete combustion of biomass fuels (e.g., wood, dung, or agricultural crop waste), which were used as energy sources for cooking by 36% of the worldwide population in 2020.<sup>2</sup>

Women and children younger than 5 years of age are at highest risk for exposure to indoor air pollution owing to their time spent in the kitchen. In 2019, an estimated 9% of childhood deaths worldwide were attributed to exposures to household air pollution.<sup>3</sup> Moreover, regular exposure to household air pollution is linked to poor health outcomes, including stunted growth in children.<sup>4-7</sup> Stunting in childhood is defined by the World Health Organization (WHO) as a length or height that is more than two standard deviations below the median of the Multicentre Growth Reference Study (MGRS) standard for a given age and sex.<sup>8</sup> Mechanisms linking exposure to household air pollution and childhood stunting are not well elucidated and may include prenatal and postnatal oxidative stress and inflammation and impaired immune function leading to a higher burden of clinical and subclinical infections and increased nutrient requirements.<sup>4</sup>

Despite a better understanding of the environmental and nutritional factors that contribute to faltering of linear growth in children, stunting remains a substantial public health problem in low- and middle-income countries.<sup>9-12</sup> In 2019, an estimated 144 million children younger than 5 years of age worldwide had stunted growth.<sup>13</sup> Stunting that reflects chronic undernutrition is not only associated with short-term medical complications and death from acute illnesses and impaired cognitive development; it may also contribute to lower educational attainment in childhood and adolescence, with subsequent reduced economic performance in adulthood.<sup>14-18</sup> Therefore, environmental interventions that reduce the burden of childhood stunting are likely to have a major effect on health in low- and middle-income countries.<sup>19</sup>

The Household Air Pollution Intervention Network (HAPIN) trial was designed to assess the effects of replacing biomass cookstoves with liquefied petroleum gas (LPG) cookstoves on four

primary outcomes, including stunting in infants. We reported previously that there was no significant effect of the intervention on infant birth weight.<sup>20</sup> Here, we report the effects of the intervention on stunting in infants.

## METHODS

### TRIAL SETTING AND DESIGN

We conducted a randomized, controlled trial to evaluate the effect of an LPG cookstove intervention on four primary outcomes: infant birth weight, stunting in infants, severe pneumonia in infants, and blood pressure in adult women 40 to 79 years of age.<sup>21</sup> A total of 3200 women across four low- and middle-income countries were randomly assigned in a 1:1 ratio to the intervention group or the control group; the groups are described below. Randomization was stratified according to geographic region, of which there were 10 in the trial: one district in Jalapa, Guatemala; two districts in Tamil Nadu, India; six provinces in Puno, Peru; and one district in Kayaanza, Rwanda.

We enrolled pregnant women 18 to 34 years of age with a singleton pregnancy at 9 to less than 20 weeks' gestation, as confirmed by ultrasonography; eligible women were identified at prenatal clinics.<sup>21</sup> Women randomly assigned to the intervention group received an LPG cookstove, along with continuous free fuel delivery and behavioral reinforcement for 18 months (starting during pregnancy and continuing until the infants were 1 year of age). Those assigned to the control group were asked to continue their usual cooking practices and received periodic compensation, which varied by country,<sup>22</sup> to offset the economic benefits of the intervention; at the end of the 18-month trial period, they were also offered either an LPG stove and a 1-month supply of fuel or another household item.<sup>22</sup> Total compensation over the course of the trial in the control households (\$141 [U.S. dollars] in Peru, \$268 in Guatemala, \$313 in Rwanda, and \$363 in India) was one half to one fifth the cost of the intervention in Peru, Guatemala, and Rwanda (\$473, \$1,414, and \$638, respectively) but was equal to the cost in India (\$363).

We used temperature sensors on the biomass-burning stoves in the intervention households to monitor adherence to LPG stove use.<sup>23</sup> We conducted additional home visits to deliver LPG fuel

tanks to the intervention households and provided behavioral reinforcement if the stove-use monitors indicated that the biomass stoves had been used.<sup>24-26</sup>

The trial was approved by the applicable ethics committees; details are provided in the Supplementary Appendix, available with the full text of this article at NEJM.org. The first and last two authors vouch for the accuracy and completeness of the data and for the fidelity of the trial to the protocol, available at NEJM.org.

#### ASSESSMENT OF PERSONAL EXPOSURES TO AIR POLLUTANTS

We measured 24-hour personal exposures to fine particulate matter (particles with an aerodynamic diameter of  $\leq 2.5 \mu\text{m}$  [ $\text{PM}_{2.5}$ ]) using the Enhanced Children's MicroPEM monitor (RTI International) and to carbon monoxide using the Lascar EL-USB-CO300 (Lascar Electronics). Measurements of these pollutants were obtained three times in the women during pregnancy — at 9 to 19 weeks' gestation (before randomization) and at 24 to 28 weeks' and 32 to 36 weeks' gestation (after randomization) — and three times in the infants, at 3, 6, and 12 months of age<sup>26</sup>; details are provided in the Supplementary Appendix. The women carried the monitors in a vest or apron. We assessed personal exposures indirectly in the infants using beacon emitters and receivers.<sup>27</sup> Black carbon concentrations were estimated from  $\text{PM}_{2.5}$  filter samples at baseline and during pregnancy but not when the Enhanced Children's MicroPEMs were used for indirect assessment in infants. Differences between the trial groups in prenatal and postnatal exposures have been reported previously.<sup>28,29</sup> Here, we report personal exposures to fine particulate matter, black carbon, and carbon monoxide for live births only.

#### OUTCOMES

The primary outcome for this report was stunting at 12 months of age (defined as a length-for-age z score that was more than two standard deviations below the median of the WHO MGRS standard for a given age and sex<sup>8</sup>). Secondary outcomes were the length-for-age z score at 12 months of age, severe stunting (defined as a length-for-age z score that was more than three standard deviations below the median of a growth standard) at 12 months of age, and stunting at 6 months of age.

Persons who were trained in anthropometry measured the recumbent length of the infants to the nearest 1 mm with the use of a seca 417 measuring board (Seca) at birth and at 3, 6, 9, and 12 months of age in accordance with standard methods.<sup>30</sup> They measured the infants in the homes where the infants resided and thus were aware of the trial-group assignments. We developed a longitudinal training and quality-control program to ensure high-quality anthropometric assessments (see the Supplementary Appendix), and we tracked precision, as described elsewhere.<sup>31</sup>

#### INTERRUPTIONS IN DATA COLLECTION OWING TO THE COVID-19 PANDEMIC

The coronavirus disease 2019 (Covid-19) pandemic led to some interruptions in in-home visit schedules between March 2020 and October 2020; however, LPG fuel delivery was considered to be essential and continued uninterrupted during the pandemic. As restrictions eased, we adapted to local regulations by increasing the number of staff to accommodate shorter workdays because of curfews or by shifting tasks when staff had to quarantine. We followed a safety protocol as described elsewhere.<sup>32</sup> We compared the percentages of women and infants with missed assessments before and after March 17, 2020.

#### STATISTICAL ANALYSIS

We estimated that 1440 participants per trial group would be needed to provide the trial with 80% power to detect a relative risk of stunting of 0.81 favoring the intervention, with a baseline incidence of stunting of 30% among participants in the control group, at an alpha level of 0.0125 (adjusted for the four primary outcomes to preserve the family-wise type I error rate at 0.05).<sup>21</sup> The statistical analysis plan was finalized before the unblinding of the trial-group assignments (see the Supplementary Appendix). Analyses that included unblinded data were performed independently by two statisticians.

The primary-outcome analysis was based on the intention-to-treat principle, with stunting as a dichotomous variable. We used a log-binomial regression model, with stunting at 12 months of age as the outcome and the trial-group assignment (with the control group as the reference) as the main covariate, adjusted for randomization strata. We present a 98.75% confidence interval

for the relative risk of the intervention on stunting to account for the four primary outcomes. For the secondary-outcome analyses, which were also based on the intention-to-treat principle, we used a linear regression model for the length-for-age z score at 12 months of age and either a log-binomial or Poisson regression model with a robust variance estimator (as an approximation if the log-binomial model did not converge) for severe stunting at 12 months of age and stunting at 6 months of age as a function of the trial-group assignment (with the control group as the reference) and randomization strata. We performed prespecified subgroup analyses of the primary outcome with no adjustment for multiplicity (see the Supplementary Appendix).

Participants with missing length-for-age z scores were excluded from the analyses. In sensitivity analyses, we evaluated whether differential missingness affected the results of the primary analysis by using a log-binomial model with adjustment for key potential confounders (see the Supplementary Appendix). We analyzed repeated measurements of stunting at birth and at 3, 6, 9, and 12 months of age using a Poisson regression model as a function of age, the trial-group assignment (with the control group as the reference), and randomization strata with infant-specific random intercepts and robust variance estimation at the level of each observation.<sup>33</sup> We performed the statistical analyses using R software, version 4.1.2 (R Project for Statistical Computing),<sup>34</sup> and Stata SE software, version 15.1 (StataCorp).

## RESULTS

### PARTICIPANT CHARACTERISTICS

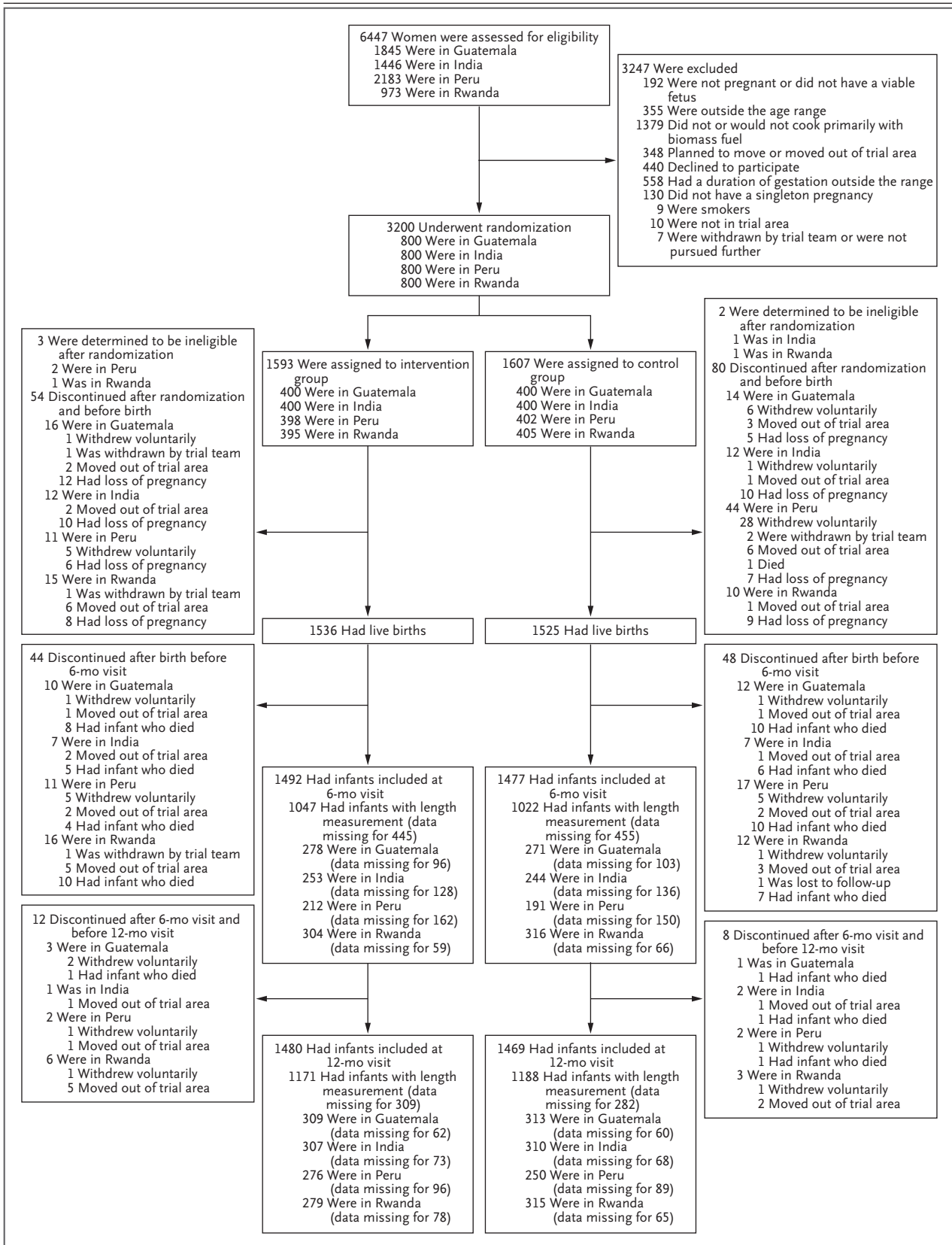
Between May 7, 2018, and February 29, 2020, a total of 3200 pregnant women underwent randomization: 1593 to the intervention group and 1607 to the control group. Five women were determined to be ineligible after randomization and were withdrawn from the trial. A total of 36 women (2.3%) in the intervention group and 31 women (1.9%) in the control group had a pregnancy loss. Among the 3200 women who had undergone randomization, 3061 (95.7%) had live births (1536 in the intervention group and 1525 in the control group). A total of 28 (1.8%) of the 1536 women in the intervention group and 36 (2.4%) of the 1525 women in the control group

had infants who died before 12 months of age (Fig. 1 and Table S2 in the Supplementary Appendix).

Length measurements at 12 months of age were obtained in 2359 infants (77.1%), with the last measurement obtained on September 21, 2021. There were no substantive differences in the percentages of infants who were missing a length measurement either before March 17, 2020 (intervention group, 9.9%; control group, 6.0%) or after March 17, 2020 (intervention group, 26.6%; control group, 25.4%) (Fig. S1). Length-for-age z scores of more than six standard deviations below the median were considered to be erroneous; there were seven such scores at 3 months of age, two at 6 months of age, three at 9 months of age, and two at 12 months of age. There were no length-for-age z scores greater than 6. Therefore, our analyses included valid z scores for 2357 infants (77.0%).

The characteristics of the infants born to women in the intervention group and the characteristics of those born to women in the control group were similar at baseline, as were the characteristics of the infants who were included in the analysis and the characteristics of those who were excluded from the analysis because of a missing or erroneous length-for-age z score (Table 1). Additional baseline information is provided in Table S3. Background information on the broader population affected by household air pollution and comments on the representativeness of the participants in the trial are provided in Table S1.

Adherence to the intervention was high; the median percentage of monitored days that intervention households used their biomass cookstove rather than the LPG cookstove during the trial period was 0.4% (interquartile range, 0 to 2.3). The intervention resulted in lower prenatal and postnatal exposures to air pollutants in the first year of life than the control (Table 2). Specifically, after randomization, the mean prenatal 24-hour personal exposure to fine particulate matter was 35.0  $\mu\text{g}$  per cubic meter in the intervention group and 103.3  $\mu\text{g}$  per cubic meter in the control group, and the mean postnatal exposures were 37.9  $\mu\text{g}$  per cubic meter and 109.2  $\mu\text{g}$  per cubic meter, respectively. The median and interquartile range values, as well as the geometric mean and geometric standard deviation values, for personal exposures to air pollutants are provided in Table S3.





**Figure 1 (facing page). Screening, Randomization, and Follow-up.**

Women could have had more than one reason for exclusion (i.e., categories are not mutually exclusive). Data are presented according to country in Table S2.

**EFFECTS OF THE INTERVENTION ON THE PRIMARY AND SECONDARY OUTCOMES**

At 12 months of age, 27.4% of the infants born to women in the intervention group and 25.2% of the infants born to women in the control group were stunted (relative risk, 1.10; 98.75% confidence interval [CI], 0.94 to 1.29;  $P=0.12$ ) (Table 3). The results were similar when the intention-to-treat analysis was adjusted for maternal height, maternal age, infant sex, socioeconomic status index, and food security (relative risk, 1.11; 98.75% CI, 0.95 to 1.31).

There was no appreciable difference in the mean length-for-age z scores at 12 months of age between the infants born to women in the intervention group and those born to women in the control group (mean difference,  $-0.03$ ; 95% CI,  $-0.11$  to  $0.05$ ) (Table 3). The percentage of infants with severe stunting at 12 months of age was 8.1% in the intervention group and 6.1% in the control group (relative risk, 1.36; 95% CI, 1.02 to 1.82) (Table 3). The percentage of infants with stunting at 6 months did not differ appreciably between the trial groups (relative risk, 1.01; 95% CI, 0.86 to 1.19) (Table 3). The sensitivity analysis, in which a model for repeated measurements of stunting at 3, 6, 9, and 12 months of age was used, included data from 3026 infants (98.9% of the live births); the results in the intervention group were similar to those in the control group (relative risk, 1.05; 95% CI, 0.94 to 1.18). In the subgroup analyses of the primary and secondary outcomes, no subgroup appeared to benefit from the intervention more than others (Fig. 2 and Figs. S2, S3, and S4).

Three infants (0.2%) born to women in the intervention group and 7 infants (0.5%) born to women in the control group had burns related to stoves. Analyses of participants with missing data are provided in the Supplementary Appendix.

**DISCUSSION**

In this multicountry, randomized, controlled trial involving women in households in which bio-

mass cookstoves were used at baseline, the provision of an LPG cookstove, continuous fuel delivery, and longitudinal behavioral messaging starting in pregnancy and continuing until infants were 1 year of age did not result in a lower risk of growth stunting at 12 months of age than households in which biomass cookstoves continued to be used. This lack of benefit was observed despite high levels of adherence to the LPG cookstove intervention and evidence that the intervention reduced prenatal and infant exposures to air pollutants. Secondary analyses that focused on stunting at other time points and on severe stunting also did not show a benefit of the intervention.

Associations between exposures to household air pollution and stunting have been reported in observational studies. For example, a review of two studies showed a 27% higher risk of stunting among children younger than 5 years of age who were exposed to household air pollution than among those who were not exposed.<sup>7</sup> A meta-analysis of 11 studies showed a 19% higher risk of stunting among children younger than 5 years of age who were exposed to household air pollution than among those who were not exposed.<sup>37</sup> In contrast, the results of the current report and the results of the Ghana Randomized Air Pollution and Health Study (in which LPG stoves and improved biomass stoves were compared with open-fire stoves)<sup>38</sup> did not support reductions in childhood stunting despite evidence of reduced household air pollution. Our recently reported analysis of the intervention on birth weight,<sup>20</sup> as well as our analysis of the intervention on severe infant pneumonia (reported in another article in this issue of the *Journal*),<sup>39</sup> in the HAPIN trial also failed to show a protective effect.

We propose several possible explanations for the lack of an observed effect of the intervention on stunting. First, our intervention may have needed to begin earlier during pregnancy or before conception in order to be effective. Second, our intervention, which used LPG, may not have been clean enough. Despite substantial reductions in personal exposures to fine particulate matter in the intervention group, the measured exposures were still higher than the value recommended by the WHO annual guidelines ( $5 \mu\text{g}$  per cubic meter).<sup>40</sup> Other pollutants resulting from the combustion of LPG, such as nitrogen dioxide, may also be present when unvented stoves are used.

**Table 1. Baseline Characteristics of the Infants Who Were Included in or Excluded from the Primary-Outcome Analysis.\***

Characteristic	Infants Included in Analysis		Infants Excluded from Analysis	
	Intervention (N=1171)	Control (N=1186)	Intervention (N=365)	Control (N=339)
Demographic data				
Maternal age — yr	25.4±4.4	25.5±4.5	25.2±4.4	25.3±4.7
Maternal height — cm	152.2±6.4	152.3±5.9	152.5±5.7	151.5±6.6
Male sex — no. (%)	608 (51.9)	605 (51.0)	192 (52.6)	182 (53.7)
Household socioeconomic status indicators				
Bank account — no. (%)	508 (43.4)	466 (39.3)	169 (46.3)	141 (41.6)
Television — no. (%)	586 (50.0)	582 (49.1)	167 (45.8)	157 (46.3)
Radio — no. (%)	528 (45.1)	491 (41.4)	183 (50.1)	179 (52.8)
Cellular telephone — no. (%)	1017 (86.8)	1016 (85.7)	325 (89.0)	303 (89.4)
Maternal education — yr	8.2±3.8	7.9±3.6	8.3±3.7	8.3±3.5
No. of persons living in the house	4.3±2.0	4.2±2.0	4.2±2.1	4.4±2.0
Socioeconomic status index†	0.1±1.0	−0.1±1.1	0.0±1.0	−0.1±1.0
Pregnancy factors				
Gestational age — wk	15.4±3.1	15.1±3.2	15.9±3.1	15.8±3.0
Nulliparous — no. (%)	470 (40.1)	421 (35.5)	147 (40.3)	129 (38.1)
Hypertension during pregnancy — no. (%)	22 (1.9)	24 (2.0)	3 (0.8)	5 (1.5)
Preterm birth — no. (%)	60 (5.1)	58 (4.9)	30 (8.2)	25 (7.4)
Minimum dietary diversity score — no. (%)‡				
<4, Low diversity	653 (55.8)	681 (57.4)	200 (54.8)	190 (56.0)
4 or 5, Medium diversity	364 (31.1)	393 (33.1)	119 (32.6)	108 (31.9)
>5, High diversity	154 (13.2)	111 (9.4)	46 (12.6)	41 (12.1)
Household food insecurity score — no. (%)§				
0, Food secure	697 (59.5)	662 (55.8)	207 (56.7)	158 (46.6)
1–3, Mild insecurity	309 (26.4)	313 (26.4)	94 (25.8)	111 (32.7)
4–8, Moderate or severe insecurity	147 (12.6)	193 (16.3)	61 (16.7)	66 (19.5)
Smoking in the household — no. (%)	115 (9.8)	138 (11.6)	31 (8.5)	36 (10.6)
Exclusive breast-feeding through 6 mo of age — no. (%)	558 (47.7)	602 (50.8)	144 (39.5)	145 (42.8)

\* Plus-minus values are means ±SD. This table shows the baseline characteristics of infants born to women in the intervention or control group according to whether the infants were included in or excluded from the analysis of the primary outcome, stunting at 12 months of age. Infants were excluded from the primary-outcome analysis if their length-for-age z scores were either missing or considered to be erroneous. In total, 2357 infants were included in the analysis, and 704 were excluded from the analysis.

† Scores range from −0.22 to 0.21, with higher scores indicating a higher socioeconomic status.

‡ Minimum dietary diversity during the previous 30 days was assessed with the use of an adapted version of the Food and Agriculture Organization Minimum Dietary Diversity for Women indicator.<sup>35</sup>

§ Household food insecurity during the previous 30 days was assessed with the use of the Food and Agriculture Organization Food Insecurity Experience Scale.<sup>36</sup>

**Table 2. Personal Exposures to Fine Particulate Matter, Black Carbon, and Carbon Monoxide.\***

Variable	Intervention		Control	
	value	no.	value	no.
Personal exposure to fine particulate matter — $\mu\text{g}/\text{m}^3$				
Prenatal maternal exposure at baseline†	119.5±133.6	1352	111.9±110.9	1352
Prenatal maternal exposure after randomization‡	35.0±37.2	1437	103.3±97.9	1409
Postnatal infant exposure§	37.9±97.4	848	109.2±122.7	933
Personal exposure to black carbon — $\mu\text{g}/\text{m}^3$				
Prenatal maternal exposure at baseline†	12.6±10.9	1223	12.4±9.2	1211
Prenatal maternal exposure after randomization‡	4.1±5.6	1413	11.2±9.3	1376
Personal exposure to carbon monoxide — ppm				
Prenatal maternal exposure at baseline†	2.7±4.5	1384	2.3±4.0	1375
Prenatal maternal exposure after randomization‡	0.7±1.2	1450	2.2±3.6	1430
Postnatal infant exposure§	0.9±2.0	965	2.6±4.1	916

\* Plus-minus values are means  $\pm$ SD. Personal exposures to fine particulate matter, black carbon, and carbon monoxide were measured over a period of 24 hours at baseline and after randomization. The abbreviation ppm denotes parts per million.

† These exposures were measured at enrollment in pregnant women before randomization.

‡ These values are the means of exposures measured during the first and second visits during pregnancy by means of a direct method (i.e., women wore the monitors).

§ These values are the means of exposures measured when infants were 3, 6, and 12 months of age by an indirect method (i.e., infants wore a beacon emitter).

**Table 3. Primary and Secondary Outcomes.\***

Outcome	Intervention	Control	Intervention Effect (98.75% CI or 95% CI)†
Primary outcome			
Stunting at 12 mo of age — no./total no. (%)	321/1171 (27.4)	299/1186 (25.2)	1.10 (0.94 to 1.29)
Secondary outcomes			
Length-for-age z score at 12 mo of age‡	-1.32±1.17	-1.30±1.10	-0.03 (-0.11 to 0.05)
Severe stunting at 12 mo of age — no./total no. (%)§	95/1171 (8.1)	72/1186 (6.1)	1.36 (1.02 to 1.82)
Stunting at 6 mo of age — no./total no. (%)	219/1046 (20.9)	211/1021 (20.7)	1.01 (0.86 to 1.19)

\* Plus-minus values are means  $\pm$ SD.

† Relative risks are shown for the dichotomous outcomes, and mean differences are shown for the continuous outcomes. A 98.75% confidence interval was used for the primary outcome, and a 95% confidence interval was used for the secondary outcomes. The 95% confidence intervals for the secondary outcomes and other measurements were not adjusted for multiplicity and should not be used in place of hypothesis testing.

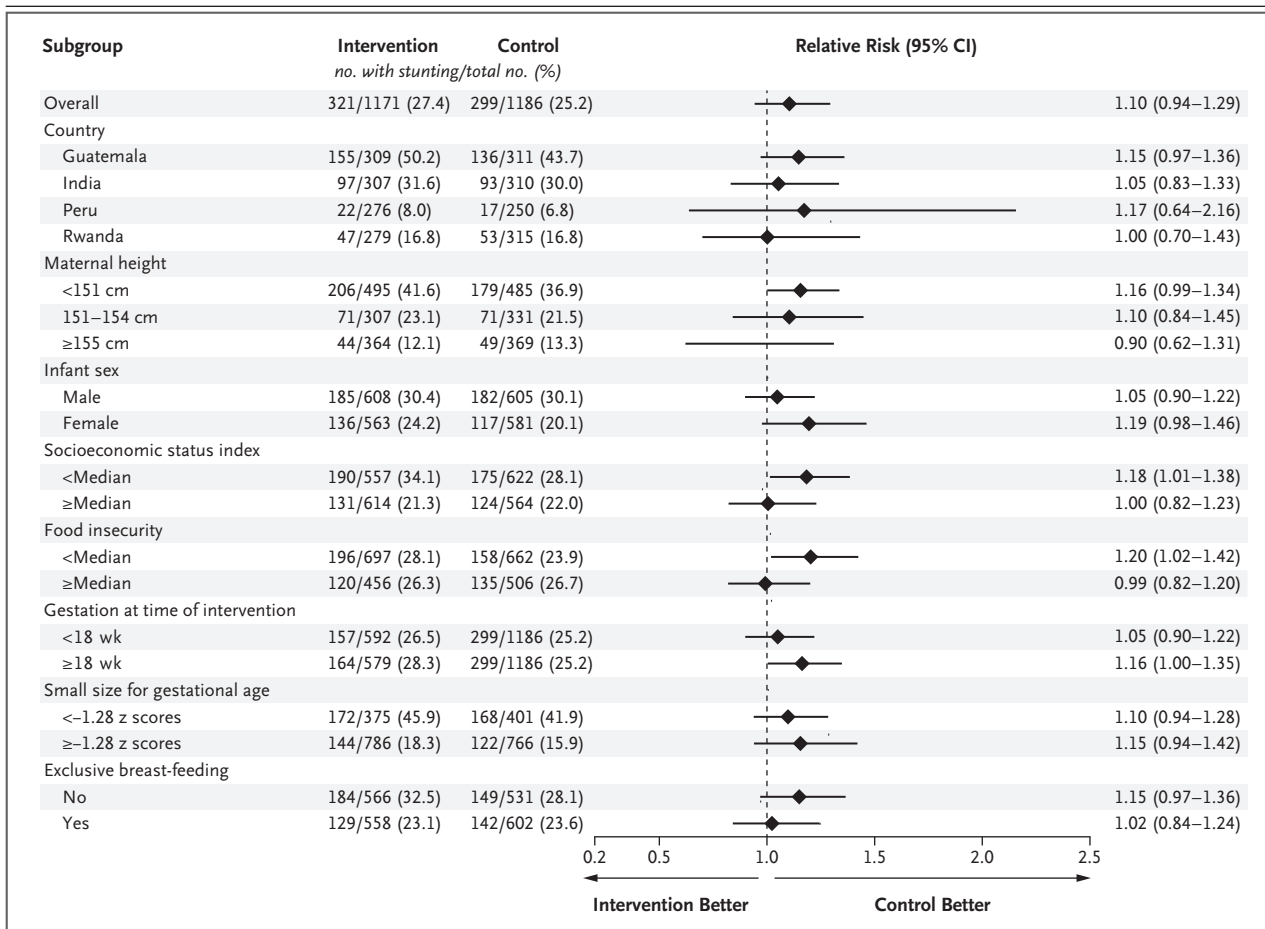
‡ This analysis included 1171 infants born to women in the intervention group and 1186 infants born to women in the control group.

§ Severe stunting was defined as a length-for-age z score that was more than three standard deviations below the median of the World Health Organization Multicentre Growth Reference Study standard for a given age and sex.

For example, in a previous randomized, controlled trial in which unvented LPG stoves were compared with biomass stoves in Peru, kitchen concentrations of nitrogen dioxide, as well as personal exposures to nitrogen dioxide, were found to be higher on average than those recommended by

the WHO 2021 annual air quality guidelines, although the values were lower among participants in the intervention group than among those in the control group, in which biomass stoves were used.<sup>40,41</sup> In future studies, evaluation of LPG stoves with ventilation hoods should be consid-





**Figure 2. Subgroup Analyses of the Effects of the Intervention on the Risk of Stunting at 12 Months of Age.**

Shown is the analysis of the effects of the intervention on the risk of stunting at 12 months of age in the overall sample and in prespecified subgroups. Household food insecurity during the previous 30 days was assessed with the use of the Food and Agriculture Organization Food Insecurity Experience Scale.<sup>36</sup> Gestation at the time of intervention refers to the time at which the women in the intervention group received an LPG cookstove. Exclusive breast-feeding refers to the first 6 months of life. We defined stunting as a length-for-age z score that was more than two standard deviations below the median of the World Health Organization Multicentre Growth Reference Study standard for a given age and sex. We estimated the relative risk using a log-binomial regression model for stunting at 12 months of age as a function of the trial-group assignment and randomization strata. The number of stunted infants with length measurements and the total number of infants with length measurements who were born to women in each trial group are presented. A 98.75% confidence interval was used for the total sample included in the analysis (primary outcome), and 95% confidence intervals were used for each subgroup. The 95% confidence intervals for the subgroup analyses were not adjusted for multiplicity and should not be used in place of hypothesis testing.

ered as a strategy to reduce exposures to pollutants still present in LPG stove emissions.

Another possible explanation for the lack of an observed effect on stunting is related to the fact that child growth is a complex and multifactorial process. Household air pollution may have only minor effects on stunting as compared with other factors such as nutritional status. It is possible that household air pollution is not causally related to stunting but rather is associated with

low socioeconomic status, poor nutrition and sanitation, coexisting illnesses, and other effects of poverty that themselves lead to stunting.

Although adherence to the intervention was extremely high across four low- and middle-income countries, and personal exposures to fine particulate matter were lowered to levels near or below the WHO Annual Interim Target 1 recommendation of 35  $\mu\text{g}$  per cubic meter<sup>42</sup> among infants born to women in the intervention group,

our trial had limitations. First, we were unable to measure linear growth in approximately 20% of the infants because of challenges during the Covid-19 pandemic. However, a sensitivity analysis, in which a model for repeated measurements of stunting between birth and 12 months of age was used, also did not show a benefit of the intervention. Second, we were unable to measure direct personal exposures to household air pollutants in the infants and thus used indirect methods instead. As a result, our estimates of exposure reduction in the infants may not be entirely accurate; however, our formative research indicated a high degree of agreement between direct and indirect measures.<sup>27</sup>

Whereas LPG has been considered to be a near-term solution for energy needs in low- and middle-income countries, an LPG cookstove interven-

tion starting in pregnancy and continuing until infants were 1 year of age did not reduce stunting at 1 year despite high adherence and large reductions in household air pollution. These findings do not support the use of unventilated LPG cookstoves to achieve reductions in childhood stunting.

The views expressed here are those of the authors and do not necessarily represent the official position of the National Institutes of Health or the Department of Health and Human Services.

Supported by the National Institutes of Health (cooperative agreement 1UM1HL134590) in collaboration with the Bill and Melinda Gates Foundation (OPP1131279).

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

A data sharing statement provided by the authors is available with the full text of this article at NEJM.org.

We thank Drs. Patrick Breyse, Donna Spiegelman, and Joel Kaufman (the members of the advisory committee) for their valuable insight and guidance throughout the implementation of the trial and the research staff and trial participants for their dedication to and participation in this trial.

## APPENDIX

The authors' full names and academic degrees are as follows: William Checkley, M.D., Ph.D., Lisa M. Thompson, R.N., Ph.D., Sheela S. Sinharoy, Ph.D., Shakir Hossen, M.B., B.S., M.S.P.H., Lawrence H. Moulton, Ph.D., Howard H. Chang, Ph.D., Lance Waller, Ph.D., Kyle Steenland, Ph.D., Ghislaine Rosa, Ph.D., Alexie Mukeshimana, Adv.Dip., Florian Ndagijimana, B.Sc., M.P.H., John P. McCracken, Sc.D., Anaité Díaz-Artiga, M.P.H., Kalpana Balakrishnan, Ph.D., Sarada S. Garg, D.N.B., Gurusamy Thangavel, M.Sc., Vigneswari Aravindalochanan, Ph.D., Stella M. Hartinger, Ph.D., Marilú Chiang, M.D., M.P.H., Miles A. Kirby, Ph.D., Aris T. Papageorgiou, M.D., Usha Ramakrishnan, Ph.D., Kendra N. Williams, Ph.D., Laura Nicolaou, Ph.D., Michael Johnson, Ph.D., Ajay Pillariseti, Ph.D., Joshua Rosenthal, Ph.D., Lindsay J. Underhill, Ph.D., Jiantong Wang, M.S., Shirin Jabbarzadeh, M.D., M.P.H., Yunyun Chen, M.S.P.H., Victor G. Dávila-Román, M.D., Luke P. Naeher, Ph.D., Eric D. McCollum, M.D., M.P.H., Jennifer L. Peel, Ph.D., and Thomas F. Clasen, J.D., Ph.D.

The authors' affiliations are as follows: the Division of Pulmonary and Critical Care (W.C., S.H., K.N.W., L.N.), the Johns Hopkins Center for Global Non-Communicable Disease Research and Training (W.C., S.H., K.N.W., L.N., E.D.M.), the Eudowood Division of Pediatric Respiratory Sciences, School of Medicine (E.D.M.), and the Program in Global Disease Epidemiology and Control, Department of International Health, Bloomberg School of Public Health (W.C., L.H.M., E.D.M.), Johns Hopkins University, Baltimore, and Fogarty International Center, National Institutes of Health, Bethesda (J.R.) — both in Maryland; Nell Hodgson Woodruff School of Nursing (L.M.T.) and the Hubert Department of Global Health (S.S.S., U.R.), the Gangarosa Department of Environmental Health (K.S., T.F.C.), and the Department of Biostatistics and Bioinformatics (H.H.C., L.W., J.W., S.J., Y.C.), Rollins School of Public Health, Emory University, Atlanta, and the Departments of Epidemiology and Biostatistics (J.P.M.) and Environmental Health Science (L.P.N.), College of Public Health, University of Georgia, Athens — both in Georgia; the Faculty of Infectious and Tropical Diseases, London School of Hygiene and Tropical Medicine, London (G.R.), and Nuffield Department of Women's and Reproductive Health, University of Oxford, Oxford (A.T.P.) — both in the United Kingdom; Eagle Research Center, Kigali, Rwanda (A.M., F.N.); the Center for Health Studies, Universidad del Valle de Guatemala, Guatemala City, Guatemala (J.P.M., A.D.-A.); the Indian Council of Medical Research Center for Advanced Research on Air Quality, Climate, and Health, Department of Environmental Health Engineering, Sri Ramachandra Institute of Higher Education and Research, Chennai, India (K.B., S.S.G., G.T., V.A.); the Latin American Center of Excellence in Climate Change and Health, Universidad Peruana Cayetano Heredia (S.M.H.), and the Biomedical Research Unit, Asociación Benéfica Prisma (M.C.) — both in Lima, Peru; the Department of Global Health and Population, Harvard T.H. Chan School of Public Health, Boston (M.A.K.); Berkeley Air Monitoring Group (M.J.) and the Division of Environmental Health Sciences, University of California at Berkeley (A.P.) — both in Berkeley; the Cardiovascular Imaging and Clinical Research Core Laboratory, Department of Medicine, Washington University in St. Louis, St. Louis (L.J.U., V.G.D.-R.); and the Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins (J.L.P.).

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