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Spirometric Profile of Rural Women Chronically Exposed to Household Biomass Fuel Smoke: A Matched Case-Control Study from Western Kenya

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ABS TRAC T

Background*:** Household air pollution arising from the combustion of solid biomass fuel remains a dominant environmental exposure for rural women in sub-Saharan Africa, yet objective lung function data from Kenyan community settings remain scarce. The present study was designed to compare spirometric indices between chronically biomass-exposed rural women and women using clean cooking fuel, and to examine the exposure-response relationship between cumulative smoke exposure and ventilatory impairment. ***Methods: A matched case-control study was conducted over eighteen months in a rural sub-county of western Kenya. One hundred and fifty never-smoking women aged 20 to 65 years who had cooked exclusively with wood, crop residue or animal dung for at least five years were enrolled as cases, and 150 age-matched women using liquefied petroleum gas were enrolled as controls. A cumulative biomass exposure index, expressed in hour-years, was computed for every participant. Post-bronchodilator spirometry was performed in accordance with the 2019 American Thoracic Society and European Respiratory Society technical standards and interpreted using the Global Lung Function Initiative 2012 reference equations. Comparisons employed the independent samples t test and the chi-square test, and determinants of airflow obstruction were examined by multivariable logistic regression. ***Results*:** Cases recorded a substantially higher cumulative exposure index than controls (118.6 plus or minus 52.4 versus 59.7 plus or minus 28.3 hour-years, p less than 0.001). Mean forced expiratory volume in one second as a percentage of predicted was lower among cases (79.3 plus or minus 13.6 versus 90.8 plus or minus 12.1, p less than 0.001), as was the FEV1/FVC ratio (75.4 plus or minus 9.2 versus 80.9 plus or minus 6.4 per cent, p less than 0.001). Airflow obstruction was documented in 26.7 per cent of cases and 10.0 per cent of controls (odds ratio 3.27, 95 per cent confidence interval 1.72 to 6.24, p less than 0.001). The exposure index correlated inversely with FEV1 per cent predicted (r equals minus 0.412, p less than 0.001). Biomass exposure independently predicted obstruction (adjusted odds ratio 2.98, 95 per cent confidence interval 1.48 to 6.00, p equals 0.002). ***Conclusion*:** Chronic household biomass smoke exposure was associated with significant and dose-related ventilatory impairment among never-smoking rural Kenyan women, supporting the prioritisation of clean cooking transitions and community spirometry screening.

Keywords: *Biomass Fuel, Household Air Pollution, Spirometry, Airflow Obstruction, Rural Women, Kenya.*

INTRODUCTION

Chronic respiratory disease has emerged as one of the most consequential and least addressed components of the global non-communicable disease burden. Chronic obstructive pulmonary disease alone was estimated to affect approximately 392 million people aged 30 to 79 years worldwide in 2019, with close to nine-tenths of the affected population residing in low-income and middle-income countries, where diagnostic spirometry is least available and case detection is weakest [1]. The conventional attribution of chronic airflow limitation to tobacco smoking accounts poorly for this distribution, since a substantial proportion of affected individuals in these settings, and the overwhelming majority of affected women, have never smoked. Attention has therefore shifted towards the environmental exposures that dominate domestic life in resource-limited communities, of which household air pollution generated by the incomplete combustion of solid biomass fuel is the most pervasive.

Approximately one-third of the world population continues to cook and heat with wood, charcoal, crop residue, animal dung or coal, generally in unvented or poorly ventilated kitchens using open three-stone fires or rudimentary stoves. The resulting emissions contain respirable particulate matter, carbon monoxide, nitrogen oxides, polycyclic aromatic hydrocarbons and free radicals at concentrations that routinely exceed World Health Organization air quality guidance by one to two orders of magnitude. The exposure is profoundly gendered. In most rural African households, adult women assume near-exclusive responsibility for cooking and fuel collection, frequently accumulating four to six hours of daily proximity to the combustion source across three or four decades of adult life, often with an infant carried on the back. The cumulative inhaled dose sustained by such women is therefore comparable in magnitude, although not in composition, to that of a moderately heavy cigarette smoker.

The epidemiological association between this exposure and chronic airway disease has been examined repeatedly. A systematic review and meta-analysis of solid fuel exposure reported an approximate doubling of the risk of chronic obstructive pulmonary disease and chronic bronchitis among exposed populations [2]. A parallel synthesis restricted to rural women and children estimated pooled odds ratios of 2.40 for chronic obstructive pulmonary disease and 2.52 for chronic bronchitis among biomass-exposed women [3]. A more recent meta-analysis confined to women reported a significant overall association with physician-diagnosed disease, although the pooled estimate derived from spirometry-defined disease alone did not reach statistical significance, an inconsistency the authors attributed to heterogeneity in exposure assessment and in the spirometric criteria applied across studies [4].

Direct comparative evidence has come principally from Latin America and Asia. A landmark case-control study among Mexican women reported that prolonged wood smoke exposure carried a risk of chronic airway obstruction comparable to that conferred by tobacco, and a subsequent cross-sectional survey in the same population demonstrated an exposure-dependent decline in ventilatory function together with an excess of chronic respiratory symptoms [5, 6]. Countervailing evidence exists. An analysis of more than eighteen thousand participants from the multinational Burden of Obstructive Lung Disease study failed to demonstrate a consistent association between self-reported solid fuel use and post-bronchodilator airflow obstruction, and reported that spirometric restriction rather than obstruction was the more frequently observed abnormality [7]. This discordance, which turns largely upon whether exposure is captured as a crude binary fuel category or as a quantified cumulative dose, constitutes the central unresolved question in the field and provides the principal justification for further work employing objective exposure metrics and standardised post-bronchodilator spirometry.

The evidence base from sub-Saharan Africa, and from Kenya in particular, remains thin. Environmental sampling in rural Kenyan households has confirmed that carbon monoxide and total suspended particulate concentrations regularly exceed international safety thresholds during cooking, and screening spirometry performed alongside that sampling suggested impaired lung function in a large majority of the inhabitants examined, although the instrumentation used was acknowledged to be unsuitable for diagnostic classification [8]. Community surveys in western Kenya have similarly documented that the great majority of women and children in wood-burning and kerosene-burning households report recurrent cough and other respiratory symptoms [9]. What these studies have not supplied is diagnostic-grade, post-bronchodilator, quality-assured spirometry in an age-matched comparative design that distinguishes obstructive from restrictive patterns and relates the observed impairment to a quantified exposure burden.

Accurate interpretation of such data requires appropriate reference standards. The Global Lung Function Initiative 2012 equations provide continuous, multi-ethnic prediction equations and lower limits of normal across the age spectrum, and permit the expression of results as z scores, which avoids the systematic misclassification that arises when fixed ratios or reference values derived from populations of European ancestry are applied to African populations [10]. Against this background, the present study was undertaken to characterise the spirometric profile of chronically biomass-exposed rural Kenyan women relative to age-matched clean fuel users, to determine whether the observed impairment followed an exposure-response gradient, and to identify the household and personal determinants independently associated with airflow obstruction in this population.

AIMS AND OBJECTIVES

The aim of the study was to characterise pulmonary function, as measured by standardised post-bronchodilator spirometry, among never-smoking rural Kenyan women chronically exposed to household biomass fuel smoke, and to compare this profile with that of age-matched rural women who cooked with clean fuel.

The primary objective was to compare mean spirometric indices, comprising forced vital capacity, forced expiratory volume in one second, the ratio of forced expiratory volume in one second to forced vital capacity, peak expiratory flow rate and forced expiratory flow between 25 and 75 per cent of vital capacity, between biomass-exposed cases and clean fuel controls, and to determine the proportion in each group meeting spirometric criteria for airflow obstruction.

The secondary objectives were to quantify cumulative biomass smoke exposure using an hour-year exposure index and to examine its correlation with individual spirometric indices; to determine the prevalence and pattern of chronic respiratory symptoms in the two groups; to classify the ventilatory defects observed as obstructive, restrictive or mixed and to grade the severity of airflow obstruction; and to identify the personal, household and exposure-related factors independently associated with airflow obstruction after adjustment for potential confounders.

MATERIALS AND METHODS

Study Design and Setting

A hospital-linked, community-based, matched case-control study was carried out over a period of eighteen months, from January 2024 to June 2025, in a predominantly agrarian rural sub-county of western Kenya served by Jaramogi Oginga Odinga University of Science and Technology. Fieldwork was conducted through the outreach network of the Department of Community Health, with participants recruited from ten purposively selected villages in which household energy use had been documented as heterogeneous, thereby permitting the identification of both biomass-using and clean-fuel-using households within the same socio-cultural and geographical setting.

Ethical Considerations

The study protocol was reviewed and approved by the Institutional Ethics and Research Committee of Jaramogi Oginga Odinga University of Science and Technology (JOOUST) under Approval No. IREC/JOOUST/2024/047, and research authorisation was obtained from the National Commission for Science, Technology and Innovation (NACOSTI), Kenya, under Licence No. NACOSTI/P/24/1847. Written informed consent was obtained from every participant in English or Kiswahili, or in the participant's local language through a trained interpreter, after the purpose, procedures, potential benefits and risks, confidentiality measures, and voluntary nature of participation had been explained. Participants found to have significant ventilatory impairment were counselled and referred to the outpatient chest clinic of the study institution for further evaluation and management at no cost. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and applicable national research regulations.

Study Population and Case Definition

Cases were defined as women aged 20 to 65 years who had cooked exclusively or predominantly with solid biomass fuel, comprising firewood, crop residue or animal dung, for a minimum of five consecutive years, with an average daily cooking exposure of at least two hours. Controls were defined as women in the same age range, resident in the same villages, who had used liquefied petroleum gas as the principal cooking fuel for at least five years and who reported no more than incidental biomass use. Controls were individually matched to cases in a one-to-one ratio by age within five-year strata.

Inclusion Criteria

Women were eligible for inclusion if they were aged between 20 and 65 years, had been resident in the study area for a minimum of five years, were lifelong non-smokers of tobacco in any form, were able to perform acceptable and repeatable spirometric manoeuvres, and provided written informed consent.

Exclusion Criteria

Women were excluded if they reported any current or previous use of tobacco or of shisha; if they had a physician-documented history of asthma diagnosed in childhood, pulmonary tuberculosis, bronchiectasis, interstitial lung disease, thoracic surgery, kyphoscoliosis or other chest wall deformity; if they were pregnant at the time of assessment; if they had experienced an acute respiratory infection within the preceding four weeks; if they had significant cardiac failure, uncontrolled hypertension, recent myocardial infarction, recent ocular or abdominal surgery, or any other recognised contraindication to forced expiratory manoeuvres; if they had an occupational history involving dust, fume or fibre exposure; or if they were unable to produce at least three acceptable and two repeatable spirometric curves.

Sample Size Estimation

The sample size was computed for the comparison of two independent proportions. On the basis of previously published community data, the prevalence of spirometric airflow obstruction among biomass-exposed rural women was anticipated to be approximately 25 per cent, against an anticipated 10 per cent among clean fuel users. Assuming a two-sided alpha error of 5 per cent, a power of 80 per cent and a case to control ratio of one to one, the minimum requirement was 121 women per group. This figure was inflated to 150 per group to accommodate an anticipated 15 to 20 per cent loss from technically unacceptable spirometry and incomplete exposure data, yielding a total planned sample of 300 women. Consecutive eligible women were enrolled until the target for each group was attained.

Data Collection and Exposure Assessment

A pre-tested, interviewer-administered

structured proforma was used to record socio-demographic particulars, obstetric history, education, occupation and household characteristics. Respiratory symptoms were elicited using an adapted version of a standardised respiratory questionnaire covering chronic cough, chronic phlegm, wheeze, chest tightness and exertional breathlessness, the last being graded on the modified Medical Research Council dyspnoea scale. Household characteristics recorded included the type of kitchen, whether cooking was performed indoors within the living structure or in a separate detached kitchen, the presence or absence of a window, chimney or other deliberate ventilation aperture, the type of stove and the predominant fuel used.

Cumulative biomass smoke exposure was quantified as an exposure index expressed in hour-years, calculated as the product of the average number of hours spent cooking each day and the total number of years of cooking with the fuel concerned. Where a participant had used more than one fuel over her lifetime, the contributions of each period were computed separately and summed. Anthropometric measurements were obtained with the participant in light clothing and without footwear, standing height being measured to the nearest 0.5 centimetre using a stadiometer and weight to the nearest 0.1 kilogram using a calibrated digital scale, from which body mass index was derived.

Spirometry

Spirometry was performed using a calibrated portable turbine spirometer, with volume calibration verified daily against a three-litre syringe and ambient temperature, barometric pressure and humidity recorded at each session. All testing was undertaken by a single operator trained and certified in spirometry, in accordance with the 2019 American Thoracic Society and European Respiratory Society technical standards. Testing was performed in the seated position with a nose clip applied, at least two hours after a meal, and not less than four weeks after any acute respiratory illness. A minimum of three acceptable manoeuvres was obtained, with repeatability defined as a difference of no more than 150 millilitres between the two largest values of forced vital capacity and of forced expiratory volume in one second. A maximum of eight manoeuvres was permitted.

Baseline measurements were followed by the administration of 400 micrograms of inhaled salbutamol through a metered dose inhaler with a valved holding chamber, and spirometry was repeated after 15 minutes. All analyses were based on post-bronchodilator values. Recorded indices comprised forced vital capacity, forced expiratory volume in one second, the FEV1/FVC ratio, peak expiratory flow rate and forced expiratory flow between 25 and 75 per cent of forced vital capacity. Predicted values, lower limits of normal and z scores were derived using the Global Lung Function Initiative 2012 equations applied with the African ancestry module.

Definitions

Airflow obstruction was defined as a post-bronchodilator FEV1/FVC ratio below the lower limit of normal for age, height and sex. Spirometric restriction was defined as a forced vital capacity below the lower limit of normal in the presence of a preserved FEV1/FVC ratio. A mixed defect was recorded when both criteria were satisfied. The severity of airflow obstruction was graded according to the forced expiratory volume in one second expressed as a percentage of predicted, as mild at 80 per cent or above, moderate between 50 and 79 per cent, severe between 30 and 49 per cent and very severe below 30 per cent. Chronic cough and chronic phlegm were each defined as the symptom occurring on most days for a minimum of three consecutive months in each of two successive years.

Follow-up Protocol

Every participant was reviewed at three months and at six months after enrolment. At each visit the respiratory symptom questionnaire was re-administered and post-bronchodilator spirometry was repeated using the same instrument and the same operator. Participants with newly identified airflow obstruction were reviewed additionally at the chest clinic, where the diagnosis was confirmed and management initiated according to prevailing national guidance. Participants who could not attend a scheduled visit were traced through community health volunteers, and up to three contact attempts were made before a participant was recorded as lost to follow-up.

Statistical Analysis

Data were entered into a spreadsheet, checked for internal consistency and analysed using statistical software and version. Continuous variables were summarised as mean and standard deviation, and categorical variables as frequency and percentage. The normality of continuous variables was assessed using the Shapiro-Wilk test. Between-group comparisons of normally distributed continuous variables were performed using the independent samples t test, and the Mann-Whitney U test was applied where the distribution departed from normality. Categorical variables were compared using the Pearson chi-square test, with the Fisher exact test substituted where any expected cell frequency was below five. Unadjusted odds ratios with 95 per cent confidence intervals were computed for categorical outcomes. The relationship between the cumulative exposure index and continuous spirometric indices was examined using the Pearson correlation coefficient. Trend across exposure tertiles was tested using the chi-square test for trend and one-way analysis of variance as appropriate. Variables associated with airflow obstruction at a significance level below 0.10 on univariate analysis, together with variables of established biological relevance, were entered into a multivariable binary logistic regression model, and adjusted odds ratios with 95 per cent confidence intervals were derived. Model fit was assessed using the Hosmer-Lemeshow goodness-of-fit test. A two-tailed p value below 0.05 was considered statistically significant throughout.

RESULTS

A total of 364 women were screened for eligibility, of whom 48 were excluded on the basis of the predetermined exclusion criteria and 16 were excluded because they could not produce technically acceptable spirometric curves. The final analysis therefore comprised 300 women, consisting of 150 biomass-exposed cases and 150 age-matched clean fuel controls. Follow-up at six months was completed by 142 cases (94.7 per cent) and 145 controls (96.7 per cent).

The two groups were closely comparable with respect to the principal demographic and anthropometric variables, as presented in Table 1. The mean age was 42.6 plus or minus 10.8 years among cases and 41.9 plus or minus 11.2 years among controls (p equals 0.581), and mean standing height was 159.2 plus or minus 6.1 centimetres and 159.8 plus or minus 5.8 centimetres respectively (p equals 0.383). The mean body mass index was marginally lower among cases at 23.4 plus or minus 3.6 kilograms per square metre against 24.1 plus or minus 3.5 kilograms per square metre among controls, although the difference did not attain statistical significance (p equals 0.089). Educational attainment differed significantly, with 62.0 per cent of cases having received no more than primary schooling against 40.7 per cent of controls (p less than 0.001), and subsistence farming was the principal occupation of 74.0 per cent of cases as compared with 52.0 per cent of controls (p less than 0.001). Median parity was four in the case group and three in the control group.

Exposure characteristics differed markedly between the groups, as shown in Table 2. The mean duration of cooking was 24.3 plus or minus 9.6 years among cases and 22.8 plus or minus 9.1 years among controls (p equals 0.168), but the mean daily cooking duration was 4.8 plus or minus 1.2 hours among cases against 2.6 plus or minus 0.9 hours among controls (p less than 0.001). The resulting cumulative exposure index was 118.6 plus or minus 52.4 hour-years among cases and 59.7 plus or minus 28.3 hour-years among controls (p less than 0.001). Cooking was performed inside the main living structure by 58.7 per cent of cases against 24.0 per cent of controls (p less than 0.001), and a deliberate ventilation aperture was absent in the cooking area of 68.0 per cent of cases as compared with 21.3 per cent of controls (p less than 0.001). Firewood was the predominant fuel of 71.3 per cent of cases, with crop residue and animal dung accounting for 18.7 per cent and 10.0 per cent respectively, and 84.7 per cent of cases used an open three-stone fire rather than an improved cookstove.

Chronic respiratory symptoms were consistently more frequent among cases, as detailed in Table 3. Chronic cough was reported by 62 cases (41.3 per cent) and 24 controls (16.0 per cent), yielding an odds ratio of 3.70 with a 95 per cent confidence interval of 2.16 to 6.34 (p less than 0.001). Chronic phlegm was reported by 52 cases (34.7 per cent) and 19 controls (12.7 per cent), giving an odds ratio of 3.65 with a 95 per cent confidence interval of 2.04 to 6.53 (p less than 0.001). Wheeze was recorded in 42 cases (28.0 per cent) and 16 controls (10.7 per cent), corresponding to an odds ratio of 3.26 and a 95 per cent confidence interval of 1.74 to 6.09 (p less than 0.001). Exertional breathlessness of grade 2 or higher on the modified Medical Research Council scale was present in 37 cases (24.7 per cent) and 12 controls (8.0 per cent), with an odds ratio of 3.77 and a 95 per cent confidence interval of 1.89 to 7.53 (p less than 0.001). At least one chronic respiratory symptom was present in 85 cases (56.7 per cent) as against 38 controls (25.3 per cent), representing an odds ratio of 3.86 with a 95 per cent confidence interval of 2.36 to 6.31 (p less than 0.001).

Post-bronchodilator spirometric indices are summarised in Table 4. Mean forced vital capacity was 2.62 plus or minus 0.44 litres among cases and 2.89 plus or minus 0.46 litres among controls (p less than 0.001), corresponding to 84.6 plus or minus 11.8 per cent and 92.7 plus or minus 11.2 per cent of predicted respectively (p less than 0.001). Mean forced expiratory volume in one second was 1.98 plus or minus 0.42 litres among cases and 2.34 plus or minus 0.43 litres among controls (p less than 0.001), representing 79.3 plus or minus 13.6 per cent and 90.8 plus or minus 12.1 per cent of predicted respectively (p less than 0.001). The mean FEV1/FVC ratio was 75.4 plus or minus 9.2 per cent among cases and 80.9 plus or minus 6.4 per cent among controls (p less than 0.001). Mean peak expiratory flow rate was 4.32 plus or minus 1.06 litres per second among cases against 5.18 plus or minus 1.02 litres per second among controls (p less than 0.001), and mean forced expiratory flow between 25 and 75 per cent of vital capacity was 1.86 plus or minus 0.72 litres per second against 2.54 plus or minus 0.78 litres per second (p less than 0.001). Expressed as z scores, the mean value for forced expiratory volume in one second was minus 1.42 plus or minus 1.05 among cases and minus 0.61 plus or minus 0.92 among controls (p less than 0.001), and the corresponding values for the FEV1/FVC ratio were minus 1.08 plus or minus 1.12 and minus 0.43 plus or minus 0.86 (p less than 0.001).

The distribution of ventilatory patterns is presented in Table 5. Spirometry was normal in 84 cases (56.0 per cent) and 118 controls (78.7 per cent). An isolated obstructive defect was identified in 33 cases

(22.0 per cent) and 12 controls (8.0 per cent), a mixed defect in 7 cases (4.7 per cent) and 3 controls (2.0 per cent), and spirometric restriction in 26 cases (17.3 per cent) and 17 controls (11.3 per cent). Airflow obstruction of any type, defined by a post-bronchodilator FEV1/FVC ratio below the lower limit of normal, was therefore present in 40 cases (26.7 per cent) and 15 controls (10.0 per cent), yielding an unadjusted odds ratio of 3.27 with a 95 per cent confidence interval of 1.72 to 6.24 (p less than 0.001). The excess of spirometric restriction among cases did not reach statistical significance (p equals 0.141). Among the 40 obstructed cases, the defect was mild in 15 women (37.5 per cent), moderate in 18 (45.0 per cent), severe in 6 (15.0 per cent) and very severe in 1 (2.5 per cent), whereas among the 15 obstructed controls the defect was mild in 9 women (60.0 per cent), moderate in 5 (33.3 per cent) and severe in 1 (6.7 per cent).

A clear exposure-response gradient was demonstrable across tertiles of the cumulative exposure index, as set out in Table 6. Among the 101 women in the lowest tertile, corresponding to an exposure index below 75 hour-years, airflow obstruction was present in 7 women (6.9 per cent) and the mean forced expiratory volume in one second was 91.2 plus or minus 11.6 per cent of predicted. Among the 99 women in the middle tertile, spanning 75 to 140 hour-years, the corresponding values were 17 women (17.2 per cent) and 84.6 plus or minus 12.4 per cent of predicted, and among the 100 women in the highest tertile, exceeding 140 hour-years, they were 31 women (31.0 per cent) and 79.3 plus or minus 13.1 per cent of predicted. The chi-square test for trend across tertiles was significant at p less than 0.001, as was the analysis of variance for forced expiratory volume in one second per cent predicted (F equals 24.68, p less than 0.001). The cumulative exposure index correlated inversely with forced expiratory volume in one second per cent predicted (r equals minus 0.412, p less than 0.001), with forced vital capacity per cent predicted (r equals minus 0.284, p less than 0.001), with the FEV1/FVC ratio (r equals minus 0.338, p less than 0.001) and with forced expiratory flow between 25 and 75 per cent of vital capacity (r equals minus 0.376, p less than 0.001).

On multivariable binary logistic regression, presented in Table 6, biomass fuel exposure remained independently associated with airflow obstruction after adjustment for age, body mass index, kitchen ventilation, fuel subtype and passive smoke exposure, with an adjusted odds ratio of 2.98 and a 95 per cent confidence interval of 1.48 to 6.00 (p equals 0.002). Advancing age was independently associated with obstruction, with an adjusted odds ratio of 1.06 per year and a 95 per cent confidence interval of 1.03 to 1.10 (p less than 0.001), as was every additional ten hour-years of cumulative exposure, with an adjusted odds ratio of 1.09 and a 95 per cent confidence interval of 1.04 to 1.15 (p less than 0.001). The absence of a kitchen ventilation aperture retained independent significance, with an adjusted odds ratio of 2.11 and a 95 per cent confidence interval of 1.09 to 4.08 (p equals 0.026). A body mass index below 18.5 kilograms per square metre, the use of dung or crop residue in preference to firewood, and household exposure to environmental tobacco smoke were each associated with obstruction in the expected direction but did not attain statistical significance, with adjusted odds ratios of 1.94 (p equals 0.082), 1.72 (p equals 0.145) and 1.58 (p equals 0.221) respectively. The Hosmer-Lemeshow test indicated satisfactory model fit (chi-square equals 6.42, degrees of freedom equals 8, p equals 0.600), and the model correctly classified 79.3 per cent of observations.

At the six-month review, symptom reporting and spirometric indices remained stable in both groups, with no statistically significant within-group change in mean forced expiratory volume in one second per cent predicted among cases (79.3 plus or minus 13.6 at baseline against 78.9 plus or minus 13.9 at six months, p equals 0.804) or among controls (90.8 plus or minus 12.1 against 90.5 plus or minus 12.4, p equals 0.836), confirming the stability and reproducibility of the observed impairment.

Table 1: Baseline demographic and anthropometric characteristics of the study groups (N = 300)

Variable	Cases (n = 150)	Controls (n = 150)	p value
Age (years), mean +/- SD	42.6 +/- 10.8	41.9 +/- 11.2	0.581
Height (cm), mean +/- SD	159.2 +/- 6.1	159.8 +/- 5.8	0.383
Weight (kg), mean +/- SD	59.3 +/- 9.8	61.6 +/- 9.6	0.041
BMI (kg/m2), mean +/- SD	23.4 +/- 3.6	24.1 +/- 3.5	0.089
BMI < 18.5 kg/m2, n (%)	21 (14.0)	12 (8.0)	0.098
Parity, median (IQR)	4 (3-5)	3 (2-4)	0.003
Education up to primary, n (%)	93 (62.0)	61 (40.7)	< 0.001
Subsistence farming, n (%)	111 (74.0)	78 (52.0)	< 0.001
Married, n (%)	124 (82.7)	119 (79.3)	0.460
Passive tobacco smoke at home, n (%)	34 (22.7)	26 (17.3)	0.246

SD, standard deviation; IQR, interquartile range; BMI, body mass index. Independent samples t test for continuous variables, Mann-Whitney U test for parity and Pearson chi-square test for categorical variables.

Table 2: Household energy use and cumulative biomass smoke exposure characteristics

Exposure variable	Cases (n = 150)	Controls (n = 150)	p value
Total years of cooking, mean +/- SD	24.3 +/- 9.6	22.8 +/- 9.1	0.168
Daily cooking hours, mean +/- SD	4.8 +/- 1.2	2.6 +/- 0.9	< 0.001
Cumulative exposure index (hour-years)	118.6 +/- 52.4	59.7 +/- 28.3	< 0.001
Cooking inside living structure, n (%)	88 (58.7)	36 (24.0)	< 0.001
No ventilation aperture in kitchen, n (%)	102 (68.0)	32 (21.3)	< 0.001
Open three-stone fire, n (%)	127 (84.7)	0 (0.0)	< 0.001
Predominant fuel: firewood, n (%)	107 (71.3)	0 (0.0)	< 0.001
Predominant fuel: crop residue, n (%)	28 (18.7)	0 (0.0)	< 0.001
Predominant fuel: animal dung, n (%)	15 (10.0)	0 (0.0)	< 0.001
Kerosene lamp use at home, n (%)	71 (47.3)	29 (19.3)	< 0.001

SD, standard deviation. The cumulative exposure index was computed as average daily cooking hours multiplied by total years of cooking with the fuel concerned.

Table 3: Prevalence of chronic respiratory symptoms in cases and controls

Symptom	Cases n (%)	Controls n (%)	Odds ratio (95% CI)	p value
Chronic cough	62 (41.3)	24 (16.0)	3.70 (2.16-6.34)	< 0.001
Chronic phlegm	52 (34.7)	19 (12.7)	3.65 (2.04-6.53)	< 0.001
Wheeze	42 (28.0)	16 (10.7)	3.26 (1.74-6.09)	< 0.001
Chest tightness	38 (25.3)	18 (12.0)	2.49 (1.35-4.58)	0.003
Breathlessness (mMRC >= 2)	37 (24.7)	12 (8.0)	3.77 (1.89-7.53)	< 0.001
Any chronic symptom	85 (56.7)	38 (25.3)	3.86 (2.36-6.31)	< 0.001

CI, confidence interval; mMRC, modified Medical Research Council dyspnoea scale. Chronic cough and chronic phlegm were defined as symptoms present on most days for at least three months in each of two consecutive years.

Table 4: Post-bronchodilator spirometric indices in cases and controls

Spirometric index	Cases (n = 150)	Controls (n = 150)	Mean difference	p value
FVC (L)	2.62 +/- 0.44	2.89 +/- 0.46	-0.27	< 0.001
FVC (% predicted)	84.6 +/- 11.8	92.7 +/- 11.2	-8.1	< 0.001
FEV1 (L)	1.98 +/- 0.42	2.34 +/- 0.43	-0.36	< 0.001
FEV1 (% predicted)	79.3 +/- 13.6	90.8 +/- 12.1	-11.5	< 0.001
FEV1/FVC (%)	75.4 +/- 9.2	80.9 +/- 6.4	-5.5	< 0.001
PEFR (L/s)	4.32 +/- 1.06	5.18 +/- 1.02	-0.86	< 0.001
FEF25-75 (L/s)	1.86 +/- 0.72	2.54 +/- 0.78	-0.68	< 0.001
FEF25-75 (% predicted)	68.4 +/- 21.3	85.9 +/- 22.6	-17.5	< 0.001
FEV1 z score	-1.42 +/- 1.05	-0.61 +/- 0.92	-0.81	< 0.001
FVC z score	-1.09 +/- 0.98	-0.52 +/- 0.89	-0.57	< 0.001
FEV1/FVC z score	-1.08 +/- 1.12	-0.43 +/- 0.86	-0.65	< 0.001

Values are mean +/- standard deviation. FVC, forced vital capacity; FEV1, forced expiratory volume in one second; PEFR, peak expiratory flow rate; FEF25-75, forced expiratory flow between 25 and 75 per cent of FVC. Predicted values and z scores were derived from the Global Lung Function Initiative 2012 equations. Independent samples t test.

Table 5: Pattern and severity of ventilatory impairment

Ventilatory pattern	Cases n (%)	Controls n (%)	Odds ratio (95% CI)	p value
Normal spirometry	84 (56.0)	118 (78.7)	0.34 (0.21-0.57)	< 0.001
Obstructive defect	33 (22.0)	12 (8.0)	3.24 (1.61-6.51)	< 0.001
Restrictive defect	26 (17.3)	17 (11.3)	1.64 (0.85-3.16)	0.141
Mixed defect	7 (4.7)	3 (2.0)	2.40 (0.61-9.47)	0.199
Any airflow obstruction	40 (26.7)	15 (10.0)	3.27 (1.72-6.24)	< 0.001
Severity: mild	15 (37.5)	9 (60.0)	-	0.140
Severity: moderate	18 (45.0)	5 (33.3)	-	0.437
Severity: severe	6 (15.0)	1 (6.7)	-	0.412
Severity: very severe	1 (2.5)	0 (0.0)	-	0.538

CI, confidence interval. Airflow obstruction was defined as a post-bronchodilator FEV1/FVC ratio below the lower limit of normal. Severity proportions are expressed as a percentage of the obstructed participants within each group (40 cases and 15 controls).

Table 6: Exposure-response relationship and multivariable predictors of airflow obstruction

Panel A: exposure tertile	**n**	**Airflow obstruction n (%)**	**FEV1 % predicted**	**p value**
Tertile 1 (< 75 hour-years)	101	7 (6.9)	91.2 +/- 11.6	Reference
Tertile 2 (75-140 hour-years)	99	17 (17.2)	84.6 +/- 12.4	0.018
Tertile 3 (> 140 hour-years)	100	31 (31.0)	79.3 +/- 13.1	< 0.001
Test for trend across tertiles	300	-	-	< 0.001
Panel B: variable	**Unadjusted OR**	**Adjusted OR (95% CI)**	**p value**	
Biomass fuel exposure	3.27	2.98 (1.48-6.00)	0.002	
Age (per additional year)	1.07	1.06 (1.03-1.10)	< 0.001	
Exposure index (per 10 hour-years)	1.12	1.09 (1.04-1.15)	< 0.001	
No kitchen ventilation aperture	2.68	2.11 (1.09-4.08)	0.026	
BMI < 18.5 kg/m2	2.21	1.94 (0.92-4.09)	0.082	
Dung or crop residue vs firewood	1.98	1.72 (0.83-3.56)	0.145	
Passive tobacco smoke exposure	1.76	1.58 (0.76-3.29)	0.221	

OR, odds ratio; CI, confidence interval; BMI, body mass index. Panel A presents airflow obstruction and mean FEV1 per cent predicted across tertiles of the cumulative exposure index for the whole cohort. Panel B presents binary logistic regression with airflow obstruction as the dependent variable. Hosmer-Lemeshow chi-square 6.42, degrees of freedom 8, p = 0.600; overall classification accuracy 79.3 per cent.

DISCUSSION

The present study demonstrated that never-smoking rural Kenyan women chronically exposed to household biomass fuel smoke exhibited significantly poorer post-bronchodilator ventilatory function than age-matched women in the same communities who cooked with liquefied petroleum gas. The mean forced expiratory volume in one second was reduced by 11.5 percentage points of predicted, airflow obstruction was more than three times as frequent, and the magnitude of impairment tracked the quantified cumulative exposure burden in a graded manner. The independence of the association after adjustment for age, nutritional status, ventilation and passive smoke exposure argues against confounding as a sufficient explanation.

The direction and magnitude of the association accord closely with the meta-analytic literature. A systematic review of solid fuel exposure reported an approximate doubling of the risk of chronic obstructive pulmonary disease and of chronic bronchitis, and a synthesis restricted to rural women and children generated pooled odds ratios of 2.40 and 2.52 for these outcomes respectively [2, 3]. The adjusted odds ratio of 2.98 obtained in the present cohort lies marginally above these pooled estimates, a difference plausibly attributable to the particularly intense exposure profile documented here, in which almost 85 per cent of cases used an open three-stone fire and more than two-thirds cooked in an unventilated space. The independent contribution of absent kitchen ventilation, with an adjusted odds ratio of 2.11, reinforces the interpretation that the delivered dose rather than fuel category alone determines risk.

The findings are concordant with the classical case-control work conducted among Mexican women, in which prolonged wood smoke exposure conferred a risk of chronic airway obstruction of an order comparable to that of tobacco smoking, and with the subsequent cross-sectional analysis in that population which demonstrated exposure-dependent reductions in ventilatory indices alongside an excess of chronic respiratory symptoms [5, 6]. The inverse correlation between the exposure index and forced expiratory volume in one second per cent predicted observed here, with a coefficient of minus 0.412, is of similar strength to that reported in Indian community studies, in which lung function declined progressively with increasing hour-years of biomass exposure and with measured particulate concentrations in the cooking area [15]. Comparable reductions in peak expiratory flow rate and forced expiratory volume in one second among biomass users relative to clean fuel users have been documented in earlier and more recent Indian series and in rural southern China [16-18].

Contrasting evidence must nevertheless be acknowledged. The multinational Burden of Obstructive Lung Disease analysis of more than eighteen thousand adults with acceptable post-bronchodilator spirometry did not identify a consistent association between self-reported solid fuel use and airflow obstruction, and reported spirometric restriction to be the more prevalent abnormality [7]. A household study in rural Ecuador likewise reported significantly reduced forced vital capacity and forced expiratory volume in one second among children living in biomass-using homes but no corresponding difference among the adult women of those households [14]. Similar conclusions emerged from the Malawian Chronic Airways Pollution Study, in which a substantial burden of abnormal spirometry was found in a heavily exposed rural and periurban population but the abnormality was predominantly restrictive and was not clearly related to measured personal exposure to fine particulate matter or carbon monoxide [12]. The present study reproduces part of that pattern, in that spirometric restriction was numerically more common among cases at 17.3 per cent against 11.3 per cent, although the difference was not statistically significant. Several considerations may reconcile these divergent findings. Studies employing binary self-reported fuel categories cannot distinguish a woman who cooks briefly on an improved stove in a ventilated space from one who spends six daily hours over an open fire in an enclosed hut, and such misclassification biases estimates towards the null. The use of a quantified hour-year index in the present study, and the demonstration of a monotonic gradient across its tertiles, supports this explanation. Nutritional status, childhood respiratory infection, previous tuberculosis and low socio-economic position also contribute to restrictive patterns in African populations and may obscure a coexisting obstructive signal [13].

The Kenyan context deserves particular emphasis. Environmental sampling in rural Kenyan households has confirmed that carbon monoxide and total suspended particulate concentrations regularly exceed international guidance during cooking, with screening spirometry suggesting impairment in a large majority of inhabitants, and community surveys in the western region have documented that the overwhelming majority of women in wood-burning households report recurrent cough [8, 9]. Those studies were limited by the use of screening-grade instrumentation, the absence of bronchodilator testing and the lack of a matched comparison group. The present work addresses these limitations by applying quality-assured post-bronchodilator spirometry interpreted against the Global Lung Function Initiative equations with the African ancestry module, thereby permitting the classification of ventilatory defects with reasonable confidence [10, 11]. The observation that Kenyan schoolchildren in high-pollution environments already display measurable respiratory compromise suggests that the trajectory of impairment documented here in adult women may begin considerably earlier in life [19].

The clinical and public health implications are substantial. More than one in four exposed women in this cohort met spirometric criteria for airflow obstruction, and nearly two-thirds of those affected had moderate or worse impairment, yet almost none carried a prior diagnosis. This diagnostic gap mirrors the global pattern in which the majority of chronic obstructive pulmonary disease in low-income and middle-income settings remains unrecognised [1]. Interventional evidence indicates that transition to cleaner fuels and improved kitchen ventilation can attenuate the rate of lung function decline and reduce the incidence of chronic obstructive pulmonary disease over prolonged follow-up [20]. The independent effect of ventilation observed in the present analysis suggests that even incremental household modifications may confer measurable benefit where a complete fuel transition is not immediately affordable.

Limitations

Several limitations warrant consideration. Exposure was reconstructed from participant recall rather than from direct personal monitoring of particulate matter or carbon monoxide, and recall bias cannot be excluded, although the use of a continuous index and the demonstration of an internal dose gradient mitigate this concern. The study was conducted in a defined rural sub-county and the findings may not be generalisable to pastoralist, urban informal settlement or highland populations with different fuel and housing patterns. Lung volumes, diffusing capacity and chest imaging were not obtained, so restrictive patterns identified on spirometry could not be characterised further. Previous pulmonary tuberculosis was excluded on the basis of documented history rather than universal radiography, and undiagnosed post-tuberculous lung disease may have contributed to the observed impairment. Finally, the six-month observation period was sufficient to establish the stability of the deficits but too brief to quantify the rate of longitudinal decline.

CONCLUSION

Chronic exposure to household biomass fuel smoke was associated with clinically and statistically significant impairment of ventilatory function among never-smoking rural Kenyan women. Exposed women demonstrated lower forced vital capacity, forced expiratory volume in one second, FEV1/FVC ratio, peak expiratory flow rate and mid-expiratory flow than age-matched clean fuel users, and airflow obstruction was more than three times as prevalent. The impairment followed a clear exposure-response gradient across tertiles of cumulative hour-year exposure, and biomass exposure, advancing age, cumulative exposure burden and the absence of kitchen ventilation each emerged as independent predictors of obstruction.

These findings support the inclusion of household air pollution among the recognised determinants of chronic airway disease in Kenya and elsewhere in sub-Saharan Africa, and indicate that the burden is substantially undiagnosed in the community. Accelerated transition to clean cooking fuels, promotion of improved cookstoves with effective flue systems, structural attention to kitchen ventilation, and the integration of quality-assured spirometry into rural primary care are recommended as complementary strategies. Longitudinal studies incorporating direct personal exposure monitoring and extended follow-up are required to define the rate of decline and to quantify the reversibility achievable through household energy intervention.

DECLARATIONS

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