

Household cooking fuel, kitchen ventilation, and incident hemorrhagic stroke in Chinese adults: a prospective cohort study

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Research Article

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Additional Declarations: No competing interests reported.

Abstract

Background

Household air pollution from solid-fuel combustion remains common in China, but prospective evidence for individual stroke subtypes and the role of household ventilation is limited. We examined associations of cooking fuel and stove ventilation with incident hemorrhagic stroke.

Methods

We analyzed 390197 China Kadoorie Biobank participants without baseline stroke or transient ischemic attack. Cooking fuel was classified as clean (gas or electricity) or polluting (coal or wood), using information from the present residence and, when unavailable, up to two previous residences. The primary outcome was first hemorrhagic stroke (ICD-10 I60-I61) before a competing stroke subtype or censoring. Cause-specific Cox models compared participants within region and adjusted for demographic, socioeconomic, lifestyle, and medical factors. Ventilation was examined only among polluting-fuel users.

Results

During 3774336 person-years (mean 9.67 years), 5782 hemorrhagic strokes occurred. Compared with clean fuel, polluting fuel was associated with hemorrhagic stroke after full adjustment (hazard ratio [HR] 1.146, 95% confidence interval [CI] 1.043–1.259; $P = 0.004$). Among 194904 polluting-fuel users, partial ventilation was not associated with risk relative to ventilation of all stoves (HR 0.981, 95% CI 0.896–1.074), whereas no ventilation was associated with higher risk (HR 1.135, 95% CI 1.018–1.264). Current-fuel-only, one-year landmark, and post hoc region-overlap analyses were consistent. Adding blood pressure reduced the fuel log-HR by 33.2%; this was covariate attenuation, not causal mediation. Polluting fuel was inversely associated with ischemic stroke (HR 0.949, 95% CI 0.911–0.989).

Conclusions

Polluting cooking fuel was associated with a modestly higher hazard of hemorrhagic stroke. Among polluting-fuel users, no ventilation identified a higher-risk group, but the observational design does not establish an intervention effect. The inverse ischemic-stroke association should not be interpreted as protective and warrants investigation of residual confounding and outcome ascertainment.

Background

Stroke is a leading cause of death and long-term disability worldwide, and its ischemic and hemorrhagic subtypes differ in burden and determinants [1, 2]. China has a high absolute stroke burden and a larger

proportional contribution from hemorrhagic stroke than many Western populations [3, 4]. Chinese cohort and prediction studies also demonstrate substantial heterogeneity in vascular risk across populations and settings [5–8], while national reviews and burden estimates emphasize the continuing prevention challenge [9, 10].

Household exposure from coal- and wood-burning stoves remains a public-health concern in China [11, 12]. Field measurements have documented gaseous and particulate emissions from residential cooking and heating [16]. Observational studies have associated indoor pollution or solid-fuel use with higher blood pressure [13], cardiovascular disease [15, 17, 19], and cardiopulmonary or all-cause mortality [14, 18]. National mortality analyses further underscore the importance of potentially modifiable vascular risks [20].

In the present cohort, cooking-fuel category was strongly patterned by urban residence, education, income, and health characteristics (Table 1). More generally, prospective and systematic evidence shows that socioeconomic circumstances and health behaviours cluster with cardiovascular risk [21, 22]. We therefore avoided a composite three-level HAP variable that would mix fuel type with ventilation. The prespecified primary exposure compared clean with polluting cooking fuel; ventilation was evaluated separately among polluting-fuel users. We hypothesized that polluting fuel would be associated with higher hemorrhagic-stroke risk and that absence of ventilation would identify the highest-risk polluting-fuel subgroup.

Table 1
Baseline characteristics by cooking fuel category

Characteristic	Clean fuel	Polluting fuel
Participants	195112	195085
Age, years	51.8 (10.4)	52.0 (10.6)
Women	133756 (68.6)	151626 (77.7)
Urban region	165611 (84.9)	22746 (11.7)
Body mass index, kg/m ²	24.3 (3.4)	23.3 (3.4)
Systolic blood pressure, mmHg	128.9 (20.8)	132.6 (21.9)
Diagnosed hypertension	25351 (13.0)	19092 (9.8)
Diagnosed diabetes	8224 (4.2)	4223 (2.2)
Physical activity, MET-h/day	16.0 (9.7–28.0)	19.0 (11.2–30.7)
Education		
No formal school	24700 (12.7)	56469 (28.9)
Primary school	41981 (21.5)	80765 (41.4)
Middle school	62218 (31.9)	44022 (22.6)
High school	45207 (23.2)	12618 (6.5)
Technical school or college	12909 (6.6)	882 (0.5)
University	8097 (4.1)	329 (0.2)
Income		
<2500 yuan/year	1749 (0.9)	10670 (5.5)
2500–4999 yuan/year	4370 (2.2)	21967 (11.3)
5000–9999 yuan/year	18591 (9.5)	51820 (26.6)
10000–19999 yuan/year	55267 (28.3)	57754 (29.6)
20000–34999 yuan/year	63644 (32.6)	34874 (17.9)
≥35000 yuan/year	51491 (26.4)	18000 (9.2)
Smoking		
Never smoker	137990 (70.7)	148439 (76.1)
Values are mean (standard deviation), median (interquartile range), or n (%). MET-h/day, metabolic-equivalent hours per day. Percentages are calculated within fuel category.		

Characteristic	Clean fuel	Polluting fuel
Occasional smoker	9713 (5.0)	7879 (4.0)
Former regular smoker	10166 (5.2)	7138 (3.7)
Current smoker	37243 (19.1)	31629 (16.2)
Alcohol		
Never regular	90249 (46.3)	110270 (56.5)
Former regular	2003 (1.0)	3195 (1.6)
Occasional	65381 (33.5)	57469 (29.5)
Monthly	6353 (3.3)	3888 (2.0)
Reduced intake	3648 (1.9)	3138 (1.6)
Weekly	27478 (14.1)	17125 (8.8)
Values are mean (standard deviation), median (interquartile range), or n (%). MET-h/day, metabolic-equivalent hours per day. Percentages are calculated within fuel category.		

Methods

Study design and population

The China Kadoorie Biobank (CKB) is a prospective cohort of adults recruited from 10 geographically diverse Chinese regions, including five urban and five rural study areas. Baseline recruitment was conducted principally during 2004–2008 using standardized interviewer-administered questionnaires and physical measurements. Details of the cohort design, recruitment, and follow-up have been published previously [23, 24]. Reporting follows the STROBE recommendations for cohort studies; the completed checklist is provided as Additional file 3.

The source extract contained 512724 records. We sequentially excluded 113544 participants without cooking-fuel information after applying the residential-history hierarchy, 2786 participants reporting an ambiguous 'Other' fuel, 6192 participants with self-reported stroke or transient ischemic attack at baseline, and 5 participants with missing key dates or demographics or non-positive follow-up. The final primary analytical cohort comprised 390197 participants (Fig. 1).

Exposure assessment

Participants reported the principal cooking fuel used in their present residence and in up to two previous residences. To retain the most recent interpretable exposure, we used present-residence fuel first, previous-residence fuel when present-residence fuel was unavailable, and residence-before-previous fuel

when both more recent values were unavailable. Gas and electricity were classified as clean fuels; coal and wood were classified as polluting fuels. This proxy-based classification is consistent with prior CKB household-air-pollution research [11, 25]. The 'Other' category was excluded because its emissions profile could not be assigned reliably.

The primary exposure was binary cooking fuel (polluting versus clean). Ventilation was analyzed only among polluting-fuel users with nonmissing stove ventilation information. Participants were categorized according to whether all stoves had a chimney or extractor, not all stoves were ventilated (partial ventilation), or no stoves were ventilated. This separation avoided combining clean-fuel use with a ventilation attribute that is principally relevant to combustion sources.

Outcome ascertainment

Incident stroke was ascertained through the established CKB follow-up system using linked disease registries, health-insurance records, hospital records, and mortality data [23, 24]. The primary outcome was the first hemorrhagic stroke, defined by ICD-10 codes I60 (subarachnoid hemorrhage) or I61 (intracerebral hemorrhage). The secondary outcome was first ischemic stroke (I63). Unspecified stroke was treated as a competing stroke subtype. For each subtype-specific analysis, follow-up ended at the first occurrence of the outcome, a competing stroke subtype, or the available censoring date. Coincident hemorrhagic and ischemic dates were conservatively not counted as either subtype-specific event to avoid double counting.

Covariates

Baseline covariates were selected a priori rather than by statistical significance. Age was modeled continuously and sex was binary. Socioeconomic covariates were highest education and annual household income. Lifestyle covariates were smoking category, alcohol category, total physical activity in metabolic-equivalent hours per day, and body mass index. Medical covariates were self-reported physician-diagnosed hypertension and diabetes. Region was used as a stratification factor so that each of the 10 study areas had its own baseline hazard and fuel comparisons were made within region. Urban status was not entered separately because it was fixed at the region level.

Statistical analysis

Baseline characteristics were summarized separately for clean- and polluting-fuel users using means with standard deviations, medians with interquartile ranges, or counts with percentages. Cause-specific Cox proportional-hazards regression with Breslow handling of ties estimated hazard ratios (HRs) and 95% confidence intervals (CIs). Model 1 included cooking fuel, age, and sex and was stratified by region. Model 2 additionally included education and household income. Model 3 further included smoking, alcohol, body mass index, hypertension, diabetes, and physical activity. All categorical model covariates

were complete. Body mass index was missing for one participant and was replaced by the cohort median; physical activity and blood-pressure variables were complete.

The proportional-hazards assumption for the primary fuel term was evaluated using scaled Schoenfeld residuals with a rank time transform. Among polluting-fuel users, the fully adjusted model compared partial and no ventilation with ventilation of all stoves. Secondary analyses estimated the fully adjusted association with ischemic stroke. Prespecified sensitivity analyses restricted exposure to present-residence fuel and excluded events during the first year of follow-up. Because regional polluting-fuel prevalence ranged from 1.9% to 97.8%, a post hoc overlap analysis retained regions in which both fuel groups represented at least 5% of participants. Aalen-Johansen estimators described cumulative incidence while treating other first stroke subtypes as competing events. Secondary and sensitivity analyses were interpreted as supportive or exploratory; no multiplicity adjustment was applied.

To explore blood pressure as a possible explanatory pathway, systolic and diastolic blood pressure were added to Model 3 and the percentage change in the fuel log-HR was calculated. Because this comparison did not implement a counterfactual mediation model, did not estimate indirect-effect uncertainty, and could not exclude mediator-outcome confounding, it was interpreted only as covariate attenuation, not as a causal mediated proportion. Analyses were performed in Python 3 using lifelines 0.30.3. Two-sided P values below 0.05 were considered statistically significant. Reproducible analysis scripts, without participant-level data, are provided in Additional file 2.

Use of generative AI in manuscript preparation

A large language model was used to assist with manuscript drafting, organization, and language editing. It was not used to generate or alter study data, perform the statistical analyses, or create the scientific figures. The authors are responsible for verifying all text, citations, numerical results, and interpretations before submission.

Results

Participant characteristics

The final cohort included 195112 clean-fuel users and 195085 polluting-fuel users. Mean age was 51.8 years in the clean-fuel group and 52.0 years in the polluting-fuel group. Polluting-fuel users were more often women (77.7% versus 68.6%) and much less often residents of an urban study region (11.7% versus 84.9%). Mean systolic blood pressure was higher among polluting-fuel users (132.6 versus 128.9 mmHg), whereas mean body mass index and reported prevalences of hypertension and diabetes were lower (Table 1). Polluting-fuel use was concentrated among participants with lower education and household income. All 10 regions included both fuel groups, although region-specific polluting-fuel prevalence ranged from 1.9% to 97.8%. Region-specific fuel distributions and overlap diagnostics are provided in Additional file 1.

Cooking fuel and hemorrhagic stroke

During 3774336 person-years of subtype-specific follow-up (mean 9.67 years), 5782 first hemorrhagic strokes occurred. Crude incidence rates were 0.97 per 1000 person-years among clean-fuel users and 2.09 per 1000 person-years among polluting-fuel users. Polluting versus clean fuel was associated with higher hemorrhagic-stroke hazard in Model 1 (HR 1.182, 95% CI 1.078–1.297; $P < 0.001$). The estimate was attenuated in Model 2 (HR 1.091, 95% CI 0.993–1.198; $P = 0.069$) and increased after additional lifestyle and medical adjustment in Model 3 (HR 1.146, 95% CI 1.043–1.259; $P = 0.004$) (Table 2; Fig. 2). The Schoenfeld-residual test for the fuel term did not indicate violation of proportional hazards ($P = 0.436$).

Table 2
Cooking fuel and hemorrhagic stroke risk

Model	Comparison	N	Events	HR (95% CI)	P value
Model 1	Polluting vs clean	390197	5782	1.182 (1.078–1.297)	< 0.001
Model 2	Polluting vs clean	390197	5782	1.091 (0.993–1.198)	0.069
Model 3	Polluting vs clean	390197	5782	1.146 (1.043–1.259)	0.004
All models were stratified by region. Model 1 adjusted for age and sex. Model 2 additionally adjusted for education and household income. Model 3 additionally adjusted for smoking, alcohol, body mass index, diagnosed hypertension, diagnosed diabetes, and physical activity. HR, hazard ratio; CI, confidence interval.					

Ventilation among polluting-fuel users

Ventilation information was available for 194904 of 195085 polluting-fuel users: 36377 reported ventilation for all stoves, 89193 reported partial ventilation, and 69334 reported no ventilation. In the fully adjusted model, partial ventilation was not associated with hemorrhagic stroke compared with ventilation of all stoves (HR 0.981, 95% CI 0.896–1.074; $P = 0.674$). No ventilation was associated with higher risk (HR 1.135, 95% CI 1.018–1.264; $P = 0.022$) (Table 3; Fig. 2). Supplementary descriptive rates and covariate missingness are provided in Additional file 1.

Table 3
Ventilation, secondary outcome, and sensitivity analyses

Analysis	Comparison	N	Events	HR (95% CI)	P value
Ventilation Model 3	Partial vs all stoves ventilated	194904	3961	0.981 (0.896–1.074)	0.674
Ventilation Model 3	None vs all stoves ventilated	194904	3961	1.135 (1.018–1.264)	0.022
Current fuel only	Polluting vs clean	373514	5459	1.184 (1.068–1.312)	0.001
One-year landmark	Polluting vs clean	387486	5411	1.160 (1.053–1.278)	0.003
Region-overlap restriction	Polluting vs clean	198495	2243	1.124 (1.008–1.253)	0.035
Ischemic stroke Model 3	Polluting vs clean	390197	29632	0.949 (0.911–0.989)	0.012
All estimates used the Model 3 covariate set and region stratification. Ventilation analyses were restricted to polluting-fuel users. The ischemic-stroke analysis was secondary. Current-fuel and one-year landmark analyses were prespecified; the region-overlap restriction was post hoc and retained regions with 5%-95% polluting-fuel prevalence. HR, hazard ratio; CI, confidence interval.					

Secondary and sensitivity analyses

There were 29632 first ischemic strokes. Polluting fuel was associated with a small reduction in ischemic-stroke hazard after full adjustment (HR 0.949, 95% CI 0.911–0.989; $P = 0.012$). Given the strong urban-rural and socioeconomic separation between fuel groups, this exploratory estimate was not interpreted as a protective effect. The hemorrhagic-stroke association remained after restriction to present-residence fuel (HR 1.184, 95% CI 1.068–1.312; $P = 0.001$) and after excluding the first year of follow-up (HR 1.160, 95% CI 1.053–1.278; $P = 0.003$). In the post hoc analysis restricted to five regions with 5%-95% polluting-fuel prevalence, the estimate was similar but less precise ($N = 198495$; HR 1.124, 95% CI 1.008–1.253; $P = 0.035$) (Table 3; Fig. 2).

At 10 years, the Aalen-Johansen cumulative incidence of hemorrhagic stroke was 0.93% among clean-fuel users and 2.00% among polluting-fuel users; corresponding ischemic-stroke estimates were 8.54% and 6.48%, respectively (Table 4; Fig. 3). These are unadjusted descriptive estimates and reflect differences in baseline risk structure between the fuel groups. Adding systolic and diastolic blood pressure to Model 3 changed the polluting-fuel HR from 1.146 to 1.095, corresponding to 33.2% attenuation of the log-HR.

Table 4. Cumulative incidence by fuel and stroke subtype

Fuel group	Year	Hemorrhagic stroke, %	Ischemic stroke, %
Clean	2	0.13	0.87
Clean	5	0.39	3.12
Clean	10	0.93	8.54
Polluting	2	0.31	0.57
Polluting	5	0.91	2.02
Polluting	10	2.00	6.48

Aalen-Johansen cumulative incidence estimates treated other first stroke subtypes as competing events. Estimates are descriptive and unadjusted.

Discussion

In this large prospective cohort, polluting cooking fuel was associated with a modestly higher hazard of first hemorrhagic stroke after adjustment for demographic, socioeconomic, lifestyle, and medical factors. Among polluting-fuel users, complete absence of stove ventilation was associated with higher hazard than ventilation of all stoves, whereas partial ventilation showed no clear association. Current-fuel-only, one-year landmark, and post hoc region-overlap analyses yielded estimates in the same direction.

The findings extend earlier Chinese evidence on household fuels. Field studies have documented gaseous and particulate emissions from residential cooking and heating [16], and observational studies have linked indoor pollution or solid-fuel use with blood pressure [13], cardiovascular outcomes [15, 17, 19], and mortality [14, 18]. Previous CKB analyses also associated solid-fuel use with chronic respiratory disease [25], while another Chinese cohort linked household air pollution with incident lung cancer [11]. The present analysis adds a subtype-specific hemorrhagic-stroke outcome and separates fuel type from stove ventilation rather than combining them into a single ordinal exposure.

Adding measured blood pressure reduced the fuel coefficient, which is compatible with a blood-pressure-related pathway because blood pressure is an established stroke determinant [1, 2]. However, this covariate comparison is insufficient to establish mediation. Blood pressure may act as a mediator, confounder, or marker of diagnosis and treatment; formal mediation would require explicit causal assumptions, temporal ordering, and uncertainty estimation for an indirect effect.

The ventilation analysis adds a practical household dimension. The elevated risk was confined to participants reporting no stove ventilation relative to ventilation of all stoves. Partial ventilation was not distinguishable from full ventilation, and its confidence interval included both modest benefit and modest harm. This does not demonstrate that incomplete ventilation is equivalent to full ventilation: the questionnaire did not measure extractor performance, fuel quantity, cooking duration, stove stacking,

room volume, or pollutant concentrations. Direct exposure measurement is needed before translating the category contrast into an intervention effect.

The ischemic-stroke result requires particular caution. The fully adjusted HR was slightly below one, and unadjusted cumulative incidence was also lower among polluting-fuel users. Polluting-fuel users were overwhelmingly rural and differed substantially in education, income, sex, body mass index, and diagnosed cardiometabolic disease. Region stratification compares participants within study area, but fuel prevalence still approached separation in several regions. Measured adjustment and the overlap analysis reduce, but cannot remove, confounding by healthcare access, diagnostic practice, competing mortality, or unmeasured household conditions. The analysis therefore does not support a protective interpretation for polluting fuel.

The non-monotonic change across adjustment sets also merits attention. Adjustment for education and income attenuated the association toward the null, while adding smoking, alcohol, body mass index, hypertension, diabetes, and physical activity increased the estimate. This pattern is compatible with negative confounding by one or more lifestyle or health variables and argues against interpreting any single adjustment step as a mechanistic decomposition. More detailed socioeconomic, dietary, and longitudinal exposure information may improve control of residual confounding. Healthy lifestyle research in CKB supports the broader value of modifiable behaviors [26], but the present analysis did not test a healthy-lifestyle interaction.

Strengths include the large sample, prospective follow-up, geographically diverse recruitment, separation of first stroke subtypes, region-stratified models, explicit handling of competing stroke subtypes, and concordant sensitivity analyses. Several limitations should be considered. Cooking fuel and ventilation were self-reported proxies rather than direct measurements of PM2.5 or carbon monoxide. Fuel from prior residences was used for 16683 participants when current fuel was missing, which improved completeness but may introduce temporal misclassification. Heating fuel, stove use intensity, fuel switching, and exposure duration were not included in the primary model. Approximately 22% of source records lacked usable cooking-fuel data, creating potential selection bias. Extreme regional differences in fuel prevalence limited covariate overlap, although the post hoc overlap analysis was consistent. Hypertension and diabetes were self-reported and may be underdiagnosed in rural settings. Death was censored rather than modeled as a separate competing event. Residual confounding, outcome misclassification, and limited generalizability beyond Chinese adults remain possible.

Conclusions

Polluting cooking fuel was associated with a modestly higher hemorrhagic-stroke hazard in Chinese adults. Among polluting-fuel users, absence of stove ventilation identified a higher-risk group, whereas partial ventilation was not clearly different from ventilation of all stoves. These observational findings add to the rationale for evaluating clean-fuel transitions and effective ventilation, but they do not

establish an intervention effect. The inverse ischemic-stroke association and blood-pressure attenuation should not be interpreted as evidence of protection or causal mediation.

Abbreviations

CI, confidence interval; CKB, China Kadoorie Biobank; HAP, household air pollution; HR, hazard ratio; HS, hemorrhagic stroke; ICD-10, International Classification of Diseases, 10th Revision; IS, ischemic stroke; MET, metabolic equivalent of task; SBP, systolic blood pressure; TIA, transient ischemic attack.

Declarations

Ethics approval and consent to participate

The CKB study was approved by the Ethics Review Committee of the Chinese Academy of Medical Sciences, Peking Union Medical College (005-2004), and the Oxford Tropical Research Ethics Committee, University of Oxford (025-04). All participants provided written informed consent. The present analysis used deidentified data supplied under the CKB data-access process.

Consent for publication

Not applicable.

Availability of data and materials

The individual-level CKB data are not publicly available because of participant confidentiality and data-use restrictions. Bona fide researchers may apply to the CKB Data Access Committee through the CKB data-access procedures. Analytical definitions and aggregate results supporting this manuscript are reported in the article and accompanying tables and figures.

Competing interests

The authors declare that they have no competing interests.

Preprint

An earlier version of this work was posted on SSRN (Jia Y, Liang H. Household Air Pollution, Ventilation, and Stroke Risk in China: A Prospective Cohort Study. 2026. doi:10.2139/ssrn.6724549). The present manuscript uses corrected exposure and outcome definitions and supersedes the numerical results and interpretations in that version.

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Authors' contributions

YJ and HL contributed to study conception and design. YJ performed the analysis and drafted the manuscript. HL supervised the work, interpreted the findings, and critically revised the manuscript. Both authors read and approved the final manuscript.

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Figures

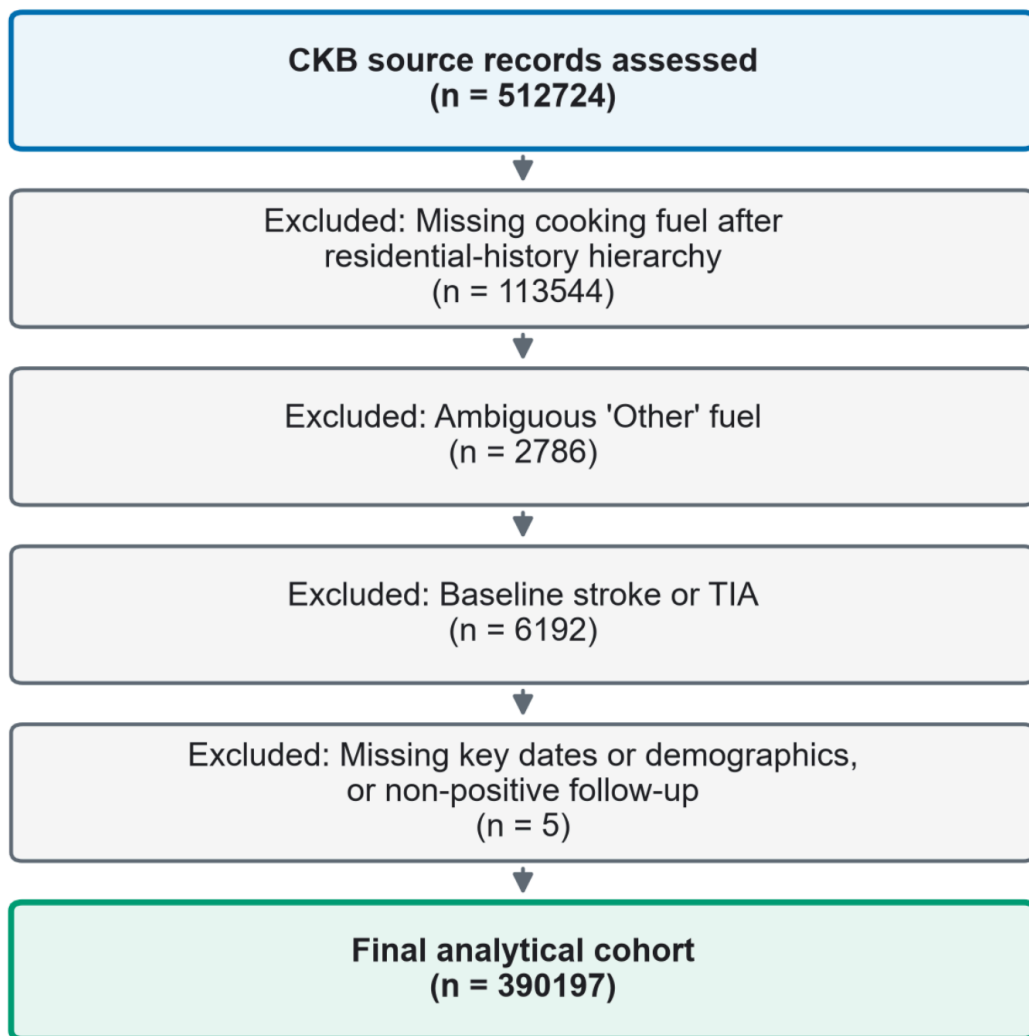


Figure 1

Participant selection flow

Flow diagram of sequential exclusions from the CKB source extract to the final analytical cohort. TIA, transient ischemic attack.

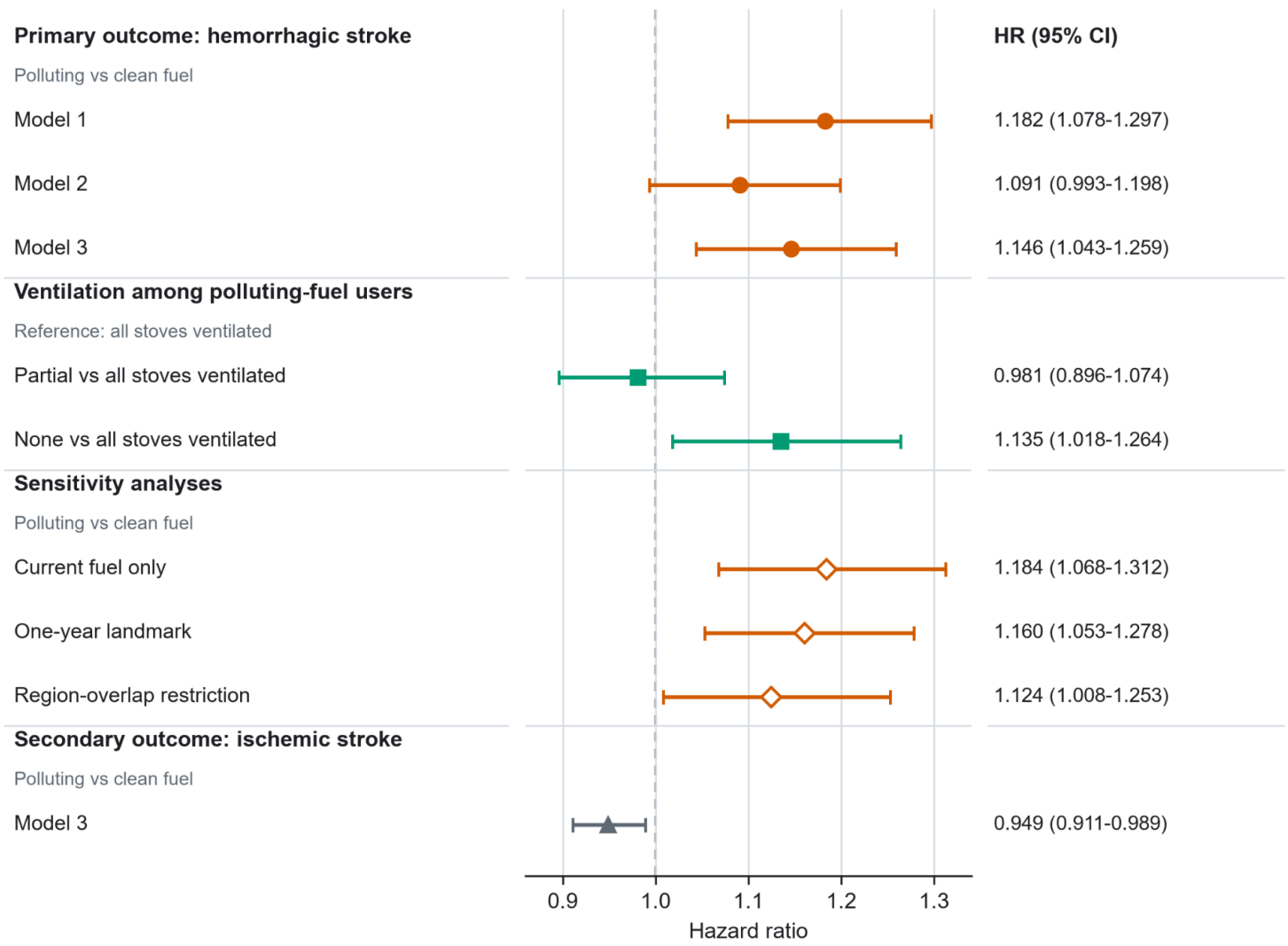


Figure 2

Associations of cooking fuel and ventilation with stroke

Hazard ratios and 95% confidence intervals from the primary hemorrhagic-stroke models, ventilation analysis among polluting-fuel users, sensitivity analyses, and the secondary ischemic-stroke model. Model definitions are provided in Tables 2 and 3. HS, hemorrhagic stroke; IS, ischemic stroke.

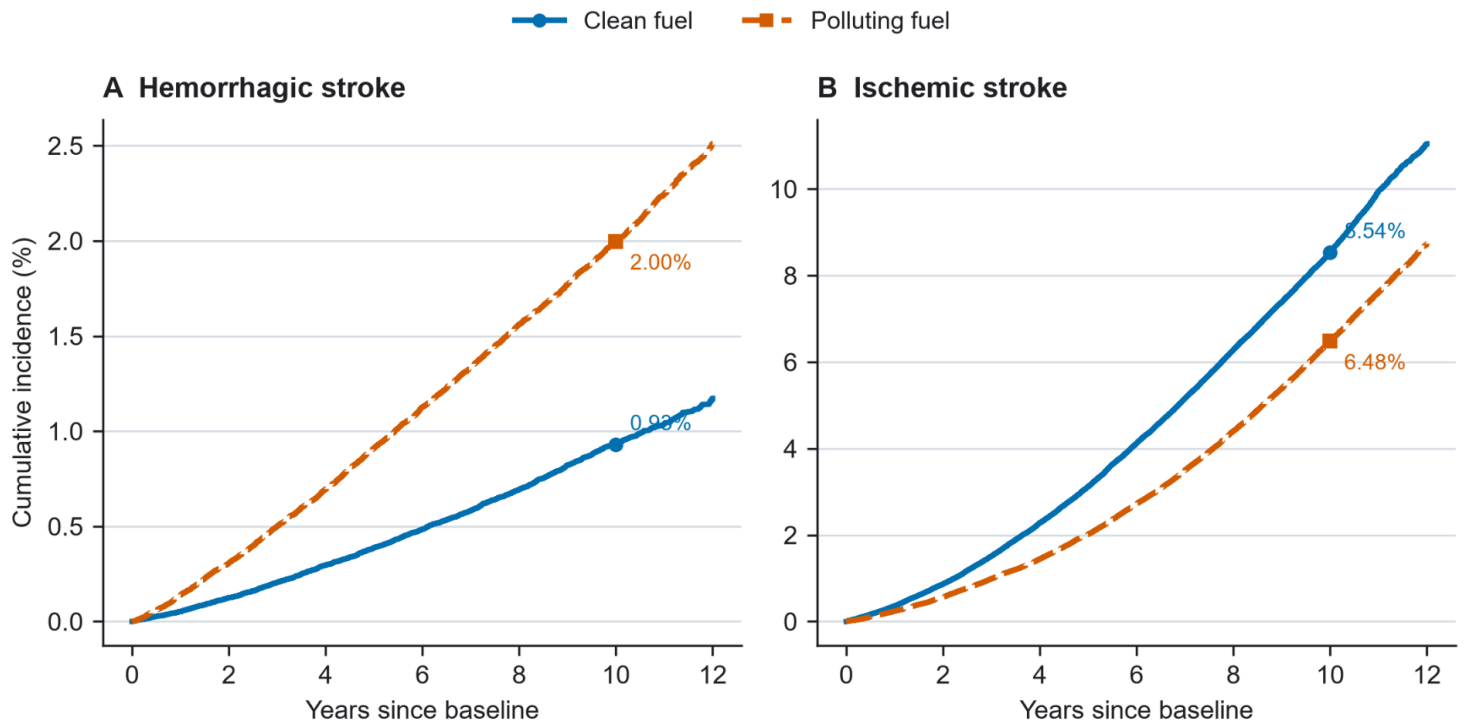


Figure 3

Cumulative incidence of first stroke subtype

Aalen-Johansen cumulative incidence functions for (A) hemorrhagic stroke and (B) ischemic stroke by cooking-fuel group, treating other first stroke subtypes as competing events. Curves are unadjusted and descriptive.