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Original Article

# Household fuel use and motoric cognitive risk syndrome among older adults: Evidence from cohort study and life course analysis

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ABSTRACT

*Background:* Motoric cognitive risk syndrome (MCRS) is a predementia syndrome, and its prevention is valuable for reducing the incidence of dementia. However, few studies have focused on the association between indoor air pollution caused by household cooking fuel use and MCRS. This study aimed to investigate whether clean cooking fuel use is associated with reduced MCRS risk and whether the timing of clean fuel adoption across the life span is associated with MCRS prevalence.

*Methods:* We used data from the China Health and Retirement Longitudinal Study. A prospective cohort analysis ($n$ = 4251) examined baseline fuel use (2011) and incident MCRS over four years. A cross-sectional life course analysis ($n$ = 6964) linked retrospective fuel use histories (2014 life history survey) to MCRS status in 2015. Modified Poisson regression was used to estimate relative risks (RRs) and 95 % confidence intervals (CIs), adjusting for covariates.

*Results:* In the cohort study, clean fuel use at baseline was associated with a reduced risk of MCRS (RR = 0.76; 95 % CI: 0.61–0.96). Lower risks were also observed among participants who transitioned from solid to clean fuels and those who consistently used clean fuels. In the life course analysis, clean fuel adoption in early or middle adulthood was linked to lower MCRS prevalence.

*Conclusion:* Clean fuel use for cooking and transitioning from solid to clean fuels decreases MCRS risk among older adults. Moreover, earlier adoption of clean cooking fuels is associated with a lower prevalence of MCRS in later life.

## 1. Introduction

Motoric cognitive risk syndrome (MCRS) is a predementia syndrome characterized primarily by a slow gait and subjective cognitive concerns [1]. A meta-analysis of 62 studies with 180 thousand samples found a global MCRS prevalence of 9.0 % in older adults aged 60 years and above [2]. Several observational studies have found that MCRS is associated with adverse health outcomes, such as all-cause mortality [3], dementia [4], and disability [5]. The risk of future vascular dementia in people with MCRS is 12.8 times higher than that in those without MCRS [1], which will significantly increase the burden of care on societies and families. Given the high MCRS prevalence and resulting health risks, early prevention is valuable to reduce MCRS risk and its subsequent adverse health events.

Identifying MCRS risk factors is critical for designing and implementing targeted interventions. The association of demographic characteristics (age, sex, and marital status) [6], lifestyles (sleep and physical inactivity) [7,8] and health-related conditions (chronic pain [9], cardiometabolic multimorbidity [10], and polypharmacy [11]) with MCRS has been explored in studies. Recent studies have also focused on the association between social factors, such as social isolation [12] and social frailty [13], and an increased MCRS risk in older adults. However, few studies have explored the association between environmental factors, especially the residential environment, and MCRS. Considering that the activity ability of older adults gradually decreases with age, they spend most of their time indoors. Therefore, exploring the potential impact of indoor environmental factors on MCRS is important. Indoor air pollution caused by household solid fuel use is an important environmental factor affecting human health [14]. Using solid fuels to cook is a major source of indoor air pollution, especially in developing countries, and using clean fuels can effectively avoid this problem [15]. Many studies have confirmed that indoor air pollution caused by solid fuel use

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is related to various adverse health outcomes in older adults, such as renal function decline [16], frailty [17], and visual impairment [18]. Solid fuel use increases the risk of cognitive impairment in older adults [19,20]. Indoor air pollution may also be associated with MCRS based on the strong association between MCRS and cognitive function. In the context of the United Nations Sustainable Development Goals, which explicitly promote clean energy [21], elucidating the association between clean fuel use and MCRS has important public health implications for promoting clean energy in aging societies.

Clean fuels, such as natural gas, electricity, and solar energy, are considered modern household energy sources that emit lower levels of indoor air pollutants compared to traditional solid fuels like coal and biomass [22]. In recent years, the Chinese government has made the promotion of clean household fuels a key component of its broader public health and environmental protection strategies. From a sociological perspective, the use of household fuel is deeply entwined with socio-economic status, cultural norms, and access to resources [23]. The type of cooking fuel used reflects underlying social inequalities. Wealthier, urban households are more likely to have access to clean fuels, while lower-income and rural populations often rely on solid fuels such as biomass, coal, or wood, which contribute to indoor air pollution [24]. These disparities are not merely a matter of economic access but are also shaped by cultural traditions, societal values, and historical factors [25,26]. Household fuel use, therefore, becomes a marker of broader social inequalities that can influence health outcomes such as MCRS, especially in older adults who may be more vulnerable to the effects of poor indoor air quality. Recently, considering factors related to the health status of older adults from a whole-life perspective has become an important topic in the field of aging health. Exposure to adverse childhood or adult experiences is associated with an increased risk of cardiovascular diseases in middle-aged and older Chinese adults [27]. A recent prospective cohort study also explored the association between adverse childhood experiences and MCRS [28]. However, to the best of our knowledge, no previous study has focused on whether clean fuel use in life course is associated with MCRS.

Additionally, approaching this issue from a life course perspective highlights how long-term exposure to solid fuels may have cumulative effects on health. The life course framework considers how early-life exposures, including environmental factors like household fuel use, shape health trajectories across the lifespan [29]. In this context, the use of clean cooking fuels during childhood and adulthood may not only have immediate benefits but could also have long-lasting effects on cognitive health in older adulthood. Exploring the potential long-term benefits of clean fuel use in reducing MCRS risk is helpful to understand the importance of considering the entire lifespan when evaluating the impact of environmental factors on health. This study is particularly timely, as the health implications of clean energy adoption are gaining increasing attention in global policy agendas [30], including those targeting aging populations. The shift towards clean fuels, especially in aging societies, is not only a technological challenge but also a socio-cultural one. It involves understanding how socio-economic disparities, cultural norms, and access to resources influence the adoption of cleaner fuels. The benefits of such a transition are likely to be cumulative, with early and sustained use of clean fuels leading to better health outcomes over the life course. Therefore, this research seeks to explore two key questions: (1) whether the use of clean cooking fuels reduces the risk of MCRS in older adults, and (2) whether clean fuel use throughout the life course is associated with a lower risk of MCRS in later life.

By integrating a life course perspective and a sociological understanding of household fuel use, this study aims to provide deeper insights into how environmental factors interact with social determinants of health to influence MCRS risk. These findings will not only contribute to the understanding of MCRS but also inform public health strategies aimed at promoting cleaner cooking technologies and reducing health inequities in aging populations.

## 2. Methods

### 2.1. Participants

Data were obtained from the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative survey of middle-aged and older people in China. The CHARLS conducted a baseline survey in 2011, collecting data from 17,708 middle-aged and older adults aged ≥45 years. Information on sampling and recruitment has been described in detail in a previous study [31]. CHARLS was approved by the Biomedical Ethics Review Committee of Peking University (IRB00001052-11015), and all participants provided informed consent. This study was conducted and reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines for observational research. A completed STROBE checklist is provided in the Supplementary Materials.

#### 2.1.1. Prospective cohort analysis

We used longitudinal data from the 2011 (baseline), 2013, and 2015 waves of CHARLS to examine the association between baseline household cooking fuel and incident MCRS. Participants were included if they were aged ≥60 years in 2011 and had complete data on baseline exposure, baseline MCRS status, and MCRS outcome during follow-up. Individuals with MCRS or dementia (Self-reported by oneself or family members and diagnosed by a doctor) at baseline, missing covariates, or loss to follow-up in 2013 or 2015 were excluded. MCRS was assessed at two discrete follow-up time points (2013 and 2015), and the total observation period was four years. The participant selection process for this section is shown in Fig. 1a.

#### 2.1.2. Cross-sectional life course analysis

We also conducted a cross-sectional life course analysis using the 2014 CHARLS Life History Survey, which retrospectively collected the calendar year in which households first began using solid or clean cooking fuels. These data were linked with MCRS outcomes assessed in 2015. Participants aged ≥60 years with no dementia and complete data on life course fuel exposure, MCRS status in 2015, and relevant covariates were included in this analysis. The participant selection process for this section is shown in Fig. 1b.

### 2.2. Measurements

#### 2.2.1. Cooking fuels in cohort study

The participants were asked, "What is the main source of cooking fuel?" Their responses included coal, natural gas, marsh gas, liquefied petroleum gas, electricity, and crop residue/wood burning. In this study, cooking fuels were classified into two mutually exclusive categories: clean (natural gas, marsh gas, liquefied petroleum gas, and electricity) and solid (coal and crop residue/wood burning) fuels. In addition, we compared the changes in cooking fuels at baseline and at follow-up to define fuel transitions, including persistent solid fuel users, participants who switched from solid to clean fuel, participants who switched from clean to solid fuel, and persistent clean fuel users. Based on previous studies [32,33], when we analyzed fuel transitions, we excluded participants who changed cooking fuel types more than once across the three survey waves. This decision was made to ensure consistent exposure classification, as frequent switching may reflect inconsistent behaviors or transitional household energy status, which are difficult to interpret in the context of long-term health effects.

#### 2.2.2. Lifespan fuel use definition and measurement

Information on participants' historical household fuel use was obtained from the 2014 wave of the CHARLS life history survey, which included retrospective questions on the calendar year in which the household first started using clean fuels (e.g., electricity, natural gas) for cooking. Participants were asked to recall the year each type of fuel was first

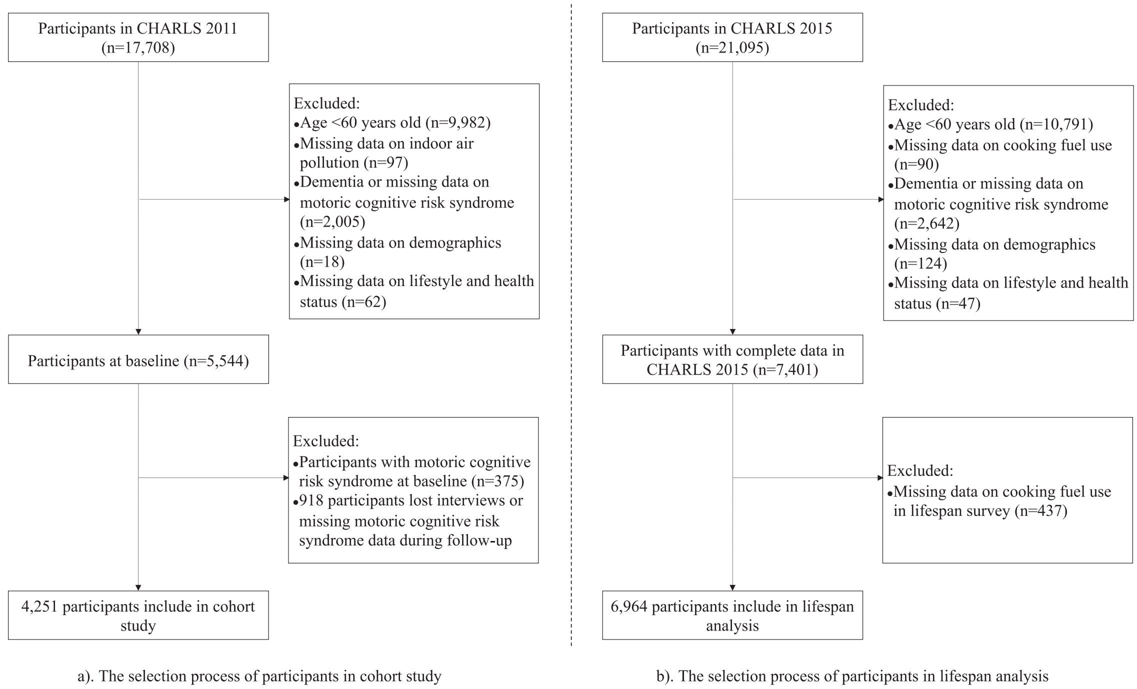


**Fig. 1.** The selection process of participants in this study.

introduced in their household. To reduce potential confounding due to cohort effects (i.e., older participants more likely to report earlier use simply because of their birth year), we calculated the age at which each participant first initiated clean fuel use by subtracting the reported start year from the survey year (2014) and further subtracting this from the participant's age in 2014. This derived variable was used to approximate the timing of initial exposure to clean fuel across the life course.

We then categorized participants into four mutually exclusive exposure groups based on the life stage at which clean fuel use was first initiated: childhood (<18 years), early adulthood (18–44 years), middle adulthood (45–59 years), and never used clean fuel (reference group). These categories reflect the onset of exposure rather than the cumulative duration, intensity, or exclusive use during each period. As the CHARLS life history module did not collect annual usage data or confirm continuous exposure, we focused on the timing of first adoption as a meaningful proxy for early environmental transition.

### 2.2.3. MCRS

In this study, the MCRS definition was based on subjective cognitive complaints and measured gait speed, consistent with previous epidemiologic studies [7,34]. Subjective cognitive complaints were assessed through self-reported memory performance (rated as "poor"), a method widely used in aging studies [2,3]. Previous studies have confirmed that subjective cognitive complaints reliably indicate impaired objective cognitive function [35]. Gait speed was objectively measured by a 2.5 m walk, and we calculated the average time between participants' two 2.5 m walks. Timed and instrumented methods have been reported to measure gait speed with high reliability [36]. Based on previous studies [37,38], slow gait speed was defined as one standard deviation below the age- (60–74 and ≥75 years) and sex-adjusted mean of gait speed. The specific cutoffs for slow gait speed are presented in Table S1. MCRS does not require neuropsychological testing, as its diagnostic validity relies on the combination of gait speed and self-reported complaints [39]. Participants with subjective cognitive complaints and slow gait speed were judged to have MCRS.

### 2.2.4. Covariate

In this study, the covariates included sociodemographic characteristics, lifestyle, and health status. Sociodemographic characteristics included age, sex (male or female), residence (urban or rural), marital status (married or unmarried), education level (below middle school, middle school and above), and family wealth (low or high). Among them, the family wealth was derived from household-level economic variables (e.g., income, assets, housing), and participants were categorized into high or low wealth based on a median split. Lifestyle factors included smoking (no or yes), drinking (no or yes), exercising (rarely or regularly), and social activity (rarely or regularly). Exercise and social activity were assessed in CHARLS through a two-step process. Participants were first asked whether they engaged in any physical exercise or participated in social activities. If they answered yes, a follow-up question assessed frequency, with response options: "almost daily", "almost every week", and "not regularly". For analysis, we categorized participants into two groups: "hardly" (those who reported no participation or selected "not regularly") and "regularly" (those who participated "almost weekly" or "almost daily"). The term "hardly" was chosen to reflect the original Chinese expression, and this categorization approach captures both non-participation and low-frequency engagement in the "hardly" group, and is consistent with prior CHARLS-based analyses [40]. However, we acknowledge that such dichotomization may obscure variation among infrequent participants.

Health status included hypertension (no or yes), diabetes (no or yes), cardiovascular disease (no or yes), body mass index (self-reported weight/height$^2$, classified as underweight [<18.5], normal [18.5–23.9], overweight [24.0–27.9], obesity [≥28.0], unit: kg/m$^2$) [41], arthritis (no or yes), pain (measured by currently feel any body pains, and the answers were no or yes), hip fracture history (no or yes). All covariates were measured at baseline in 2011 and treated as fixed variables in the analysis. While some variables such as lifestyle and chronic conditions may vary over time, time-dependent covariate data were not consistently available and thus not incorporated into the models.

### 2.3. Statistical analysis

Statistical analyses were performed using Stata 17.0 (StataCorp, College Station, TX, USA), and statistical significance was defined as $p < 0.05$. Participants with missing data on the exposure, outcome, or covariates were excluded using a complete-case analysis approach. Notably, assessment of MCRS required valid gait speed measurement, which is part of the CHARLS physical function examination. Consequently, a considerable proportion of older participants did not complete this physical function examination, resulting in missing data for both MCRS and related measures such as body mass index. After exclusion of participants with missing data on the primary exposure (cooking fuel) and main outcome (MCRS), the proportion of missing data for other covariates was low (generally less than 2 % for most variables; see Supplementary Table S2). Given that the majority of missingness was due to non-participation in the physical function examination, we assumed data were missing at random and no imputation was applied.

#### 2.3.1. Cohort analysis (baseline fuel use and incident MCRS)

Given the structured follow-up schedule of CHARLS, with assessments conducted in 2011 (baseline), 2013, and 2015, we defined incident MCRS as a binary outcome indicating whether participants without MCRS at baseline developed the condition by 2015. The median follow-up duration was four years. We conducted univariate analyses to explore the association between baseline participant characteristics and incident MCRS in the cohort study. Chi-square tests were used to compare MCRS incidence across categories of demographic, lifestyle, and health-related variables. The results are presented in Supplementary Table S3 and S4. Because all participants were assessed at fixed intervals, we did not calculate person-time or conduct time-to-event analyses. Instead, we used modified Poisson regression with robust standard errors to directly estimate relative risks (RR) and 95 % confidence intervals (CI), which is appropriate for binary outcomes in cohort studies with uniform follow-up time.

The cohort analysis was conducted in two steps. As a preliminary step, we examined the association between baseline fuel type (solid vs. clean) and MCRS risk. We then analyzed fuel transition patterns (fuel transition from baseline to follow-up, such as persistent solid fuel use, switching from solid to clean) and MCRS risk using the same modeling framework. Four sequential models were constructed: Model 1 was unadjusted; Model 2 adjusted for age, sex, residence, marital status, education, and household wealth; Model 3 additionally adjusted for smoking, drinking, physical activity, and social engagement; Model 4 further included hypertension, diabetes, cardiovascular disease, body mass index, arthritis, pain, and hip fracture history.

#### 2.3.2. Life course analysis (age of clean fuel usage and MCRS)

In the life course analysis, we performed univariate comparisons of MCRS prevalence across key participant characteristics and timing of clean fuel adoption. Chi-square tests were used to assess statistical differences between groups. Results are presented in Supplementary Table S5. To explore the association between the timing of clean fuel adoption and MCRS risk, we applied modified Poisson regression with robust error variance. This approach was chosen instead of logistic regression to provide more interpretable relative risks and account for the non-rare nature of the outcome. Exposure categories were based on the life stage at which participants first initiated clean fuel use, as described above. The same four adjustment models (Models 1–4) were used.

#### 2.3.3. Sensitivity analyses

To assess the potential impact of environmental confounding, we conducted sensitivity analyses for both the prospective analysis and the life course analysis. In both cases, we added average outdoor $PM_{2.5}$ concentrations, mean temperature, and mean humidity during the year prior to the 2015 follow-up as covariates. These city-level environmental variables were linked to participants based on their residential location, and their measurement details are provided in the supplementary materials. We also performed additional sensitivity analyses using the E-value methodology to assess the potential impact of unmeasured confounding on our primary and key secondary findings. The E-value quantifies the minimum strength of association, on the risk ratio scale, that an unmeasured confounder would need to have with both the exposure and the outcome to fully explain away the observed association [42]. E-values were calculated for the primary exposure (clean versus solid fuel use), as well as for the most important contrasts in the fuel transition and life course analyses where significant associations were observed. The E-value for the point estimate and for the lower confidence limit of the 95 % CI were obtained using the publicly available online calculator (https://www.evalue-calculator.com/evalue/) [43,44].

The additional adjustment was applied to the fully adjusted model (Model 4) in each analysis.

## 3. Results

### 3.1. Descriptive statistics

Table 1 shows the characteristics of the participants in the cohort study and life course analysis. A total of 4251 participants were included in the cohort analysis, and 6964 participants were included in the life course analysis.

In the cohort analysis, 37.2 % of participants used clean fuels for cooking at baseline, and the overall incidence of MCRS during a mean 4-year follow-up was 9.4 %. When stratified by fuel type, the incidence of MCRS was 6.7 % among clean fuel users and 11.0 % among solid fuel users, suggesting a lower risk associated with clean fuel use.

In the life course analysis, the proportions of participants who initiated clean fuel use at different life stages were: never used (51.5 %), started in middle adulthood (45–59 years) (32.9 %), early adulthood (18–44 years) (15.1 %), and childhood (<18 years) (0.4 %). The overall prevalence of MCRS in this sample was 6.5 %. When stratified by age of clean fuel initiation, MCRS prevalence was 8.4 % among participants who never used clean fuels, 5.0 % among those who started in middle adulthood, 3.8 % among those who started in early adulthood, and 3.6 % among those who started in childhood. Additional details are provided in Table 1.

### 3.2. Associations between cooking fuels, its transitions, and MCRS in the cohort study

Table 2 presents the association between cooking fuel type, fuel-use transitions, and the risk of developing MCRS during follow-up. In the unadjusted model (Model 1), baseline clean fuel use was significantly associated with lower MCRS risk compared to solid fuel use (RR = 0.59; 95 % CI: 0.48–0.74). After adjusting for sociodemographic, lifestyle, and health-related covariates (Model 4), this association remained statistically significant, with clean fuel users having a 24 % lower risk of MCRS than solid fuel users (RR = 0.76; 95 % CI: 0.61–0.96). In the fuel-use transition analysis, participants who switched from solid to clean fuel had a significantly lower MCRS risk compared to persistent solid fuel users (RR = 0.67; 95 % CI: 0.47–0.97 in Model 4). The lowest risk was observed among persistent clean fuel users (RR = 0.62; 95 % CI: 0.45–0.85). In contrast, those who switched from clean to solid fuel did not show a significant difference in risk (RR = 0.79; 95 % CI: 0.43–1.44).

### 3.3. Associations between clean fuel use in different life stages and MCRS

In the life course analysis (Table 3), the use of clean cooking fuel was associated with a lower prevalence of MCRS across all life stages when compared to participants who never used clean fuel. In the fully adjusted model (Model 4), participants who first used clean fuel in middle adulthood (45–59 years) had a 28 % lower risk of MCRS (RR = 0.72;

**Table 1**
Characteristics of participants.

| Variables | Cohort study | | Life course analysis | |
|---|---|---|---|---|
| | n | % | n | % |
| Total sample | 4251 | 100.0 | 6964 | 100.0 |
| Age, yeas | | | | |
| 60–69 | 2963 | 69.7 | 4496 | 64.6 |
| 70–79 | 1129 | 26.6 | 2034 | 29.2 |
| ≥80 | 159 | 3.7 | 434 | 6.2 |
| Sex | | | | |
| Male | 2164 | 50.9 | 3448 | 49.5 |
| Female | 2087 | 49.1 | 3516 | 50.5 |
| Residence | | | | |
| Rural | 3529 | 83 | 1702 | 24.4 |
| Urban | 722 | 17 | 5262 | 75.6 |
| Marital status | | | | |
| Married | 3458 | 81.3 | 5568 | 80.0 |
| Unmarried | 793 | 18.7 | 1396 | 20.0 |
| Educational level | | | | |
| Middle school below | 3487 | 82 | 5364 | 77.0 |
| Middle school and above | 764 | 18 | 1600 | 23.0 |
| Family wealth | | | | |
| Low | 2225 | 52.3 | 2935 | 42.1 |
| High | 2026 | 47.7 | 4029 | 57.9 |
| Smoking | | | | |
| No | 2439 | 57.4 | 4770 | 68.5 |
| Yes | 1812 | 42.6 | 2194 | 31.5 |
| Drinking | | | | |
| No | 2905 | 68.3 | 4679 | 67.2 |
| Yes | 1346 | 31.7 | 2285 | 32.8 |
| Exercise | | | | |
| Hardly | 2437 | 57.3 | 5509 | 79.1 |
| Regularly | 1814 | 42.7 | 1455 | 20.9 |
| Social activity | | | | |
| Hardly | 561 | 13.2 | 3451 | 49.6 |
| Regularly | 3690 | 86.8 | 3513 | 50.4 |
| Hypertension | | | | |
| No | 3011 | 70.8 | 4978 | 71.5 |
| Yes | 1240 | 29.2 | 1986 | 28.5 |
| Diabetes | | | | |
| No | 3982 | 93.7 | 6473 | 92.9 |
| Yes | 269 | 6.3 | 491 | 7.1 |
| Cardiovascular disease | | | | |
| No | 3570 | 84 | 5792 | 83.2 |
| Yes | 681 | 16 | 1172 | 16.8 |
| Body mass index (kg/m$^2$) | | | | |
| Underweight (<18.5) | 396 | 9.3 | 532 | 7.6 |
| Normal (18.5–23.9) | 2371 | 55.8 | 3606 | 51.8 |
| Overweight (24.0–27.9) | 1106 | 26 | 2075 | 29.8 |
| Obesity (≥28.0) | 378 | 8.9 | 751 | 10.8 |
| Arthritis | | | | |
| No | 2635 | 62.0 | 4092 | 58.8 |
| Yes | 1616 | 38.0 | 2872 | 41.2 |
| Pain | | | | |
| No | 2780 | 65.4 | 4680 | 67.2 |
| Yes | 1471 | 34.6 | 2284 | 32.8 |
| Hip fracture history | | | | |
| No | 4186 | 98.5 | 6810 | 97.8 |
| Yes | 65 | 1.5 | 154 | 2.2 |
| Cooking fuel | | | | |
| Clean | 1583 | 37.2 | 3688 | 53.0 |
| Solid | 2668 | 62.8 | 3276 | 47.0 |
| Motoric cognitive risk syndrome | | | | |
| No | 3851 | 90.6 | 6508 | 93.5 |
| Yes | 400 | 9.4 | 456 | 6.5 |

95 % CI: 0.57–0.91), while those who started in early adulthood (18–44 years) had a 31 % lower risk (RR = 0.69; 95 % CI: 0.48–0.98). A similar trend was observed among participants who reported initiating clean fuel use in childhood (<18 years), although the association was not statistically significant due to the extremely small sample size ($n$ = 28; RR = 0.61; 95 % CI: 0.09–4.38). The decreasing trend in relative risks from middle adulthood to early adulthood and childhood suggests a potential life course gradient, whereby earlier adoption of clean fuel may confer greater protection against MCRS.

### 3.4. Sensitivity analysis

Fig. 2 presents the results of the sensitivity analysis, in which models were additionally adjusted for average outdoor PM2.5 concentration, temperature, and humidity in the participants' residential cities. The results remained consistent with the primary analysis. In the cohort analysis, clean fuel use at baseline was still significantly associated with a reduced risk of developing MCRS (RR = 0.76; 95 % CI: 0.61–0.96). Regarding fuel-use transitions, participants who switched from solid to clean fuels had a lower risk of MCRS (RR = 0.66; 95 % CI: 0.46–0.96), as did persistent clean fuel users (RR = 0.60; 95 % CI: 0.44–0.83).

In the life course analysis, earlier initiation of clean fuel use remained significantly associated with lower MCRS risk. Participants who began using clean fuel in middle adulthood (45–59 years) and early adulthood (18–44 years) had lower risks of MCRS (RR = 0.73; 95 % CI: 0.57–0.92 and RR = 0.69; 95 % CI: 0.48–0.98, respectively) compared to never users. Clean fuel initiation in childhood (<18 years) was also associated with reduced risk (RR = 0.61), but the estimate was not statistically significant due to small sample size and wide confidence intervals (95 % CI: 0.08–4.36). These findings indicate that the observed protective associations between clean fuel use and MCRS are robust even after accounting for environmental exposures.

In addition, sensitivity analyses using the E-value indicated that the observed associations were moderately robust to potential unmeasured confounding (Supplementary Table S6, Figs. S1–S5). For example, for the association between clean fuel use and MCRS risk, an unmeasured confounder would need to be associated with both exposure and outcome by a risk ratio of at least 1.96 to fully explain away the observed association. Similar findings were observed in the fuel transition and life course analyses. For persistent clean fuel users, the E-value for the point estimate was 2.61 (lower confidence bound: 1.63), and for participants initiating clean fuel use in early or middle adulthood, and E-values ranged from 2.12 to 2.26 for the point estimates. These results suggest that a relatively strong unmeasured confounder would be necessary to

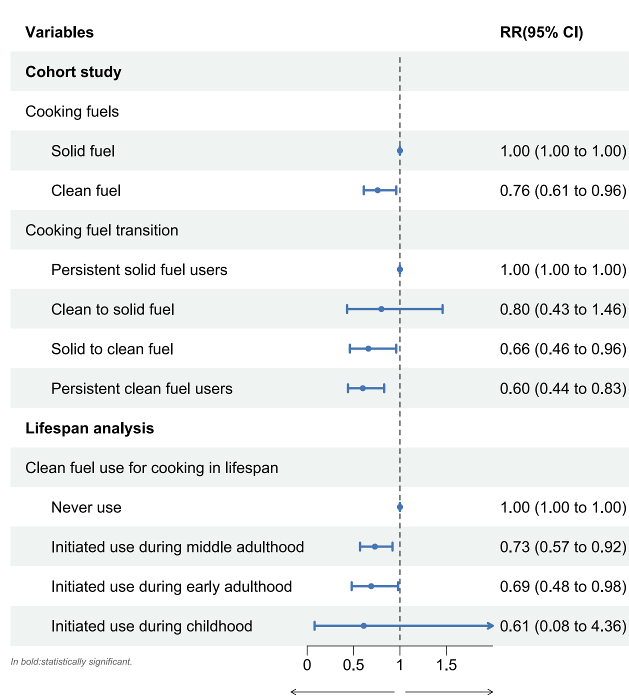


**Fig. 2.** Sensitivity analysis.

**Table 2**
Associations between clean fuel use for cooking, its transition and motoric cognitive risk syndrome in cohort study.

| Variable | Case/n | Model 1 RR (95 %CI) | Model 2 RR (95 %CI) | Model 3 RR (95 %CI) | Model 4 RR (95 %CI) |
|---|---|---|---|---|---|
| Household fuel use | | | | | |
| Solid fuel | 294/2668 | 1.00 (reference) | 1.00 (reference) | 1.00 (reference) | 1.00 (reference) |
| Clean fuel | 106/1583 | 0.59 (0.48–0.74) | 0.71 (0.57–0.9) | 0.73 (0.58–0.92) | 0.76 (0.61–0.96) |
| Cooking fuel transition | | | | | |
| Persistent solid fuel users | 182/1470 | 1.00 (reference) | 1.00 (reference) | 1.00 (reference) | 1.00 (reference) |
| Clean to solid fuel | 11/120 | 0.72 (0.40–1.30) | 0.76 (0.42–1.38) | 0.77 (0.42–1.40) | 0.79 (0.43–1.44) |
| Solid to clean fuel | 35/454 | 0.62 (0.43–0.89) | 0.63 (0.44–0.91) | 0.64 (0.45–0.92) | 0.67 (0.47–0.97) |
| Persistent clean fuel users | 68/1164 | 0.46 (0.35–0.60) | 0.56 (0.41–0.76) | 0.57 (0.42–0.78) | 0.62 (0.45–0.85) |

Notes: "Case/n" = number of participants with MCRS / total number in that fuel-use category. Model 1 was no adjustment; Model 2 adjusted for age, sex, residence, marital status, education level, family wealth; Model 3 adjusted for smoking, drinking, exercise, and social activity based on model 2. Model 4 further adjusted for hypertension, diabetes, cardiovascular disease, body mass index, arthritis, pain and hip fracture history based on model 3.

**Table 3**
Associations between clean fuel use for cooking and motoric cognitive risk syndrome in life course analysis.

| **Clean fuel use for cooking in lifespan** | Case/n | Model 1 RR (95 %CI) | Model 2 RR (95 %CI) | Model 3 RR (95 %CI) | Model 4 RR (95 %CI) |
|---|---|---|---|---|---|
| Never use | 301/3588 | 1.00 (Reference) | 1.00 (Reference) | 1.00 (Reference) | 1.00 (Reference) |
| Initiated use during middle adulthood (45–59 years old) | 114/2294 | 0.59 (0.48–0.73) | 0.69 (0.55–0.88) | 0.71 (0.56–0.9) | 0.72 (0.57–0.91) |
| Initiated use during early adulthood (18–44 years old) | 40/1054 | 0.45 (0.33–0.63) | 0.63 (0.44–0.90) | 0.66 (0.46–0.95) | 0.69 (0.48–0.98) |
| Initiated use during childhood (< 18 years old) | 1/28 | 0.43 (0.06–3.03) | 0.62 (0.09–4.48) | 0.69 (0.10–4.91) | 0.61 (0.09–4.38) |

Notes: "Case/n" = number of participants with MCRS / total number in that fuel-use category. Model 1 was no adjustment; Model 2 adjusted for age, sex, residence, marital status, education level, family wealth; Model 3 adjusted for smoking, drinking, exercise, and social activity based on model 2. Model 4 further adjusted for hypertension, diabetes, cardiovascular disease, body mass index, arthritis, pain and hip fracture history based on model 3. Timing of clean fuel initiation was defined based on self-reported year of first use, transformed into age at adoption, and categorized into life stages. 'Never used clean fuel' refers to participants who reported never using clean fuels for cooking as of 2014.

explain away the observed associations, supporting the robustness of our findings.

## 4. Discussion

In this large-scale, nationally representative survey of older Chinese adults, we explored the association between the cooking fuel use and MCRS using a cohort study and life course analysis. This study's main findings included: (1) clean fuel use for cooking decreased MCRS risk (2) participants who transitioned from solid to clean fuel had a lower MCRS risk (3) the earlier older adults used clean fuels for cooking across different life stages, the lower the MCRS prevalence. These findings confirm the health benefits of clean fuel use and enhance understanding of environmental determinants of MCRS.

The first finding of this study was that clean fuel use for cooking is associated with a lower MCRS risk in older adults. Although no study has focused on this association, studies have explored the association between the cooking fuel use and MCRS components. A cross-sectional study of six low- and middle-income countries, including China, suggested that using unclean cooking fuel is associated with slower gait speed in older adults [45]. Additionally, indoor air pollution is associated with poor memory performance in older people [46,47]. Moreover, individuals who perceived air pollution were more likely to experience subjective cognitive decline [48]. These indirect associations provide a foundation for understanding how indoor air pollution, a consequence of solid fuel use, could be influencing MCRS. This finding aligns with the concept of environmental determinants of health [49], specifically highlighting how exposure to harmful environmental factors such as indoor air pollution can worsen health inequalities. In this case, disadvantaged communities, particularly in rural areas, are disproportionately exposed to solid fuels due to lower socioeconomic status and limited access to cleaner energy sources [50]. This exposure leads to significant public health burdens, which can perpetuate social stratification in health outcomes among older adults.

Two main explanatory mechanisms exist for the association between the cooking fuel use and MCRS. First, compared with clean fuels, inadequate combustion of solid fuels may produce high levels of particulate matter [51], especially fine and ultrafine particulate matter that can be inhaled into human lungs, which increases inflammatory responses and contributes to the development of inflammation-related diseases [52]. In addition, this particulate matter can cross the blood-brain barrier and enter the brain, inducing neurodegenerative changes that increase the risk of cognitive impairment and other neurodegenerative diseases [53]. This mechanism links environmental exposures to neurodegenerative diseases, which are becoming a major focus in understanding how environmental factors impact health, especially due to their social and economic consequences in aging populations. Second, socioeconomic status (SES) plays a crucial role in determining cooking fuel use. Access to clean fuels is often linked to higher SES [32,54]. Older adults with a higher socioeconomic status had a lower MCRS risk [55]. This relationship underscores the social determinants of health framework, which emphasizes that health disparities arise from structural inequalities, such as differences in income, education, and access to resources [56]. In this study, the finding that participants with higher SES were more likely to use clean fuels highlights how social structures shape health behaviors and outcomes, reinforcing the need for social policy interventions that address fuel access and environmental health.

This study also found that participants who switched from solid to clean fuel had a lower MCRS risk than persistent solid fuel users. Similarly, switching from solid to clean fuels mitigates the risk of declining intrinsic capacity in older adults [57]. Although the follow-up period in our study was relatively short (four years), prior three national surveys suggest that changes in exposure to indoor air pollution may affect cognitive decline even in the short to medium term [19]. These findings further confirm the need for and benefits of promoting clean fuels. In addition, the four-year follow-up period (2011–2015) coincided with a critical policy window in China. The 2013 Action Plan for the Prevention and Control of Air Pollution catalyzed national efforts to reduce household air pollution by promoting the substitution of solid fuels with clean energy [58]. This policy shift led to substantial changes in domestic fuel use, particularly in rural areas. As such, the exposure transitions observed during our study period were not only biologically plausible but also temporally aligned with large-scale public health interventions, increasing the likelihood of detecting early neurocognitive effects. However, we found no significant association between the shift from clean to solid fuels and MCRS. This may be related to the small sample size in this study, and further validation is necessary. Although not significant, the RR was <1, which indirectly suggests that clean fuels may have long-term health benefits and a brief shift to solid fuels may not be significantly harmful. Considering that the proportion of solid fuel use remains high in low-income countries [59], these results underscore the potential for public health interventions that encourage fuel transition as a strategy for mitigating health risks associated with environmental exposures.

Another key finding of this study is that older adults who initiated clean fuel use earlier in life had a lower risk of developing MCRS. This finding supports the life course epidemiology framework, which suggests that early-life environmental exposures can have enduring impacts on health trajectories [60,61]. Prior studies, such as the Midlife in the United States Study, similarly showed that early-life adversity is linked to poorer cognitive functioning in later life [62]. This further supports the idea that environmental exposures accumulated over the life span play a critical role in shaping neurocognitive outcomes. Two possible explanations exist for this observation. First, prolonged exposure to pollutants from solid fuel combustion increases oxidative stress and systemic inflammation, which are recognized as contributing to cognitive decline [52,63]. If clean fuels are adopted at a later age, the brain may have already undergone prolonged exposure to harmful particles during sensitive developmental windows. Second, the age at which clean fuel was first adopted is closely tied to socioeconomic conditions. In earlier decades, access to clean energy was limited and usually only available to households with higher incomes, better education, or those living in urban areas, which are all related to cognitive health [64].

Interestingly, while participants who initiated clean fuel use during adulthood or middle age showed significantly reduced MCRS risk, those who initiated clean fuel use in childhood did not show statistically significant protection. This is likely due to the small number of those initiated clean fuel use during childhood in our cohort, given that clean fuels were not widely available in China during the 1950s and 1960s [65,66]. This historical limitation underscores structural inequalities in energy access, particularly among rural and low-income populations [67]. These contextual factors suggest that early adoption of clean fuel was likely limited to families with greater socioeconomic resources, which may themselves contribute to long-term health advantages. While we adjusted for education, residence, and wealth in adulthood, we lacked detailed information on childhood SES and energy infrastructure, which may confound the association. Notably, our exposure categories reflect the age of first clean fuel adoption, rather than the duration or consistency of use. Although this limits the ability to quantify cumulative exposure, it provides insight into the timing of initial transition and its potential relevance for lifelong health trajectories. These findings highlight the importance of addressing structural inequalities in energy access and suggest that early-life environmental interventions may confer long-term cognitive benefits if implemented equitably.

The findings of this study suggest the critical need to address environmental health risks among older adults through transitions to clean energy. This study highlights the interconnectedness of environmental exposure, socio-economic status, and health outcomes, reinforcing the importance of policy interventions that prioritize clean energy access for vulnerable populations. The interventions that help people switch from solid fuels to clean fuels, especially in rural and low-income areas, can bring about significant public health benefits. These benefits may include not only preventing MCRS but also reducing the wider health impacts of indoor air pollution. Moreover, this study emphasizes the critical role of early intervention and the need for life-course approaches in public health strategies. Policies that ensure access to clean cooking fuels throughout a person's life, starting from early childhood, may significantly reduce the long-term burden of MCRS and other neurodegenerative diseases among aging populations. This approach takes into account the cumulative impact of environmental exposures, advocating for policies that address these risks at key life stages to improve health outcomes and reduce inequalities in older age. Ultimately, promoting clean energy use from a young age can contribute to healthier aging, particularly in communities historically disadvantaged by limited access to clean fuels.

This study had several strengths. This is the first study to explore the association between the cooking fuel use, its transition, and MCRS. This study also analyzed the potential benefits of clean fuel use on MCRS from a life-course perspective. Second, this study's findings further extend the prevention of MCRS. Using clean fuels to cook can reduce MCRS risk in pre-dementia stages. Third, we controlled for various covariates in this study's analysis and performed a sensitivity analysis based on an adjustment for outdoor environmental factors, which supported this study's results remain robust. In addition, sensitivity analyses using the E-value indicated that relatively strong unmeasured confounding would be needed to fully explain away the observed associations, further supporting the robustness of our findings. Finally, this study used a nationally representative survey, which enhances the generalizability of our findings to the older adult population in China. These results may also offer important insights for MCRS prevention and clean fuel promotion in other low- and middle-income countries with similar demographic and energy contexts. However, caution should be exercised in generalizing to high-income settings or regions with different energy infrastructures and environmental exposures.

This study had some limitations. First, we excluded individuals without data on MCRS and cooking fuel use due to missing information, which may have led to selection bias. The assumption of data missing at random may not fully hold in this context, as participants who did not complete the physical function assessment could differ systematically in health status or cognitive function. This limitation may introduce bias, and our findings should be interpreted with caution in light of potential non-random missingness. Our life course analysis focused on the age at which participants first started using clean fuel, rather than the duration or consistency of its use. This method helped us minimize cohort bias and investigate the timing of exposure, but it does not account for the cumulative fuel use over time. Additionally, early adoption of clean fuel could indicate not just environmental improvements but also underlying socioeconomic advantages, such as higher education levels, urban living, or greater household wealth, particularly in earlier decades when clean fuels were less available in rural areas. Additionally, we excluded participants who switched cooking fuel types multiple times during follow-up, which may have introduced selection bias. These individuals may represent households with unstable energy access, limited fuel affordability, or less awareness of the differences between fuel types. While this exclusion was necessary to maintain exposure classification consistency, future studies could explore the characteristics and health outcomes of this transitional group to better understand the dynamics of household energy behavior during periods of environmental or policy change. Second, our study may face issues related to measurement error and information bias. The evaluation of subjective cognitive complaints was based on self-reports, which can be influenced by personal interpretation, mood, and educational background. Similarly, the retrospective recall of when participants began using clean fuel may not be accurate, especially among older or less-educated individuals. These factors could lead to misclassification of exposure or outcomes. Third, while our analyses accounted for a broad spectrum of sociodemographic, behavioral, and health-related factors, we cannot completely rule out the possibility of residual confounding (such as fuel usage volume and kitchen ventilation frequency). In observational studies, negative control analyses are increasingly recommended to identify the potential impact of unmeasured confounding variables [68]. Unfortunately, the CHARLS dataset lacks suitable candidate outcomes or exposures that are biologically unrelated to cognitive function but may still be linked to confounders like socioeconomic status or health awareness. For instance, many health-related variables in CHARLS, including cardiovascular disease, diabetes, and physical activity, are known to correlate with cognitive outcomes, making them invalid as negative controls. Future research that includes more comprehensive behavioral or clinical phenotyping should aim to incorporate appropriate negative control variables to enhance causal inference.

## 5. Conclusion

Clean fuel use for cooking and transitioning from solid to clean fuels decreases MCRS risk among older adults. Moreover, earlier adoption of clean cooking fuels is associated with a lower prevalence of MCRS in later life. Future studies should focus on longitudinal investigations with larger sample sizes to confirm the observed associations between the cooking fuel use and MCRS. Additionally, interventional studies are needed to evaluate the effectiveness of transitioning to clean fuels in reducing MCRS risk among older adults. Understanding the mechanistic pathways and cumulative effects of indoor air pollution on cognitive health and considering socioeconomic factors and global perspectives will further enhance our understanding and inform targeted interventions to mitigate MCRS risk.

## Data availability

The data of this study can be obtained on the official website of CHARLS (http://charls.pku.edu.cn/).

## Ethical standards

The study was conducted in accordance with the Declaration of Helsinki. CHARLS was approved by the Biomedical Ethics Review Committee of Peking University (IRB00001052-11015), and all participants provided informed consent.

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## Declaration of generative AI and AI-assisted technologies in the writing process

This manuscript did not use any artificial intelligence at all.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Guanghui Cui:** Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Shaojie Li:** Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Weiwei Li:** Writing – review & editing, Validation. **Xuezhi Zhang:** Writing – review & editing, Validation.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tjpad.2025.100227.

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