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Carbon monoxide levels in households using coal-briquette fuelled stoves exceed WHO air quality guidelines in Ulaanbaatar, Mongolia

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ABSTRACT

In 2019, a domestic raw coal ban (RCB) was introduced in Ulaanbaatar, Mongolia.Coal-briquettes have since been promoted in Ger district households, however implications for carbon monoxide (CO) exposure remains uncertain. We obtained 48-hour indoor CO concentrations in 23 Ger district households and compared these to 10 raw-coal households. Information on household characteristics, fuel use behaviour and stove venting practices was collected by survey. Mean 48-hour CO concentrations coal-briquette households was 6.1 ppm (range 1.5–35.8 ppm) with no signficant differences by household, stove or venting factors. Peak time-weighted average CO concentrations exceeded WHO Indoor Air Quality guidelines in 9 (39%) households; with all surpassing the 8-hour guideline (>8.6 ppm); 3(13%) the 24-hour guideline (>6 ppm) and 2(9%) the 1-hour guideline (>30 ppm). Median CO levels were significantly lower in coal-briquette compared to raw coal households ($p = 0.049$). Indoor CO reduction was associated with RCB implementation although hazardous levels persistin this setting.

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Indoor air quality; household air pollution; carbon monoxide, coal; mongolia

Introduction

Exposure to elevated levels of air pollution is consistently linked to adverse health effects across the human lifecourse, particularly affecting vulnerable populations such as pregnant women, neonates, and children (RCP 2016). Mongolia's capital city, Ulaanbaatar, experiences exceptionally high levels of air pollution in the winter months with average temperatures of −20° C, when ambient daily average fine particulate matter ($PM_{2.5}$) concentrations exceed 600 µg m^{-3} on the coldest days (UNICEF, 2016). Domestic coal combustion among low-income households in Ger (Mongolian traditional tent household) districts surrounding the capital has been recognised as the major source of ambient pollutant emissions, along with four power plants and vehicle emissions (Davy et al. 2011).

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In an effort to improve ambient air quality, the Mongolian national government introduced a ban on sale and use of raw coal for domestic heating and cooking in Ulaanbaatar from May 2019. The raw coal ban (RCB) policy package comprised a range of supporting measures to facilitate domestic fuel transition, including promoting, subsidizing, and distributing low(er) polluting 'coal-briquettes' (hereinafter simply referred to as briquettes) for domestic heating and cooking, typically branded as 'healthy coal'. Similar fuel restriction or transition policies in other settings have been suggested to improve air quality and health (Clancy et al. 2002; Zhang and Smith 2007; Liu et al. 2019; Zhang et al. 2021); however, effectiveness of a RCB in the Mongolian context has not yet been subject to robust evaluation. Further such policy interventions risk unintended policy consequences beyond the area of intended action (e.g. poverty, hypothermia, fuel substitution).

Since implementation of the RCB there have been several reports of acute carbon monoxide (CO) poisoning cases in Ger district households suggested to be linked to the widespread adoption of domestic coal-briquette use (Ankhtuya 2019; Jun 2021). Chronic exposure to high CO concentrations could also lead to serious health consequences, including death. Pregnant women, their foetuses and young children are particularly at risk from chronic CO exposure and high exposure can lead to reduced blood oxygen levels with multi-organ consequences. (WHO 2000). However, there is currently limited information on the domestic air quality impacts of coal to briquette fuel transition at a household level. Furthermore, evidence for impacts upon CO concentrations is lacking in this setting and is relevant to identify the need for further indoor air quality interventions in this context.

This cross-sectional study therefore aimed to identify RCB impacts upon household CO concentrations among a sample of Ger district households in Ulaanbaatar following introduction of the RCB policy. Our specific objectives were (i) to characterise indoor CO concentrations amongst coal-briquette Ger district households in Ulaanbaatar; (ii) to report household characteristics and fuel use behaviour and relationship with CO concentrations; (iii) to compare CO levels between households using coal-briquettes (post-RCB) versus those using raw coal (pre-RCB); (iv) to identify any fatal cases of acute CO poisoning in study households.

Methods

Study setting and population

This study was conducted in five selected districts of Ulaanbaatar, Mongolia (Bayangol, Bayanzurkh, Chingeltei, Sukhbaatar, and Songinokhairkhan districts) (Soyol-Erdene et al. 2021). Large areas within these official districts are comprised of so-called Ger districts, characterised by low-resource households, which were originally Gers (traditional Mongolian nomadic tents) but now a combination of Gers and rudimentary houses made from cement and/or wood (Figure 1). Ger district households often lack basic infrastructure and typically rely on solid fuel stoves for cooking and heating.

The majority of Ger district inhabitants are rural migrants with low and middle socio-economic status, who have left nomadic lifestyles in search for better prospects in the capital. Often unable to afford official housing in the city, settlement in Gers or rudimentary houses in the peripheral Ger districts is the only option.

While the use of traditional Mongolian stoves is the typical method of domestic heating in Ger households, previous air pollution mitigation interventions such as provision of subsidies for improved stoves and discounted tariffs to night-time electricity have caused a more recent shift in cooking and heating sources (World Bank 2009). Introduction of the RCB policy is also likely to have caused further changes in typical traditional heating and cooking practices (Jun 2021).

Figure 1. Traditional Mongolian Ger household (top left), rudimentary cement house (top right), cement/brick house (middle), traditional stove (bottom left) and improved stove (bottom right). Please add the additional photograph uploaded in the centre (total five photos) this is a cement-brick house

Data collection

People living in Ger district households were invited to participate in this study . Inclusion criteria for study participation was residing in a household located in the Ger district with residents reliant upon stoves for cooking and/or heating between January – April 2021 and located within the RCB policy jurisdiction. Households were excluded if residents had COVID-19 symptoms, or a positive COVID-19 test within the past 14 days at the time of study recruitment. Applying these criteria convenience sample of 23 households was selected by fieldworkers undertaking door-to-door sampling and recruitment.

Air quality, demographic and household data collection was conducted by fieldworkers who were medical students attending the Mongolian National University of Medical Sciences. Fieldworkers were trained to collect indoor air quality and survey data, which was followed by a pilot data collection session.

Household air quality measurements

Indoor measurements of CO and temperature/humidity data were collected by continuous 48-hour monitoring with data-logging at 1-minute intervals. Factory calibrated electrochemical Lascar EasyLog EL-USB-CO Carbon Monoxide Data Loggers (Lascar Electronics Ltd, PA, US) were used, with a measurement range of 0 to 1000 ppm and accuracy of ± 7 ppm, a lower Limit of Detection (LOD) of 3 ppm, and temperature range of −10 to +40°C. CO measurements below the LOD of 3 ppm were substituted with a constant half value of 1.5 ppm.

Indoor temperature and humidity measurements were collected using Lascar EL-USB-2 Temperature & Humidity Data Loggers (Lascar Electronics Ltd, PA, US). All measurement devices were co-located at a standardised distance of 1.5 m from the main stove at respiratory height to ensure comparability with previous studies (Bartington et al. 2017). Data collected outside of the Lascar EasyLog EL-USB-CO Carbon Monoxide Data Loggers temperature ranges were excluded.

All data were downloaded onto windows-based laptops immediately following data collection using EasyLog software (Lascar Electronics Ltd, PA, US).

Household survey

Residents living in study households were asked to complete a survey assessing information on household characteristics, demographics, fuel use, and venting practices (appendix a). Household characteristic questions included household, stove, and chimney type, as well as household dimensions and layout, including information on stove location relative to windows/doors and living area. Furthermore, the survey assessed average daily frequency for restoking stoves and opening windows, doors, or top vents (locally referred to as 'Toono'). Real-time fuel use and venting practices data were also collected through self-assessment logs concurrent to air quality monitoring. Participants were asked to log each restoke and venting event, as well as the presence and notifications of any CO alarms. Household demographic information included household size (number of residents), age and occupation for all household members. Surveys were administered by telephone or in person, depending upon COVID-19 measures in place at the time of data collection.

Data analysis

Descriptive analysis was undertaken to identify household hourly CO average concentrations (arithmetic mean, geometric mean and median), ranges, standard deviations, and standard errors. Household characteristics and fuel use behaviour were assessed and presented in counts and percentages. To assess and identify overall diurnal patterns in our study population, an average time series was plotted using the hourly geometric means, with standard errors. To identify which households were exposed to hazardous CO concentrations, average household hourly CO levels were assessed against the reference values from the 2021 WHO indoor CO concentration guidelines for 24-hours (6 ppm), 8-hours (8.6 ppm), 1-hour (30 ppm) and 15 minutes (85 ppm). Households surpassing any of these reference threshold values for the required consecutive time duration, were categorised as high-risk households and plotted for visualisation. Due to the small sample size, with subgroup frequencies of <5, associations between household, fuel use or venting characteristics and risk of surpassing the WHO standards were assessed using the Fisher's exact test (Kim 2017). Sub-group analysis was performed using Mann-Whitney U-test to compare the average CO levels between the following household sub-groups: building type (Gers, cement/wood houses), stove type (traditional or improved), as well as location and average amount of ventilation (through questionnaire). Associations between CO levels and average venting and restoking times were tested using non-parametric Kruskal–Wallis tests. Linear regression was used to determine the relationship between CO levels, restoking times and household size. For all statistical analyses a p-value less than 0.05 was considered statistically significant.

An additional analysis was undertaken to compare indoor CO concentrations between raw coal and briquette fuel households, using retrospective data obtained from 10 Ger district raw-coal households. This data was collected in a preliminary study in the winter of 2019–2020, in an area that at the time was outside of Ulaanbaatar RCB policy jurisdiction. Data collection methods were similar to the present study, but with 24-hour monitoring instead.

Results

Household and fuel use characteristics

In total, 23 households were included in the study, with key household and fuel use characteristics shown in Tables 1 and 2. Data was obtained from both cement/wooden-built households (65%, n = 15) and traditional Gers (22%, n = 5). All respondents indicated they had transitioned from raw coal to briquettes since introduction of the RCB. Briquettes were found to be the primary heating source in all household (100%, n = 23) and many households also used the briquettes for cooking (65% n = 15). While all households used either traditional (70%, n = 16) or improved (30%, n = 7) stoves, the majority (96%, n = 22) had access to electricity. 74% (n = 17) used the electricity for an electric stove, which was predominantly used as a secondary source for cooking (48%, n = 11). Only one household used electricity for heating, in the form of a small electric radiator. Dung and household garbage were used rarely, by 4% (n = 1) and 13% (n = 3), respectively, and always as a secondary fuel source. Stoke restoking times ranged from 3 to 6 times a day, with paper or dry wood used alongside briquettes.

The stove was in the main living area in most households (83%, n = 19), of which 53% (n = 10) had either a window or door near the stove, while 47% (n = 9) of households did not have any form of ventilation nearby. Venting rates using windows and doors were low, with 74% (n = 17) of respondents indicating to open windows once or less a day, and front doors only being opened once a day or when passing through (61%, n = 14).

Household CO levels

The overall geometric mean (SD) and median (IQR) CO concentration for all 23 participating households was 6.1 (7.1) and 9.0 (1.5–9.0), respectively. Ger households had average CO measurements of 3.8 (5.1) and 1.5 (1.5–7.3), compared to cement/wooden household whose average concentrations were 7.6 (8.8) and 4.5 (1.5–10.0). Of the 23 households, peak CO time-weighted average concentrations in nine (39%) surpassed WHO indoor guidelines. All nine surpassed the 8-hour guidelines of 8.6 ppm, three (13%) surpassed the 24-hour guidelines of 6 ppm, and two (9%) the 1-hour guidelines of 30 ppm for the required consecutive amount of time. Figure 2 illustrates the temporal pattern of CO concentrations in a single household broadly representative of those

Table 1. Household characteristics.

Household characteristics (total n=23)		
Variable		Frequency (%)
Household type	Ger	5 (21.7)
	Cement house	15 (65.2)
	Wooden house	1 (4.4)
	Combined house (wood/cement)	2 (8.7)
District	Bayangol	1 (4.4)
	Bayanzurkh	8 (34.8)
	Chingeltei	4 (17.4)
	Sukhbaatar	9 (39.1)
	Songinokhairkhan	1 (4.4)
Primary stove type	Traditional	16 (69.6)
	Improved	7 (30.4)
Stove location	Separate from living area	4 (17.4)
	In living area near door/window	10 (43.4)
	In living area not near door/window	9 (39.1)
Chimney type	Wall	14 (60.9)
	Metal	8 (34.8)
	Other	1 (4.4)
Primary fuel type	Briquettes	23 (100)
Electricity	Access to electricity	22 (95.7)
	Use of night-time electricity discount	21 (91.3)
	Electricity used for secondary stove	17 (73.9)

Table 2. Fuel use characteristics.

Fuel use characteristics (total n=23)		
Fuel type	Cooking Frequency (%)	Heating Frequency (%)
Briquettes	15 (65.22)	23 (100)
Wood	15 (65.22)	23 (100)
Electricity	11 (47.83)	1 (4.35)
Gas	5 (21.74)	0 (0)
Paper	0 (0)	1 (4.35)
Household garbage	0 (0)	3 (13.04)
Dung	23 (100)	0 (0)

surpassing the WHO guidelines. Household or fuel use characteristics were shown to have no significant impact on likelihood of surpassing the WHO standard, including household type (Ger vs cement and/or wood houses, $p = 0.61$), stove type (traditional or improved, $p = 0.34$), location to ventilation (ventilation in same room vs not in the same room $p > 0.99$) or whether ventilation was done more or less than once a day $p = 0.42$). Despite high CO concentrations in many households, none of the participants indicated they had experienced notifications from their government CO alarms, if present ($n = 9$). Further assessment revealed that the majority (who had access to a smoke alarm) did not use their CO alarms, which was primarily due to not knowing how to use it (n = 5 X%).

Due to the data skewness, subgroup analysis was performed using household median hourly CO levels. Subgroup analysis of all households ($n = 23$) showed that there were no significant differences in CO levels between household type ($U = 28.0$, $p = 0.20$), stove type ($U = 53.5$, $p = 0.87$), location to ventilation ($U = 49.5$, $p = 0.37$) or average amount of ventilation ($U = 64.5$, $p = 0.99$), as shown in Table 3. Furthermore, there was no relationship found between restoking times ($R^2 = 0.13$, $p = 0.11$), household surface area ($R^2 = 0.07$, $p = 0.22$) and CO levels.

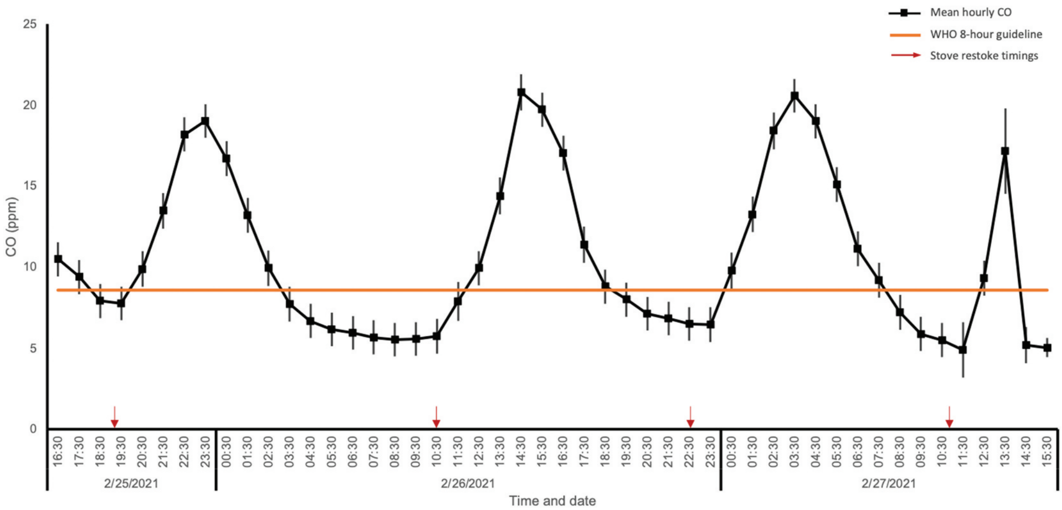

Figure 2. Mean hourly CO (ppm) concentrations and SDs continuously measured over a 48-hour period in a household surpassing the 8-hour (orange line) WHO indoor CO guideline. Red arrows indicating stove restoke timings with paper/wood.

Table 3. Subgroup analysis between household type (Ger vs cement or wood house), stove type (traditional vs improved), located near ventilation (ventilation in same room vs not in the same room) and venting frequency venting once or less vs more than once a day).

Subgroup	N	Mean (SD)	Median (IQR)	N	Mean (SD)	Median (IQR)	Mann-Whitney U
Household type	**Ger**			**House (cement, wood or cement and wood construction)**			U = 28.0, p = 0.20
	5	3.8 (5.1)	1.5 (1.5–7.3)	18	7.6 (8.8)	4.5 (1.5–10.0)	
Stove type	**Traditional**			**Improved**			U = 53.5, p = 0.87
	16	7.2 (9.5)	1.5 (1.5–8.8)	7	5.6 (5.4)	3.5 (1.5–11.0)	
Venting location	**Near ventilation**			**Not near ventilation**			U = 49.5, p = 0.37
	14	6.5 (9.8)	1.5 (1.5–8.8)	9	6.7 (6.1)	5.0 (1.5–10.0)	
Venting frequency	**Venting ≤1**			**Venting ≥1**			U = 64.5, p = 0.99
	13	7.6 (10.4)	1.5 (1.5–10)	10	5.4 (4.9)	3.3 (1.5–8.9)	

An average time series of all households was made to assess and identify the overall diurnal pattern in our study population (Figure 3), showing clear peaks at mid-morning, early evening, and midnight.

Fuel type comparisons

Retrospective data previously collected obtained raw coal using households (n = 10) in our preliminary study in the winter of 2019–2020, were compared our current briquette findings to assess differences in CO levels (Figure 4). Median household CO levels were shown to be significantly lower in the briquette households, compared to those in which raw coal was the primary fuel (p = 0.049).

Discussion

Ulaanbaatar's ambient air pollution levels during winter months have led to a public health crisis, directly and indirectly affecting its residents health (Warburton et al. 2018). Numerous small- and large-scale initiatives to reduce air pollution emissions have been introduced in the capital over the

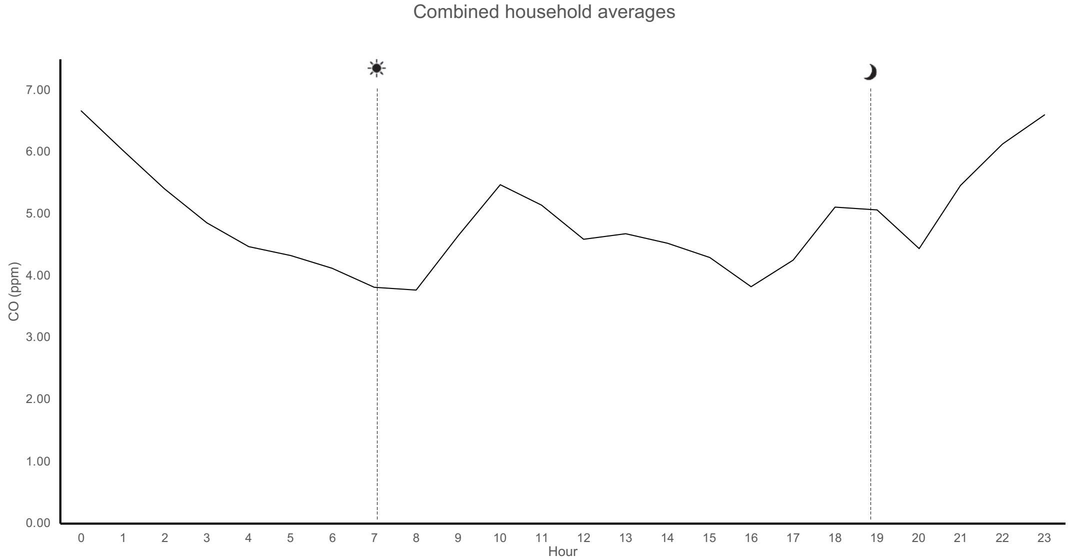

Figure 3. Average diurnal pattern of combined mean hourly household CO (ppm) concentrations. Dashed lines giving an indication of average sun rise (left) and sun set (right) in our study period. Peaks shown in morning, early evening, and midnight.

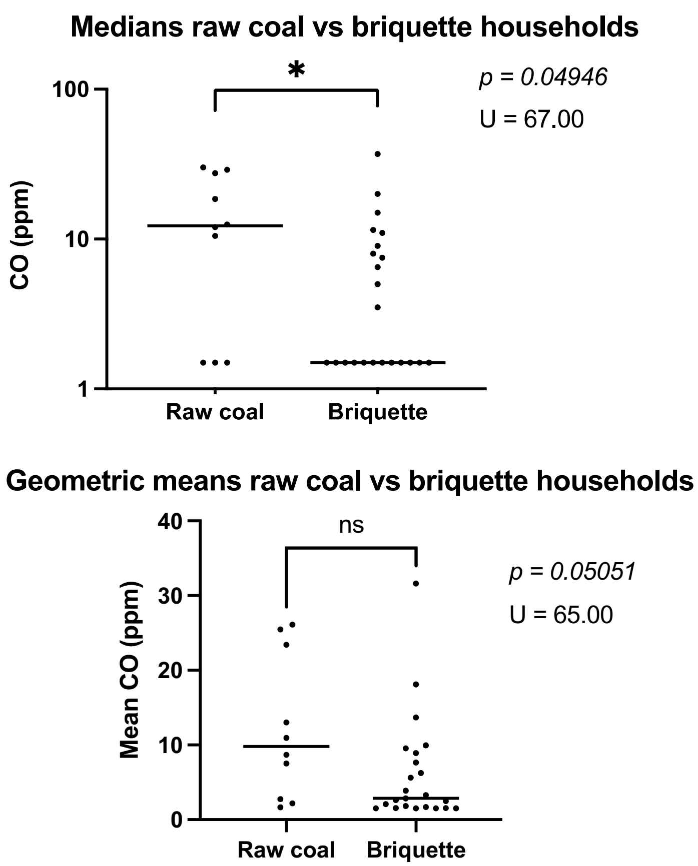

Figure 4. Median CO (ppm) levels of household using raw coal (left) versus briquettes as primary stove fuel.

past decade. The most recent citywide ban on raw coal, initiated in May 2019, was shown to be widely adopted throughout the highly polluting Ger districts of Ulaanbaatar. The phasing out of raw coal combustion is also critical for progress towards UN Sustainable Development Goal 7, to ensure access to affordable, reliable, sustainable and modern energy for all.

Characterising CO levels and fuel use behaviours in Ger district households following RCB implementation has enabled us to obtain better understanding of policy impacts on a household level. Our findings indicate that the policy itself has been effective in reducing domestic use of raw coal, and that coal-briquettes, have been widely adopted as a primary energy source for heating and cooking in the target households. Our results suggest that indoor CO concentrations among coal-briquette households are lower than previous concentrations in raw coal households, indicating potential benefits of the RCB for reducing overall domestic CO exposure, yet levels may still exceed WHO IAQ guidelines.

Our findings are broadly consistent with those obtained in a previous study (Cowlin et al. 2005) which identified that residents of Gers using coal-fuelled traditional or improved stoves were regularly exposed to high levels of air pollutants, including CO. Similar to our study, (Cowlin et al. 2005) did not find any significant differences in CO levels between households using traditional or improved stoves, however they did identify that the amount of fuel used as well as restoking times throughout the day to be positively correlated with levels of emissions. These findings suggest an influence of fuel use practices on indoor air quality, which is highly dependent upon individual behaviour, rather than physical factors. Similarly, with the current fuel transition, incorrect use of the briquettes could play a detrimental role upon indoor air quality and therefore effectiveness of the RCB to improve human health.

A further possible contributing factor to measured high CO levels is the influx of highly polluted ambient air into the households. Both types of stoves used in Mongolia (improved and traditional) are so-called closed combustion stoves with chimneys and top vents, which causes most of the pollutants to be emitted to the ambient air. Therefore, as stated previously by Cowlin et al. (2005), it is likely that detected indoor CO levels are predominantly a result of opening the stove for restoking or cooking. Influx of highly polluted ambient air during venting, when passing through the house door or air leaks could be another source of the CO measurements(Roh et al. 2021). Earlier findings on CO exposure in Mongolian children, showed CO exposure to be significantly higher in urban living children, compared to rural children (Dashdendev et al. 2011). These urban children predominantly lived in apartments and thus were merely exposed to ambient air pollution when outside or through influx through windows, compared to rural children who lived in clean ambient air and who only were exposed to indoor sources of air pollution. Findings in that study (Dashdendev et al. 2011) suggest that ambient air is a relevant factor to consider when assessing overall exposure.

The fairly stable boundary layer in Ulaanbaatar's cold winter atmosphere, which can particularly affect ambient pollution dispersion during the drop in temperature after sunset, could contribute to increased indoor CO levels at night which we found in several of our households (Soyol-Erdene et al. 2021). While ambient CO is likely to have impacted our indoor CO measurements to some extent and ideally information would be available on the insulation and air exchange rates for participating households. However, ambient air pollution was, however, unlikely to play a major role in our measured CO levels due to the fact that i) we identified clear increases in CO after restoking events, as indicated in participant logs, followed by gradual declines; ii) venting rates in our study population were found to be remarkably low, with almost three-quarters of the households indicating opening windows once or less a day iii) we found a large inter-household variation in CO means, with some hourly and 24-hour averages being below the detectable line, yet venting rates and district ambient air quality were fairly heterogenous; (iv) all measurements were taken in close proximity to the emissions source (stove).

Although our data does not provide any evidence for increased indoor CO concentrations following introduction of the RCB, understanding broader impacts of fuel use behaviour upon

CO concentrations should be a key priority for future air pollution mitigation strategies. The impact of the characteristics of the supplied briquettes is also an important aspect to consider. Further to CO levels, steep increases in ambient SO_2 levels (41% compared to before RCB) have been noted by local air quality monitoring stations since implementation of the RCB, which is hypothesised to be due to the sulphur content of the briquettes being higher than the raw coal being used previously (Soyol-Erdene et al. 2021). Similarly, concerns about the carbon content in the briquettes have been raised, and therefore further investigations on the composition and emission profiles of the distributed briquettes are therefore clearly necessary. Further research is therefore required to understand the contribution of briquettes to other indoor air pollutants associated with solid fuel combustion, including particulate matter, sulphur, poly aromatic hydrocarbons (PAHs), black carbon (BC) and brown carbon (BrC) (Shen et al. 2021).

Although we did not identify any cases of fatal CO poisoning in this current study, within the first winter months following the introduction of the RCB (October – December 2019), there were reports of roughly one thousand carbon monoxide (CO) poisoning cases and eight CO-related deaths that occurred in Ger district households using coal-briquette fuel (Oyunchimeg 2020; Jun 2021). A case-based assessment of these CO poisoning incidents revealed most cases were related to damaged stoves, blocked chimneys, poor stove handling and incorrect use of the briquettes (Ankhtuya 2019; Oyunchimeg 2020; Jun 2021).

As a result of these concerns, the Ulaanbaatar Health Department, Emergency Management team introduced a media campaign targeting correct use of the fuel alternatives, alongside mass CO alarm distribution in the Ger district households. However, when assessing our data on CO alarm use, we found that most households either did not have an alarm, did not know how to use it and/or had it turned off. Since then, efforts to raise awareness on the dangers of high CO levels, with clearer instructions on CO alarm use are ongoing. A smaller but still concerning amount of 430 CO poisoning cases were reported at the beginning of the 2021 winter season, of which 198 were children (UNEN 2021). These continuing incidents suggest either alternative causes to the problem such as profound difficulties in briquette use, hazardous briquettes compositions or, alternatively, raised awareness on an already concerning CO problem.

A key limitation in our study was the presence COVID-19 restrictions which restricted field-workers from being physically present in the household when air quality measurements were taken which would improve accuracy and comparability. However, to mitigate these impacts fieldworkers did remain in contact touch with household residents throughout the data collection period to ensure devices were employed correctly or assist with any difficulties with the devices. While our study could have been strengthened by including ambient air measurements, direct co-temporal fuel comparisons and a larger sample size, we were able to capture and characterise household air quality and fuel use behavior during a turbulent year of both a fuel transition and a pandemic. The findings in this study are an important component of RCB evaluation including impacts upon indoor and ambient air quality, and ultimately population health.

Conclusions

In this study, we have identified that transitioning from raw coal to coal-briquettes among Ger District households in Ulaanbaatar is associated with reduced indoor CO concentrations; however, levels may still exceed WHO health-based guidelines in this context. We did not identify any influence of household characteristics on indoor CO levels, however further large-scale studies are required to understand the impact of specific behavioural factors including handling and use of coal-briquettes on CO emissions and exposure in this context. Future research is also necessary to understand broader RCB impacts, including upon energy costs, access, and availability, indoor and ambient air quality, health, and quality of life of those living in the city.

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Data deposition

Data reported in this study are available from the authors upon request.

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