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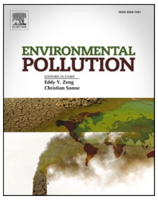

Household carbon monoxide (CO) concentrations in a large African city: An unquantified public health burden?☆

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ABSTRACT

Carbon monoxide (CO) is a poisonous gas produced by incomplete combustion of carbon-based fuels that is linked to mortality and morbidity. Household air pollution from burning fuels on poorly ventilated stoves can lead to high concentrations of CO in homes. There are few datasets available on household concentrations of CO in urban areas of sub-Saharan African countries. CO was measured every minute over 24 h in a sample of homes in Nairobi, Kenya. Data on household characteristics were gathered by questionnaire. Metrics of exposure were summarised and analysis of temporal changes in concentration was performed. Continuous 24-h data were available from 138 homes. The mean (SD), median (IQR) and maximum 24-h CO concentration was 4.9 (6.4), 2.8 (1.0–6.3) and 44 ppm, respectively. 50% of homes had detectable CO concentrations for 847 min (14h07m) or longer during the 24-h period, and 9% of homes would have activated a CO-alarm operating to European specifications. An association between a metric of total CO exposure and self-reported exposure to vapours >15 h per week was identified, however this were not statistically significant after adjustment for the multiple comparisons performed. Mean concentrations were broadly similar in homes from a more affluent area and an informal settlement. A model of typical exposure suggests that cooking is likely to be responsible for approximately 60% of the CO exposure of Nairobi schoolchildren. Household CO concentrations are substantial in Nairobi, Kenya, despite most homes using gas or liquid fuels. Concentrations tend to be highest during the evening, probably associated with periods of cooking. Household air pollution from cooking is the main source of CO exposure of Nairobi schoolchildren. The public health impacts of long-term CO exposure in cities in sub-Saharan Africa may be considerable and should be studied further.

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1. Introduction

Air pollution kills an estimated 6.7 million people per year, with approximately 2.3 million of those deaths arising from household air pollution (HAP) (Fuller et al., 2022) generated mainly from in-home combustion of fuels to cook and/or heat the home. There is also a considerable morbidity burden from a wide range of impacts including cardiovascular events, cancer and stroke (Gordon et al., 2014). Respiratory effects including pneumonia, and exacerbations of asthma and chronic obstructive pulmonary disease are widely believed to be driven by the effects of fine particulate matter ($PM_{2.5}$) and/or oxides of nitrogen (NO_x) released during combustion. Household concentrations of particulate matter in homes burning solid and biomass fuels in low- and middle-income countries (LMICs) have been measured and reported extensively (Fullerton et al., 2009; Quansah et al., 2017; Lim et al., 2022).

Carbon monoxide (CO) is known as the 'silent killer' (as it is odourless and colourless) and incomplete combustion of fuel on simple stoves or open fires can lead to the rapid build-up of CO concentrations in poorly ventilated spaces within homes: globally there are an estimated 29,000 deaths annually attributed to unintentional CO poisoning (GBD, 2021 Carbon Monoxide Poisoning Collaborators, 2023). Much of the research base describing household CO concentrations and impacts derives from high-income countries with the focus on 'leaky' gas-burning heaters, cookers and boilers (McCann et al., 2013; Braubach et al., 2013).

CO is also present in ambient outdoor air, with higher concentrations in large cities often attributed to vehicular traffic (Azhari et al., 2018) and industrial pollution including emissions from coal-fired power stations (Maga et al., 2017). To protect humans from the adverse health effects of CO, the World Health Organisation set guidance values for indoor and outdoor concentrations for particular time durations: 7 mg/m^3 (6 ppm) 24-h interim target 1; 35 mg/m^3 (30 ppm) for 1h; 100 mg/m^3 (87 ppm) for 15 min (World Health Organiz ation and Geneva, 2021).

Data on ambient concentrations from over 300 cities across 18 (mostly high-income) countries are available and report median concentrations ranging from 0.2 to 0.9 mg/m^3 (0.18–0.79 ppm) (Chen et al., 2021). Except for satellite-generated data of tropospheric carbon monoxide (at an altitude of about 12,000 feet) (Pathak et al., 2023), routine monitoring data on ambient concentrations from cities in sub-Saharan Africa (SSA) are not available. It is likely that CO concentrations are high in SSA cities as many vehicles are old, imported, and poorly maintained (Ayetor et al., 2021). Data from other low- and middle-income countries supports this, for example, occupational exposure to CO of motorcycle taxi drivers in Benin reported mean 8-h exposures of 7.6 ppm (Lawin et al., 2016). Low-level chronic CO concentrations (1–5 ppm) have been associated with low-birth weight (Kaali et al., 2023) and, more generally, an increase in daily total mortality (Gordon et al., 2014). Work in Guatemala has also suggested neurodevelopmental impacts related to CO exposure (Dix-Cooper et al., 2012).

Data on exposure to CO in home settings are scarce, with almost all generated from stove-based intervention studies primarily in rural settings in LMICs (Quansah et al., 2017). The RESPIRE study in Guatemala measured CO exposure among pregnant women and reported mean 48-h concentrations of 3.8 ppm (Dix-Cooper et al., 2012). Similarly, the GRAPHS stove intervention study in over 1400 households in Ghana described repeated personal CO in pregnant women with baseline mean 48-h values of 1.5–1.6 ppm (Chillrud et al., 2021). The Cooking and Pneumonia Study (CAPS) reported 48-h personal exposure from over 1900 children in rural villages in Malawi recruited to take part in a cookstove intervention. Baseline mean (SD; range) 48-h CO personal exposure was 0.90 (2.3; 0–49) ppm (Havens et al., 2018). More recently, the HAPIN trial reported data from a liquefied petroleum gas (LPG) fuel and stove intervention trial in rural areas of four countries (Peru, India, Rwanda and Guatemala). Baseline mean household concentrations measured in each country ranged from 1.7 to 4.4 ppm (Johnson et al., 2022).

Many urban populations in cities in SSA have moved to less polluting liquid fuels such as LPG, paraffin and alcohol-based fuels (Shupler et al., 2021). These tend to generate lower particulate emissions but may continue to create high levels of CO when the stove is of poor quality and/or the household ventilation is poor. There are very few data on household CO concentrations in homes in SSA within urban environments. A recent study of an ethanol cookstove intervention in Ibadan, a city in Nigeria, measured (but did not report) the personal exposure of 324 pregnant women to CO (Alexander et al., 2018). Despite the fact that most studies measuring CO exposure have used devices that provide temporal data on concentrations (typically with a 1-min) resolution, we are not aware of any studies that have reported on how concentrations or exposures vary with time: 8h, 24h or 48h mean or median values tend to be the exposure metric of choice (Quansah et al., 2017). There is a lack of data on variability between homes in similar settings, and, importantly, whether in-home sources (generally cooking fuel combustion) or traffic pollution are the most important contributors to measured exposure.

This paper utilises data gathered from the Tupumue study where air pollution concentrations were measured for 24h in nearly 200 homes across two contrasting areas of Nairobi, Kenya, an informal settlement and a neighbouring more affluent area. The Tupumue findings in relation to child respiratory health (Meme et al., 2023a) and birthweight (Meme et al., 2023b) have been reported elsewhere. Data on measurements of household fine particulate matter ($PM_{2.5}$) from this cohort demonstrate that children living within the informal settlement of Mukuru have approximately twice the daily $PM_{2.5}$ exposure of children in more affluent area of Buruburu (38 $\mu g/m^3$ v 20 $\mu g/m^3$) (Meme et al., 2023a).

This paper presents a sub-study of Tupumue that aimed to examine: (i) in-house CO concentrations and the potential determinants of these concentrations; and (ii) temporal variation in CO concentrations over the course of the day. In addition, this study aimed to model the proportion of a typical schoolchild's daily CO inhaled dose likely to be from evening household cooking within the home.

2. Methods

2.1. Participants and recruitment

Full details of the study setting, community involvement and sensitisation, and the recruitment process are available elsewhere (Meme et al., 2023a; Meme et al., 2023b). In summary, children were recruited from two areas (Mukuru and Buruburu) in Nairobi, Kenya. Mukuru is a large informal settlement covering approximately 450 acres in a heavily industrialised area. Housing here is high density and of low quality with poor sanitation and a lack of many basic amenities. Buruburu is a neighbouring, relatively affluent, planned, residential neighbourhood constructed in the 1970–1980 period with approximately 5000 three-bedroomed houses mainly occupied by business people and professionals. The Tupumue (Swahili: 'let us breathe') project recruited 2373 children (1277 from the Mukuru area; 1096 from Buruburu) aged 5–18 years attending school in Nairobi.

Ethical approvals were provided by the Kenya Medical Research Institute (KEMRI) Scientific and Ethics Review Unit (KEMRI/SERU/CRDR/045/3944) and the Liverpool School of Tropical Medicine Research Ethics Committee (19–069). Parents/guardians provided written informed consent with children providing written assent.

A subset of around 100 participants from each community were randomly selected and invited to participate in the air quality monitoring component of the study.

2.2. *Household carbon monoxide (CO) measurement*

Carbon monoxide concentrations were measured within participating households using LASCAR EL-USB-CO300 loggers (Lascar Electronics Ltd, UK). These standalone electrochemical sensors have a measurement range of 0–300 ppm with a resolution of 0.5 ppm. Devices were set to log concentrations every minute. Stored data were downloaded to a laptop computer at the end of each household visit using EasyLog USB software (Lascar Electronics Ltd, UK).

Factory-calibrated devices were installed in homes by trained fieldworkers recruited from the two communities. The Lascar devices were worn by the participating child attached to an armband on the upper arm when they were at home; at other times the device remained in the home and was positioned within the main living area using locally manufactured stands to ensure that devices were 1m from the ground and, where practicable, at least 1m from sources (e.g. a stove) or open doors or windows. Our aim was to gather a full 24-h period of data from each home.

Measurements took place between June and December 2021.

2.3. *Household questionnaire*

Fieldworkers administered questionnaires to parents/guardians of children aged ≤ 12 years and directly to children aged ≥ 13 years. The fieldworkers read out the questions in the respondents' preferred language (Kiswahili or English), with responses entered on electronic tablets.

The questionnaires included demographic information and self-report of potential air pollutant determinants including household energy use, proximity to traffic, refuse burning, the presence of smokers within the home, and household ventilation (the questions asked are detailed elsewhere (Meme et al., 2023a)).

2.4. *Statistical analyses*

Where CO measurement data exceeded 24 h, the first 24 h were used to calculate concentration metrics. For each home the 24-h mean was calculated together with the standard deviation. Median and interquartile range of the 1-min CO concentrations for each household was calculated, as were the number of minutes where non-zero values were recorded, and the number of minutes above particular thresholds (6 ppm, 30 ppm, 87 ppm – reflecting the WHO guidance values (World Health Organiz ation and Geneva, 2021) for particular time durations: 7 mg/m^3 24-h interim target 1; 35 mg/m^3 for 1h; 100 mg/m^3 for 15 min). A CO_cumulative exposure metric was generated: this is essentially the sum of the concentration of each of the 1440 min in the 24-h measurement period.

To better understand the temporal variation and the likely contribution from household cooking activity, the mean concentration during the evening (18:00–24:00) (CO_evening) and during the rest of the day (midnight-6pm) (CO_restofday) was also calculated for each home. The ratio of these two averages (evening: rest of the day) was generated – a value > 1 indicating that evening CO concentrations were higher than the rest of the day.

Characteristics were summarised using frequency (percent) or mean (standard deviation), median (1st, 3rd quartile) depending on distribution. Univariable Gamma regression with a log link was used to estimate association between household characteristics with the potential to influence CO concentrations and three different metrics of CO concentrations (CO_cumulative, CO_evening_mean, and CO_restofday_mean). Bootstrap confidence intervals were estimated. Various graphical methods were applied to visualise the data. Diagnostic plots were inspected visually for fit adequacy. False discovery rate correction (Benjamini-Hochberg (Benjamini and Hochberg, 1995)) was used to correct for multiple comparisons. Data were also interrogated to identify homes that had a CO concentration profile that would have activated a CO alarm operating to EN50291 standard (British Standard Institution. Gas detectors, 2018). The following thresholds were used to identify potential activation: ≥ 30 ppm for 120 continuous minutes; ≥ 50 ppm for 60 continuous minutes; ≥ 100 ppm for 10 continuous minutes; ≥ 300 ppm for 3 continuous minutes.

3. Results

In total 179 households volunteered for detailed air quality monitoring (88 in Buruburu and 91 in Mukuru). Due to logistical issues and data loss, full 24-h CO data were available from 138 of these homes (67 in Buruburu and 71 in Mukuru). The population characteristics of this sample were representative of the wider Tupumue cohort (presented in Table 1).

3.1. *CO concentrations and determinants*

Of the 138 homes where continuous data were available, 134 (97%) had an indication of measurable CO (i.e. ≥ 1 min where CO exceeded the sampler detection limit of 0.5 ppm). The overall summary statistics are shown in Table 2. The mean 24-h CO concentration was 4.9 ppm (SD 6.4), the median was 2.8 ppm (IQR 1.0–6.3 ppm) and the maximum 24-h CO concentration measured was 43.5 ppm. 50% of homes had detectable CO concentrations (≥ 0.5 ppm) for at least 847 min (14h07m) during the 24-h period.

24-h mean CO concentrations were broadly similar in homes in Mukuru (5.1 ppm) and Buruburu (4.7 ppm) ($p = 0.73$). Associations between cumulative CO exposure and self-reported exposure to vapours >15 h per week and with alcohol/ethanol fuel use; and between CO_evening_mean and locality; and between the CO_restofday_mean and stove location, room ventilation (open windows/doors vs none), exposure to vapours >15 h per week, locality and alcohol/ethanol fuel use were present in the uncorrected analysis (Fig. 1). After false discovery rate correction for multiple comparisons, the only remaining significant association was room ventilation open windows/doors with the CO_restofday_mean exposure metric.

Fig. 2 (a)-(d): CO concentration time plots showing 24h measurements from four homes illustrating peaks likely to be from cooking activity. Note that y-axes scales differ reflecting the near 30 times difference in peaks seen in different homes.

3.2. *Temporal variation in concentrations*

The 24-h plots of the CO concentrations in each home provided insight to the temporal patterns and trends, four illustrative examples

Table 1
Population characteristics of the sample of homes where full 24-h CO data were available compared to the full Tupumue dataset.

	Tupumue (n = 2373)	CO sample (n = 138)	P value
Girls (n, %)	1240 (52%)	76 (55%)	0.58
Age (median, IQR)	11 (8, 13)	10 (8–12)	
Exposed vapours, dusts, gases, fumes >15 h/week (n, %)	1380 (58%)	83 (60%)	0.71
Refuse burnt within sight of home (n, %)	815 (34%)	48 (35%)	0.99
Proximity of home to major road (n, %)			
<100m	1123 (47%)	69 (50%)	0.81
100–500m	795 (34%)	43 (31%)	
>500m	455 (19%)	26 (19%)	
Smoker in the home (n, %)	249 (10%)	15 (11%)	1.0
Burn mosquito coils in home (n, %)	539 (23%)	38 (28%)	0.29
Primary cooking fuel in home (n, %)			
Electric/solar	25 (1%)	1 (1%)	0.28
LPG	1448 (61%)	76 (55%)	
Kerosene/paraffin/ethanol	745 (31%)	54 (39%)	
Solid fuel	155 (7%)	7 (5%)	

Table 2

Summary statistics of CO concentrations from the 24-h measurements made in 138 homes in Nairobi, Kenya.

Overall (n = 138)	24h CO (ppm)	For 1-min CO concentrations in each home							
		25th percentile (ppm)	75th percentile (ppm)	Minimum (ppm)	Maximum (ppm)	#non-zero mins	#>6 ppm min	#>30 ppm min	#>87 ppm min
Mean	4.9	2.0	4.1	0.4	43	827	287	27	7.6
SD	6.4	3.5	5.4	1.9	64	556	407	58	34
Median	2.8	0.0	2.0	0.0	20	847	133	0	0
IQR	1.0–6.2	0–2.5	0–5.5	0–0	10–48	286–1406	29–306	0–22	0–0
Max	44	20	26	14	340	1440	1440	333	291

Buruburu (n=67) (affluent area)	24h CO (ppm)	For 1-min CO concentrations in each home							
		25th percentile (ppm)	75th percentile (ppm)	Minimum (ppm)	Maximum (ppm)	#non-zero mins	#>6 ppm min	#>30 ppm min	#>87 ppm min
Mean	4.7	3.0	4.8	0.8	27	781	396	13	0.6
SD	5.0	4.5	6.2	2.7	25	603	504	30	3.6
Median	2.5	0.0	1.5	0	20	631	148	0	0
IQR	0.8–7.2	0–4.5	0–8.2	0–0	13–33	186–1410	27–644	0–4	0–0
Max	23	20	26	14	128	1440	1440	159	25

Mukuru (n=71) (informal area)	24h CO (ppm)	For 1-min CO concentrations in each home							
		25th percentile (ppm)	75th percentile (ppm)	Minimum (ppm)	Maximum (ppm)	#non-zero mins	#>6 ppm min	#>30 ppm min	#>87 ppm min
Mean	5.1	1.0	3.5	0.1	59	871	184	41	14
SD	7.6	1.8	4.3	0.4	83	508	249	74	46
Median	2.9	0.0	2.5	0	24	889	117	0	0
IQR	1.2–5.4	0–1.8	0.5–4.5	0–0	9.0–71	420–1401	34–234	0–55	0–0
Max	44	9.5	25	3	340	1440	1438	333	291

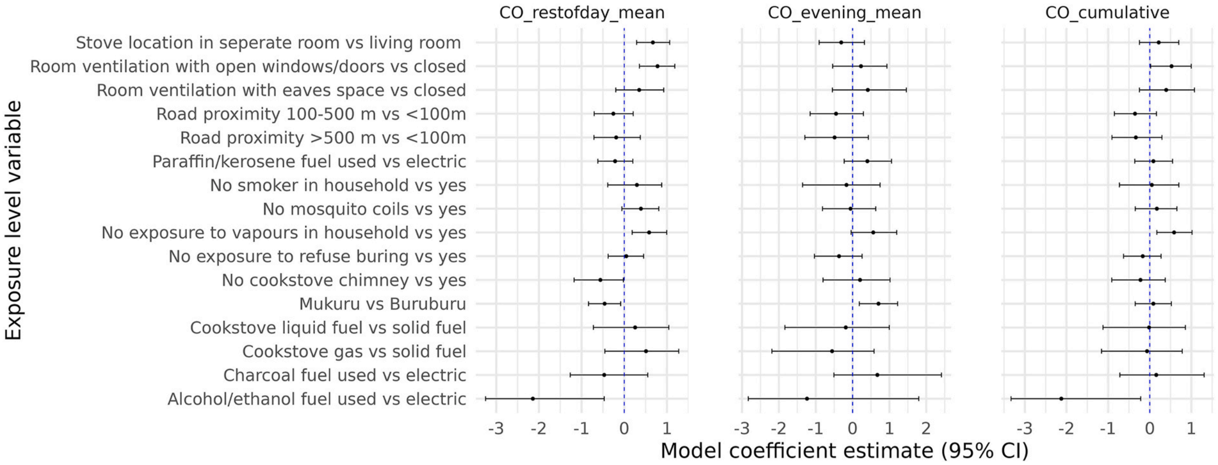

Fig. 1. Associations between selected household exposure variables and CO exposure metrics in univariable regression models. For exposures with multiple levels, all levels except the reference level are presented.

are provided in Fig. 2. Many homes had clear peaks of exposure that are likely to be associated with combustion activity related to cooking within the home (Fig. 2 a-d).

To provide a degree of objective quantification of the temporal changes in CO concentrations we examined the average concentration in the 6-h evening period (18:00–00:00) when cooking activities are most likely to occur. We then compared this value to the 'rest of day' average for the remaining (00:00–18:00) period. The mean value during the evening period was close to three times greater than the concentration during the 'rest of day' period (9.3 ppm (SD 18) v 3.5 ppm (SD 4.2)). In 112 (81%) of homes the evening period had a higher CO concentration compared to the rest of the day.

Temporal data also enabled identification of which homes would have activated a CO alarm operating to the European EN50291 standard. We identified that 13 of the 138 (9.4%) homes would have activated a CO alarm on the day of measurement. Conditions for alarm activation were more common in Mukuru (11/71) than in Buruburu homes (2/67) (Fisher exact test; p = 0.017).

3.3. *Potential sources and proportion of daily dose from household emissions*

To our knowledge there is no routine monitoring of CO concentrations in ambient air in Nairobi. Our study demonstrated concentrations below the limit of detection (0.5 ppm) in over 84,000 (43%) of the 1-min measurements within households. Other global data from 18 countries

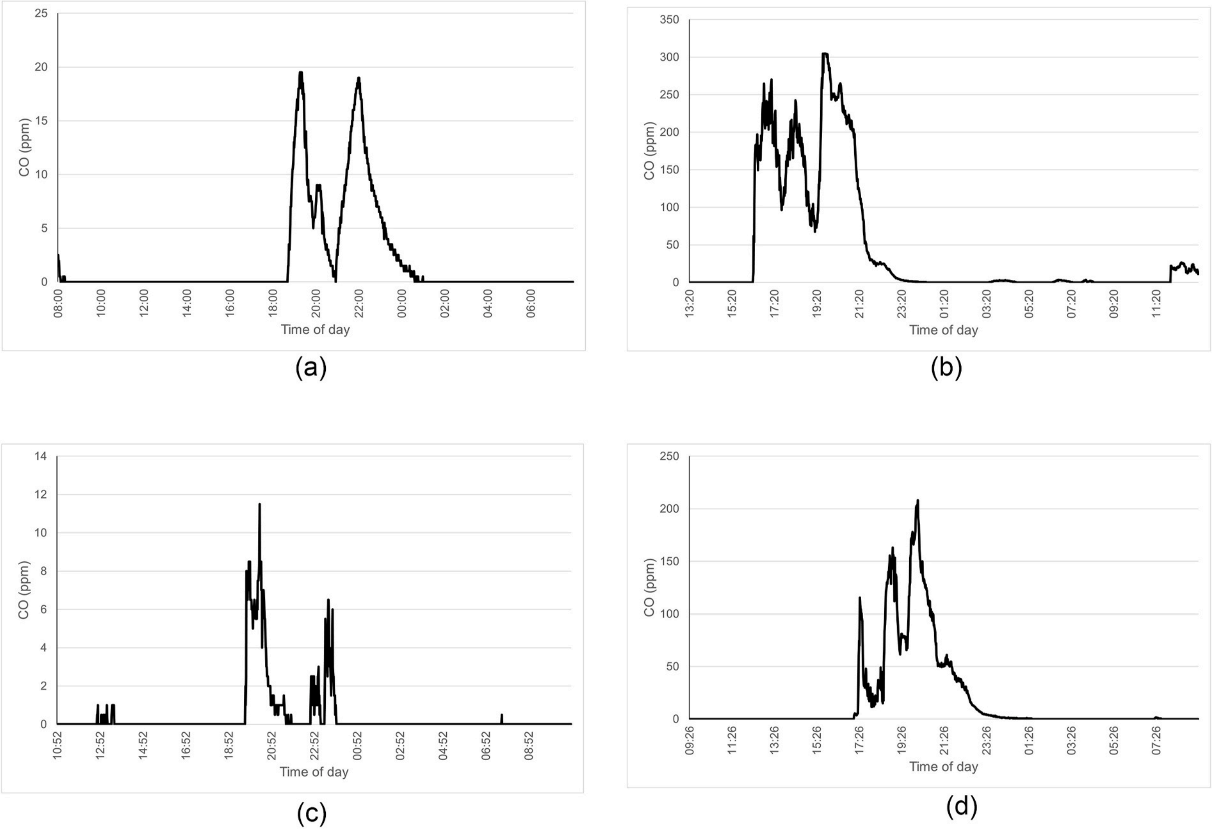

Fig. 2. (a)–(d) CO concentration time plots showing 24h measurements from four homes illustrating peaks likely to be from cooking activity. Note that y-axes scales differ reflecting the near 30 times difference in peaks seen in different homes.

where ambient CO concentrations are available suggest a daily median of between 0.5 and 1.0 ppm is typical across a sample of 337 cities (Chen et al., 2021). Data are also available from a recent study of spot sampling of ambient CO concentrations in central Nairobi on 9 days in August 2021 that indicated levels of between 0.2 and 0.7 ppm (Kirago et al., 2023). Applying an assumption of a scenario of 1 ppm ambient CO (a likely high, reasonable worst-case estimation) in the non-home micro-environments that a schoolchild in Nairobi will visit (outdoor spaces, school and other indoor settings) and a simple model that assumes the child spends time between 08:00–18:00 in these non-home environments and 18:00–08:00 at home then we are able to estimate an average exposure over a typical 24h period: $E_T = (3.5 \text{ ppm} \times 8\text{h}) + (1 \text{ ppm} \times 10\text{h}) + (9.3 \text{ ppm} \times 6\text{h}) = 94 \text{ ppm h}$. Assuming broadly similar breathing rates during these periods this suggests that for schoolchildren living in Nairobi, approximately 60% of inhaled CO comes during the time spent in the home around the evening cooking period, with less than 11% arising from their time outdoors and at school from ambient air pollution.

4. Discussion

This work reports carbon monoxide concentrations measured for 24-h in a large sample of homes located in a large city in SSA. We believe this is the first study of in-home CO concentrations in urban homes in SSA. 24-hour CO concentrations were considerable (Mean (SD) 4.9 ppm (6.4); Median (IQR) 2.8 ppm (1.0–6.3)) and much higher than those reported in ambient air in cities around the globe (Chen et al., 2021). Previous work from stove intervention studies in rural or semi-rural homes in LMICs reported pre-intervention CO exposures that are broadly similar to those measured here. Mean 48-h CO exposure of pregnant women in charcoal burning communities in Guatemala were 3.8 ppm (Dix-Cooper et al., 2012), with data from 1400 households in Ghana indicating mean 48-h values of 1.5–1.6 ppm (Chillrud et al., 2021). The HAPIN trial reported pre-intervention data from over 3000 homes in rural areas of Peru, India, Rwanda and Guatemala with a mean personal CO exposure of 2.5 ppm (Johnson et al., 2022).

Given the potential acute health impacts of peak exposures to CO, our study has examined in detail the temporal changes and time above particular threshold concentrations during the 24-h measurement period in each home. This type of analysis is lacking in most studies that report CO concentration or exposure data, despite the instruments used for measurements tending to measure and log the data with high resolution (typically 1-min concentration values). Reporting and exploring temporal resolution are both important in exposure science as they enable identification of periods and activities when concentrations may cause symptoms or effects, and can assist in designing interventions to reduce exposure.

Peak concentrations were common, with the average home experiencing a maximum 1-min peak of 43 ppm. Household concentrations frequently exceeded the thresholds set by the WHO (World Health Organiz ation and Geneva, 2021): 6 ppm was exceeded for an average of 287 min (20% of the day) across the sampled homes; >30 ppm for an average of 27 min (2.1% of the day); and >87 ppm for an average of 8 min (0.6% of the day). These peaks in concentration profiles are hypothesised to be linked to household activities, primarily stove use, as enhancements of the reported concentration are most common in the evening and early morning at times of preparation of dinner and breakfast, respectively.

Our analysis also shows that 9.4% of households had CO concentration profiles that would have activated a CO-alarm operating to European safety specifications. This is for a single day of measurement, and while we do not have data on the day-to-day variability of CO concentrations within homes, it seems safe to conclude that this 9.4% value will be an under-estimate of the proportion of households that would activate such an alarm over a given week, month or year. If we assume that our sample of homes taken from two specific areas (Mukuru – a large informal settlement; and Buruburu – a more affluent area of Nairobi) is broadly representative of homes across Nairobi (population 5.3 million), then this conservative 9.4% figure would suggest that about 500,000 people in the city live in homes where CO concentrations are high enough to activate a CO alarm and therefore pose an acute risk to health. CO poisoning is often difficult to diagnose and may be under-reported in emergency clinical settings (Chenoweth et al., 2021), this may be especially true in LMICs with limited biochemical analytical capacity. Future research should consider ways of quantifying the acute health effects of these peak exposures. It is worth noting that, despite similar mean concentrations between the poorer and more affluent communities (5.1 v 4.7 ppm), there was a significant ($p = 0.01$) difference in the ratio of homes that would have activated a CO-alarm, suggesting that the burden of acute health impacts may be higher for those living in informal settlements.

At lower concentrations, chronic CO exposure is associated with increased risk of mortality. Recent work has suggested that a 1 mg/m^3 (0.87 ppm) increase in ambient CO is associated with a 0.91% increase in daily total mortality (Chen et al., 2021). While it is unclear whether this association is independent of other air pollutants such as fine particulate matter or nitrogen dioxide, which tend to also increase when ambient CO increases, the mean household CO values reported in this study (4.9 ppm or 4.3 mg/m^3) suggest the potential for a significant impact on daily mortality in Nairobi.

Low-level chronic exposure to CO has also been associated with child development, both in terms of the potential hypoxic effects on the developing fetus in utero resulting in lower birth weight (Kaali et al., 2023), and through poorer neurodevelopment (Dix-Cooper et al., 2012). Low-birth weight is associated with many longer-term health consequences including poorer respiratory health, reduced lung function, heart disease etc. (Ashorn et al., 2023). Dix-Cooper et al. (2012) demonstrated an inverse association between CO exposure of pregnant mothers during their 3rd trimesters and child neuropsychological performance across a range of tests at age 6–7 years. Any developmental impacts of CO may be further compounded by acute effects from CO exposure in the hours prior to attending school. Prolonged exposure to CO in the evening and overnight is potentially very harmful as it will allow CO to distribute throughout the body tissues giving a high 'CO burden in the tissues' that reaches equilibrium after about 5–6 h when blood Carboxyhaemoglobin (COHb) concentrations plateau (Shimazu et al., 2000). Children in homes with higher CO concentrations in the evening and early morning may arrive at school feeling drowsy or nauseous and less able to concentrate on their learning for the first hours of the day. Future research should examine differences in performance and attainment of children who live in homes with higher CO concentrations.

Previous work has shown that women and girls in East African homes in rural communities experience much higher CO exposure than men or boys due to their role in preparing food (Okello et al., 2018). There are no similar data for urban populations in SSA but it is likely that the cultural practices underpinning these findings in rural populations persist in urban settings.

Our analysis of the temporal changes in concentrations demonstrated that most homes experienced much higher concentrations during the evening hours of 18:00–24:00 (Median (IQR): 4.3 ppm (1.4–9.4)) compared to the rest of the day (Median (IQR): 2.1 ppm (0.3–4.7)). The median (IQR) ratio between the concentrations spanning these two periods was 1.6 (1.1–4.6), indicating that concentrations tended to be elevated in the evening compared to the rest of the day. Our simple model of a typical school-child's day and the concentrations experienced within those microenvironments, suggests that 60% of inhaled daily CO comes during the 6-h period around the evening dinner when the child returns home from school. Interventions to reduce children's exposure to CO should look to target this period and consider community sensitisation and education programmes to raise awareness of the dangers of household air pollution, improved stoves and increased ventilation within the home settings. While CO emissions from vehicle exhausts are likely to also contribute to personal exposure, particularly on the journey to and from school, our findings suggest that CO from in-home sources (primarily from cooking) provide the greatest contribution to daily intake of CO within the communities studied. Previous studies in informal settlements in Nairobi have found that indoor cooking is recognised by the community as a key source of indoor air pollution (West et al., 2021).

4.1. Limitations

Our work provides data on household concentrations and so is not directly comparable to studies that have measured personal exposure. However, home is where most children spend most of their time. Measurement devices were worn by children while they were at home but taken off and placed at a fixed monitoring position in the living-room while the child went to school or was outdoors. This was the result of feedback during the community consultation process where concerns were raised by parents, teachers and community members that children carrying or wearing a monitor would be vulnerable to mugging or attack. Our sample was based on children who were attending school. Again, this was after consultation with the local community who made it clear that trying to track down and recruit children not attending school would not be acceptable. We have no data on ambient concentrations or concentrations in other non-home microenvironments such as in schools. To counter this limitation, we have calculated the in-home average concentration from 00:00–18:00 (when cooking is less common) and used a reasonable worst-case value for outdoor ambient levels based on data from over 300 cities from across 18 countries. We would encourage future work to undertake data collection on CO concentrations from outdoor monitoring sites in SSA cities and from a diverse range of indoor settings where people spend time (schools, offices, shopping and leisure areas, etc).

We used low-cost CO logging devices which enabled data collection from over 150 homes. We relied on factory calibration of these devices and did not employ any additional in-field calibration. All devices were purchased new for this monitoring campaign and were used within the 5-year guarantee period of the sensors.

We did not carry out repeat measurements within homes to investigate the variability within homes, and there is the potential that placement of the instrument within homes may have modified behaviour. Participants were not blinded to our interest in measuring household air pollution levels. Our measurements were for 24h rather than a longer period due to resource limitations and there is the possibility that the short duration may have altered people's behaviour within the home. We think the most common impact of such an observer effect would be to reduce cooking or switch to a cleaner stove or fuel, and to aim to have lower levels of pollution in the home. As such, there is the possibility that our data are under-estimates of the true CO concentrations in these homes. Equally so we cannot exclude the possibility that some families may have deliberately set out to increase indoor pollution concentrations during periods of measurement.

4.2. Conclusions

CO concentrations within homes in Nairobi are substantial and have the potential to impact on the health and mortality of the population. Despite most of these urban homes using liquid or gas fuels, concentrations of CO were comparable with those previously reported in rural homes (that use more polluting solid fuels of charcoal and wood) in LMICs and this aligns with previous findings that suggest that 'cleaner' fuels do not always generate the desired levels of reduction in household air pollution (Pope et al., 2017) A substantial proportion of homes (nearly 1 in 10) had measured concentrations that would activate a

European CO-alarm, suggesting that there is likely to be a considerable unquantified burden on health from acute CO exposure and CO poisoning. Chronic health effects, particularly in terms of child development, may also be occurring because of the CO exposures reported here. There is a need to better understand CO exposures in urban settings in SSA and to target interventions, including community education on household air pollution, that reduce exposure from evening cooking activity within the home.

5. Contribution statement

All authors meet all four criteria for authorship in the ICMJE Recommendations. HM, GD, KM and SEW conceived the original Tupumue project idea. All authors contributed to the study design. JC, RK, HM, AN, FO and contributed to instrument design, data acquisition and quality control in Kenya. SS managed the air quality measurement process of the Tupumue study. FO, RD, HP, MT, CP, MLo and SS, contributed to the design, conduct, and analysis of air quality monitoring component. Data analysis was conducted by MLe, SS, GD, FO. Study statistician was MLe. GD is the study guarantor. SS and FO wrote the first draft of the manuscript. All authors contributed to the interpretation of results, drafting of manuscripts and their revisions and agreed for the final version to be published.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sean Semple reports financial support was provided by UKRI Medical Research Council. Sean Semple reports financial support was provided by Kenya National Research Fund. Sean Semple reports financial support was provided by Wellcome Public Engagement Fund. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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