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Long-Term Monitoring of Indoor CO Levels in Disproportionately Impacted Communities in the North Denver Metropolitan Area

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Abstract: Carbon monoxide (CO) is a colorless, odorless gas emitted from carbon fuel combustion. In this study we monitored indoor carbon monoxide (CO) levels for 120 homes over three seasons in the North Denver metropolitan region as part of an environmental justice initiative to quantify health and social well-being impacts from a major freeway construction upgrade nearby. Urban outdoor CO levels are typically very low (less than 1 ppm in Denver) due to air pollution control strategies and technologies implemented over the past several decades. However, people can still be exposed to higher than outdoor levels of CO in their homes due to the operation of indoor appliances that use carbon fuels such as natural gas. Our data show that ~10% of the homes had consistent daily average levels of CO above 3.5 ppm and 24-57% of the homes showed peaks greater than 9 ppm. While much higher levels can result in CO poisoning and fatalities, these lower levels of CO have been associated with adverse health impacts, especially pregnant women, and sensitive populations. Our results highlight the need for increasing awareness regarding CO exposures in homes with gas appliances and motivate the transition from non-electrified homes toward electrification.

Keywords: gas appliance emissions; indoor air quality; electrification in homes; adverse health effects; carbon monoxide

1. Introduction

Carbon monoxide (CO) is a colorless and odorless gas usually formed as a result of incomplete combustion [1]. Common sources for CO generation indoors are unvented emissions from appliances using carbon fuels such used as stoves, water heaters, and furnaces, use of portable generators, smoking, and idling of vehicles in garages [1,2]. Due to the non-irritating and imperceptible nature of CO when inhaled, exposure can often happen without people being aware. Exposure to CO disrupts the oxygen binding capacity of hemoglobin, leading to adverse health effects including fatalities in case of acute high exposures, also known as CO poisoning [3,4]. Symptoms associated with low to moderate levels of CO exposure such as headache, nausea, and tiredness can be easily misdiagnosed that further adds to the public health burden [4,5].

The most common mitigation measure for preventing CO poisoning-related deaths in residential settings includes installing a CO monitor that is triggered to alarm at high levels (greater than about 60 ppm) when a healthy person under such exposure could lose their ability to react [5–7]. However, these monitors can't detect CO in lower concentrations that could still result in adverse health effects such as neurodevelopmental risk to fetuses and small children [4,8,9]. Previous epidemiologic studies have found associations between a moderate increase of outdoor CO (~1 ppm) and an increase in hospital admissions for cardiovascular-related hospital visits [10–14]. Unfortunately, many residents have limited knowledge of lower-level CO health effects and are unaware of the levels of CO

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concentrations in their homes. The lack of awareness regarding the risk of accidental leaks of CO from gas appliances further contributes to this public health burden [3,7].

The issue of exposure to low levels of CO should be of serious concern in non-electrified homes wherein the combination of regular usage of cooking and heating devices that use carbon fuels with inadequate indoor ventilation practices could contribute to higher indoor CO exposure than outdoor conditions [15–21]. Vanker et al. found an association between fossil fuel use and degraded indoor air quality in homes, specifically higher levels of CO and benzene [22]. Nowadays, even though there has been a push towards electrification in homes to reduce exposure to carbon fuel-burning emissions and decrease the residential carbon footprint, often people are reluctant to upgrade their gas appliances to electric due to personal preferences, cost, and time constraints [23,24]. Increasing awareness of the potential for persistent low levels of CO in homes with a gas appliance could become an effective tool to raise awareness of the need for electrification of commonly used indoor appliances and to encourage society to adopt this change.

In this study, we monitored CO levels in 120 homes in disproportionately impacted communities (DICs) around North Denver over three seasons. The objectives of this study were to highlight the prevalence of lower levels of CO concentrations in residential settings and to observe seasonal variability in indoor CO concentrations. The study also aimed to highlight how indoor sources could predominantly contribute to higher than outdoor CO concentrations, especially in homes with gas appliances. Lastly the results from this study could be instrumental in increasing awareness among local communities regarding the issue of persistently low levels of CO concentrations in non-electrified homes especially in communities already facing disproportionately higher levels of outdoor pollution exposure.

2. Materials and Methods

Indoor CO measurements were collected as part of the Social Justice and Environmental Quality in Denver (SJEQ-D) study in which about 120 homes were recruited from disproportionately impacted neighborhoods of the North Denver area (Elyria-Swansea, Cole, Clayton, and Globeville) [25]. The study was divided into three study periods or cohorts: Summer 2022 (May 20th – June 25th), Fall 2022 (October 5th – November 15th), and Winter 2023 (February 13th- March 21st). The SJEQ-D study objective was to quantify the impacts of a major freeway construction project on personal air pollution exposure for residents of adjacent neighborhoods. Each participant received a Lascar CO data logger (USB-EL-CO, Lascar Electronics, PA, USA; measurement accuracy is ±7 ppm in the 3-1000 ppm range, 5-min logging interval) and was instructed to keep it in their living room for the entire cohort. Participants also completed socio-demographic surveys, including history of smoking and the presence of any gas appliance (gas stove, oven, water heater, or heating furnace) in their homes (Institution Review Board Protocol # 20-0318; approved exempt 26 May 2021).

The CO concentration time series for each home was analyzed to initially identify homes that exceeded the World Health Organization air quality guidelines (WHO AQGs) for time-averaged exposure limits over 15-min (87 ppm), 30-min (52 ppm), 1-hour (h) (26 ppm), 8-h (9 ppm) and 24-h (3.5 ppm) [1,26,27]. The Lascar CO data loggers were purchased brand new before the study and weren't calibrated during the study since the CO sensor is calibrated annually by the manufacturer [28]. One data logger malfunctioned during deployment, recording a single data point during the cohort period, and wasn't deployed again.

3. Results and Discussion

In each cohort, 10% of the homes exceeded the 3.5 ppm daily average limit set by WHO AQGs as shown in Table 1. Within a subset of these homes, many exceeded the daily limit for up to 6 days during the measurement period. A noticeable exception occurred for one home (home ID 2077) during the Fall Cohort where daily averages were greater than 3.5 ppm for 36 days out of a total of 41 days.

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Table 1. Summary of Homes (4-digit home ID corresponds to each recruited home) Exceeding the Daily Average of 3.5 ppm During each Cohort *.

Summer Cohort 2022 Home ID [Max daily average in ppm] (#days exceeded/total days)	*Fall Cohort 2022 Home ID [Max daily average in ppm] (#days exceeded/total days)*	*Winter Cohort 2023 Home ID [Max daily average in ppm] (#days exceeded/total days)*
3007 [6.5] (1/41) x y z	1048 [6.3] (4/43)	2098 [12.9] (6/34) x y z
4006 [4.2] (1/35) x y z	4020 [4.2] (1/44) x z	3065 [5.8] (3/34) x y z
1035 [5.2] (9/39) z	2126 [4.6] (1/39) z	2155 [3.7] (1/40) x z
1004 [4.2] (3/41)	2077 [11.5] (36/41) x z	2162 [3.6] (1/40) z
2036 [7.9] (1/38) x z	2085 [3.8] (1/40)	
** 2098 [3.4] (0/35) x z	2111 [4.1] (1/39) x y z	

* Number of homes recruited during Cohort 2,3,4 was 51, 50, and 54 respectively. x 8-h average of 9 ppm WHO guideline exceeded; y 1-h average of 26 ppm WHO guideline exceeded; z Time series showed CO peaks above 9 ppm more than 6 times during the cohort; ** Home ID 2098 reported a daily average value of 3.4 ppm for the day it exceeded the 8-h 9 ppm threshold.

When the 5-minute CO time series was analyzed for WHO's AQGs concentration limits, none of the loggers exceeded the 15-min (87 ppm) or 30-min threshold (52 ppm). All the loggers that exceeded the 24-h threshold also exceeded the 1-h (26 ppm) and 8-h (9 ppm) thresholds, except the logger deployed in home ID 2098 where the CO concentrations reached the daily average value of 3.4 ppm on the day the 8-h threshold was exceeded. Notably, there were some homes (1004, 1048, 2085) with daily averages of CO above 3.5 ppm that never exceeded a shorter-term threshold, signifying the prevalence of consistent lower levels of exposure. An important point to mention here is that because the CO data logger used in the study has a measurement accuracy of ±7 ppm in the 3-1000 ppm range, there could have been instances when CO concentrations were <3 ppm and were not recorded by the logger.

The four neighborhoods included in this study were impacted by a major construction event where a section of Interstate 70 (I-70) (January 2019 – December 2022) was rebuilt, so emissions from construction vehicles infiltrating homes nearby could have elevated indoor levels of CO in some of the homes. However, the outdoor levels of CO reported by the nearest Colorado Department of Public Health and Environment (CDPHE) monitor deployed right alongside the I-70 reported less than 1 ppm concentrations, so higher indoor concentrations compared to outdoors could be better explained by indoor sources (Figure S1). Next, we investigated the history of smoking in the household (yes or no responses as reported by the residents) for any associations with indoor CO levels (# times exceeded 9 ppm) and found no statistical significance ($p > 0.05$) through the chi-square test of independence for all the three cohorts.

Indoor sources, predominantly emissions from one or more gas appliances, are likely the cause of indoor concentrations exceeding 9 ppm. 75-80% of the residents who completed the survey reported having a gas appliance, although ~40% of the residents in each cohort did not provide a response (Table S1). Multiple homes repeatedly showed peaks of CO above 9 ppm when the season changed from summer (cooling season) to winter (heating season, Figures S2-S4). The "# times CO exceeded 9 ppm" parameter was compared between the three cohorts to investigate seasonal variability using the Mann-Whitney U test with Bonferroni correction; there was a significant difference between the Summer 2022 and Winter 2023 cohorts (p-value < 0.01), suggesting that the use of gas furnaces for heating during the colder winter months in Denver increased indoor CO levels. In 2020, 76% of households in Colorado used natural gas as the main space heating fuel; also about 30% of kitchen ranges used natural gas in the mountain region of the US [29]. In a similar study done in the UK measuring indoor CO levels over six months, the main cause for a CO alarm incident was attributed to a presence of a gas appliance (boiler, gas cooker or a natural gas fireplace) [5]. A 2014 study in Wales during winter months of January and February also reported nine out of 412

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properties had CO levels between 1–9 ppm [7]. These results suggest low levels of CO exposure can be consistently attributed to emissions from gas appliance use indoors.

Next, we present CO time series for three different homes with a gas appliance to illustrate three distinct temporal trends observed. These trends are representative of most of the homes in the study. The combined data for all the homes over three cohorts is also shown in Figure S5.

Figure 1a is data for a home with CO concentrations that are mostly below WHO AQGs but could result in elevated personal CO exposures associated with adverse health impacts in pregnant women and people with cardiovascular risks. There are several days when CO levels peaked intermittently in the 3-5 ppm range, which would not exceed any WHO AQG threshold, but if the residents are consistently spending time under such conditions, the risk of adverse health effects associated with CO exposure increases. Multiple short-term peaks in CO concentrations exceeding 10 ppm were observed, which could further drive up the CO personal exposure levels for the residents in this home.

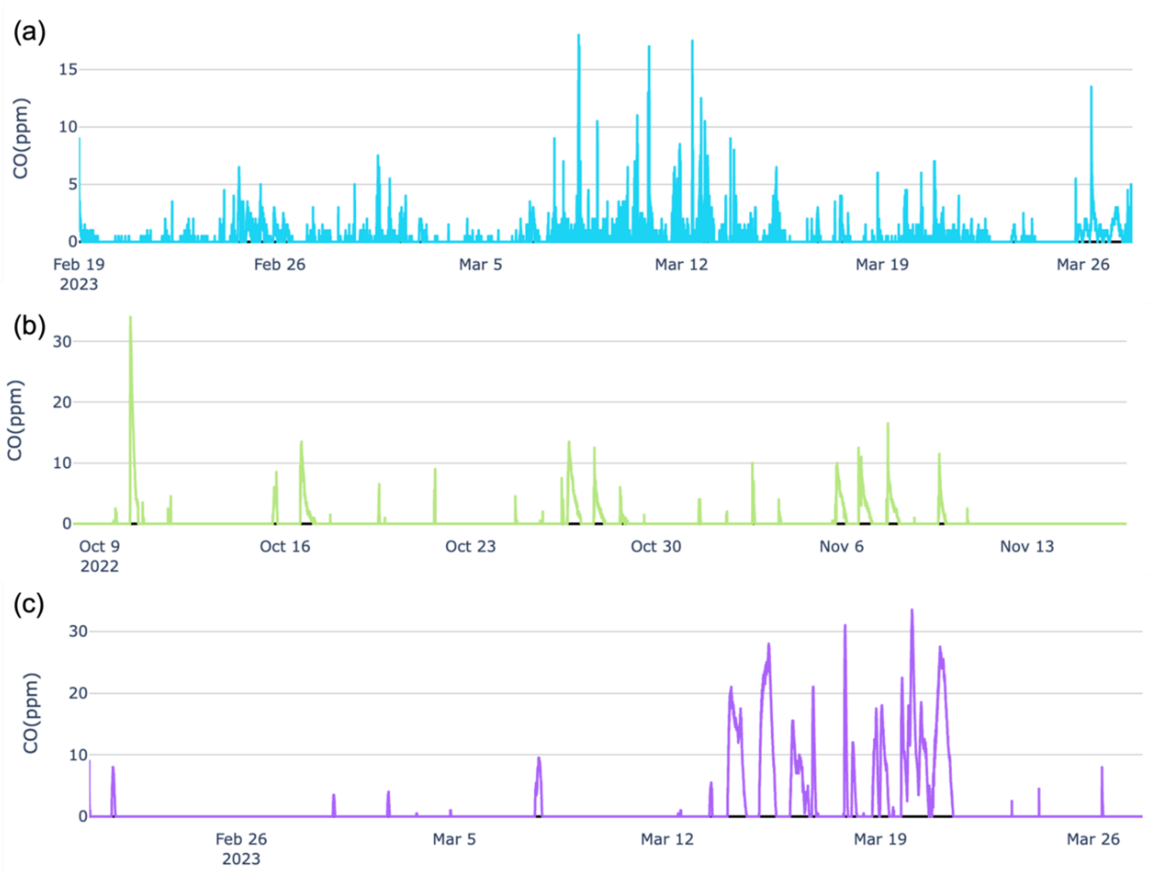

Figure 1. CO time series for three non-electrified homes (IDs 2169, 2111, 2098 respectively) in this study.

The data in Figure 1b was discussed with the resident to inform them of the elevated CO concentrations in their home, particularly the peak exceeding 30 ppm on October 9th, 2022. This peak occurred in early morning hours and was determined to be from the resident's diesel truck idling in the garage. There were several peaks above 10 ppm in the evening hours that could be attributed to a gas stove. A similar trend was observed in a study on indoor CO levels in homes in the mid-west US region where evening CO peaks were attributed to use of gas stoves, demonstrating the prominent role of gas stoves in elevating personal CO exposure in the home [2]. Interestingly, when the resident with ID 2111 whose data is shown in Figure 1b contacted the gas company for inspection in November 2023, the technician found no problems. While the actual data collected by the gas company was never shared, it is possible that either the spot check missed the actual cause behind

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the CO spikes or perhaps the CO monitor that was used was calibrated to detect leaks in higher concentration ranges.

The CO time series in Figure 1c is an example of a home in which, over the course of a three weeks, the indoor CO levels typically close to zero. However, high concentrations occurred during the week of March 14–21 when CO peaks 20 ppm were consistently observed. The resident for this household confirmed the gas appliance in their home was not routinely inspected. It is possible that these consistently high levels over a period of 7 days were due to the combination of low outdoor temperature (the highest maximum daily temperature of the month 22.6 °C and the lowest minimum daily temperature of -8.3°C were recorded in this same week as shown in Figure S6) forcing the occupant to close their home while a heater or some other gas appliance was continuously venting indoors, leading to more than 700 instances when the 5-min CO concentration exceeded 9 ppm.

Overall, these results demonstrate the need for switching gas appliances to electric appliances to mitigate the health risks associated with chronic exposure to low-levels of CO in homes with the added benefit of reducing the residential carbon footprint. In cases where electrification is not feasible, households should take extra precautions by ensuring indoor CO is monitored regularly at lower levels than what is detected by a CO detector and ensuring routine inspection of these gas appliances to prevent emissions from leaking indoors. A 1974 survey on CO levels in US homes reported that 16.8% of the total 1820 studied homes had peaks above 10 ppm attributable to a carbon fuel-burning appliance. Comparing these results to the present study signifies little change in the ventilation control aspect of gas appliance usage has been achieved over the last 50 years to justify their unsupervised use in homes with residents at risk of cardiovascular and asthma related health risks from air pollution exposure [30].

4. Conclusions

Indoor CO exposure from using gas appliances could lead to serious adverse health effects and a public health burden for communities especially for sensitive populations like young children, pregnant women, or the elderly and particularly if the residents already have existing cardiovascular illnesses. In this study we monitored CO levels in the living room of 120 homes over three seasons and more than 20% of the homes in each cohort had peaks in CO levels above 9 ppm that occurred regularly. Moreover, as the weather changed to colder months, more homes had peaks above 9 ppm suggesting risk increase in the winter months in colder climates when heating increases and ventilation rates decrease due to less window opening.

Some study homes had consistently low levels of CO (in the 3-5 ppm range) over weeks and these levels if left unchecked could also lead to accumulated adverse health effects for individuals living in proximity to a major freeway system and/or industrial areas. In the absence of an enforceable indoor air quality standard for CO in residential environments, it is imperative that the gas appliance usage should be better regulated, for example in terms of mandatory timely inspections of gas appliances or continuous monitoring of CO indoor at lower concentrations than is typically monitored by home CO alarms. Finally, electrification of homes should be prioritized to completely eliminate this risk of adverse indoor CO exposure.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: Sumit Sankhyan: Writing-original draft, Writing - review & editing, Formal Analysis, Visualization, Validation, Project administration, Conceptualization. Aniya K. Hollo: Writing - review & editing, Investigation, Data Curation, Resources. Dulce Gonzalez-Beltran: Writing - review & editing, Investigation, Resources. Nicholas Clements: Writing - review & editing, Investigation, Methodology, Project administration. Shelly L. Miller: Writing - review & editing, Supervision, Funding Acquisition, Conceptualization.

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Institutional Review Board Statement: The study was conducted according to the guidelines approved by the Institutional Review Board of University of Colorado Boulder (Protocol # 20-0318 and approved exempt May 26, 2021).

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Conflicts of Interest Statement: We do not have any competing interests to declare.

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