Influence of Differing Microenvironments on Personal Carbon Monoxide Exposure in Auckland, New Zealand

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Abstract: Epidemiological studies typically estimate pollutant exposures using data from outdoor fixed monitoring stations (FMS). However, due to individual mobility through space, time spent in indoor environments and the heterogeneity of the urban atmosphere, data from FMS provides a poor representation of the actual personal exposure to air pollutants. The aim of this study is to investigate the relative importance of time spent in common microenvironments (such as commuter, home, work and recreational) to determine personal exposure to air pollution. The study also investigates the extent to which fixed monitoring stations (FMS) are representative of personal exposures. For this purpose, 17 participants monitored their personal exposure to carbon monoxide (CO) for a full working week and completed a time activity diary identifying the particular microenvironments in which they spent their time.

Overall, the participants exposure to CO were lower than those observed in other northern hemisphere cities reported upon in the literature. FMS located in central Auckland were found to provide reasonable estimates of mean daily personal exposure but were poorly correlated with diurnal variations in personal exposure. The results found that, while the highest mean exposures were recorded in the commuter microenvironment, the home microenvironment accounted for 55% of the total CO dose during the week. Increased levels of personal CO exposure were observed in indoor areas where gas heating, gas stoves and tobacco smoke were present. Participants recorded highly variable exposure to CO in recreational microenvironments, in part explained by the wide range of recreational activities.

Keywords: Air pollution, carbon monoxide, fixed monitoring stations, microenvironment, personal exposure.

INTRODUCTION

There is increasing concern that poor air quality in urban centres has an adverse effect on human health [1]. Typically, air quality is measured at fixed monitoring stations (FMS) within urban environments. This information is commonly used in epidemiological studies to determine the health effects of poor air quality [2, 3]. However, recent studies have revealed that FMS measurements tend to underestimate individual exposure due to the disconnect between the location of FMS and the nature of microenvironments in which people spend a significant amount of their time [4-7]. Therefore, even if the levels recorded at FMS are found to comply with air quality standards, individuals may still be at risk of exposure to harmful levels of air pollutants, depending on their daily patterns of activity [2]. To accurately determine the health effects of poor air quality, better measurements of personal pollutant exposure are needed [5, 8].

Carbon monoxide (CO) is one of the pollutants frequently measured in personal exposure studies [4, 6, 8-11], due in part to the availability of low-cost and mobile monitors [12]. CO concentrations are trending downwards in most urban environments, as a result of advances in emissions technology such as catalytic converters in motor vehicles [6, 13]. However, CO remains a good indicator of urban air pollution exposure as its concentrations tend to be well correlated with the other major urban pollutants, such as nitrogen dioxide, $PM_{2.5}$ and ultrafine particulates [8].

Personal exposure during commuting has been the focus of study in recent exposure literature as it is believed that a significant proportion of peoples' daily pollution exposure tends to occur while in this microenvironment [9, 10, 14]. Studies have generally reported higher levels of CO for commuters engaged in motorised forms of transport such as cars and buses, compared with active modes such as walking and cycling, explained in part by the physical separation of active mode commuters from the main line of traffic [4, 6, 8, 11].

Other microenvironments which have also received significant attention include the indoor environment, as approximately 85% of a person's day is spent indoors [9, 15, 16]. While indoor environments are generally protected from outdoor traffic emissions, studies have found elevated levels of CO indoors from sources such as cooking appliances, heating appliances, and tobacco smoke [17-21]. These sources are not well represented by outdoor FMS but can be expected to contribute significantly to personal exposure, and to vary considerably from household to household.

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The first continuous study of personal exposure to CO was conducted by Akland *et al.* [22]. One of the largest studies of its kind, this research investigated the personal exposure of over 1,500 people in Denver and Washington D.C. The aim of this study was to provide a more accurate representation of personal exposure levels, as historically exposure had been statistically derived from a small number of FMS covering large urban areas. Similar types of personal CO exposure studies have since been conducted in large European centres such as Helsinki [10], Milan [9], Birmingham [23], Athens, Basel and Prague [17]. A small number have also been undertaken in North America including Toronto [24] and Maryland [25]. All of these studies have noted that personal exposure is highly dependent on the daily activities of individuals. Average CO exposures in these studies were typically higher during commuting than in any other microenvironment, while home environments accounted for the majority of the total CO dose (the product of exposure and time), due to the significant amount of time spent in this environment [9, 10, 17, 25].

A weakness of the personal air pollution exposure studies mentioned above is that they were all conducted over relatively short time frames of 24-48 hours, and the measurements were typically averaged over periods between 15 and 60 minutes. As such they lack in terms of significant temporal detail. High temporal resolution studies are important as CO has been found to fluctuate significantly over very short time periods [6, 8]. The current study builds on the existing literature by investigating personal CO exposures over a full working week (120 hours) at one-minute resolution, thus providing a high temporal resolution and long sampling duration dataset with which to investigate the contribution of various microenvironments to air pollution exposure in the population.

The objective of the study is to identify behavioural and environmental factors which influence personal exposures to CO, and in particular to examine the assumption that the commuter microenvironment is a dominant factor which influences total daily exposure. This is the first continuous personal CO exposure study carried out in either New Zealand or Australia beyond the commuter microenvironment [2, 8, 26, 27]. Additionally, the study examines the extent fixed monitoring stations (FMS) are representative of individual exposures. The results have implications both for our understanding of personal exposure as well as for air quality management.

METHODOLOGY

Study Site

This study was conducted in Auckland, New Zealand's largest city with a population of over 1.4 million [28] making up approximately a third of the country's population. The state of air quality within New Zealand is currently regulated from a network of FMS [2, 29]. The majority of poor air quality in Auckland is due to motorised transport, as private vehicles make up 80% of vehicle kilometres travelled and an aging vehicle fleet which has an average age of 13 years [30, 31]. As such, the transportation sector has been found to contribute approximately 86% of the ambient CO produced in Auckland [32]. Common within New Zealand is the use of unflued gas heating in both housing and recreational areas such as bars and restaurants, known to be high emitters of CO [33]. This type of heating has been banned in other countries such as Canada, as well as in a number of US and Australian states, due to their associated health risk.

Fieldwork

In this study, personal CO exposure was measured based on data from 17 students enrolled at the University of Auckland. The study was conducted for week long periods during the winter months between 20 August and 17 September 2012. Each participant collected 120 hours (five weekdays) of continuous CO exposure data and kept a time activity diary dividing their time into the following five microenvironments: commute, home, university, work and recreation. Commuting modes were divided into car, bus, train and walking modes. Within the home microenvironment, gas heating, gas cooking, and the presence of smokers were noted. The participants in this study were all non-smokers.

Monitoring Equipment

Each participant was issued with a Langan T15n portable carbon monoxide monitor (Langan Products Inc.) used to measure personal CO exposure. The device was set to log concentrations at 1-minute averages; the resolution of the monitor is 0.05 ppm and has a range of 0-200 ppm. All Langan monitors were co-located by using a 'bump' test before and after collecting field data. The monitors were placed in a garage and a car was run for 10 seconds twice at half an hour intervals. The Langans were left in this environment for a period of three hours. The Langan data was then corrected to a base Langan using simple linear regression. The unique intercept and slope for each Langan were then used to correct CO exposure data collected in the field. Results from the co-location test indicated that only minor corrections of instruments were required to be made. These settings and the basic experimental design are comparable to similar research on personal exposure carried out elsewhere where time activity diaries and portable air quality monitoring devices have been used simultaneously [9, 10, 23, 34]. FMS data from six locations around the city were obtained from Auckland Council's air quality monitoring network [35].

Data Analysis

The CO levels recorded by each participant were used to calculate the average one minute exposure (ppm) within each microenvironment. Dose (ppm.minute) was also calculated, where average exposures were multiplied by the time spent in each microenvironment, this was then converted to a percentage of total weekly dose. Exposures and doses associated with each microenvironment, commuting mode and the various home activities were then compared. A log transformation was undertaken on all data to render them normal prior to statistical testing. Homogeneity of variance was tested and the means of the activities and

Table 1. Mean CO exposure and FMS concentration in other similar microenvironment studies (from highest exposure to lowest).

Personal Exposure (ppm)	FMS Concentration (ppm)	Ratio	Location	Author
1.89	1.81	1.04	Milan, Italy	Bruinen de Bruin *et al.* [9]
1.47	3.44	0.42	Athens, Greece	Georgoulis *et al.* [17]
1.31	0.99	1.32	Prague, Czech Republic	Georgoulis *et al.* [17]
1.40	1.00	1.40	Toronto, Canada	Kim *et al.* [24]
1.10	N/A	N/A	Maryland, USA	Chang *et al.* [25]
0.72	0.81	0.89	Basel, Switzerland	Georgoulis *et al.* [17]
0.67	N/A	N/A	Birmingham, England	Harrison *et al.* [23]
0.39	0.45	0.87	Helsinki, Finland	di Marco *et al.* [10]
0.38	**0.49**	**0.78**	**Auckland, New Zealand**	**Current Study**

microenvironments compared using ANOVA, followed by Games-Howell for pairwise comparisons due to heterogeneity of variances. A Pearson correlation coefficient was used to compare the relationship between participants' exposures and FMS based on hourly and daily averages.

RESULTS AND DISCUSSION

Overview of Exposure

The mean weekly CO exposure for participants over the study period was 0.38 ± 0.31 ppm. This is lower than any of the other studies carried out in overseas cities, as reported on in the literature (Table **1**), but were similar to those observed in Helsinki, Finland [10]. Variation in exposures between cities can be explained by a number of factors including population size and density, meteorology, traffic, building, socio-economic and geographical characteristics [17].

Exposures were found to be highly variable between participants, with average weekly exposures between participants varying by a factor of 16. The highest average exposure for a single participant was 1.13 ± 1.50 ppm and the lowest 0.07 ± 0.41 ppm (Fig. **1**). The maximum mean 8-hour exposure for participants also showed significant variability and ranged from 0.30 ppm to 5.0 ppm, as such no participants exceeded the World Health Organisation standard of 9 ppm for an 8-hour exposure. Significant variability in exposure between participants has also been observed in many other studies [9, 10, 23]. Marked temporal variability of exposures between participants was also observed on a diurnal cycle (Fig. **2**). Higher exposures were often observed around rush hour (7 am-10 am and 4 pm-7 pm) by all participants. The majority of exposures observed were close to 0 ppm at background locations, but rapidly increased when CO sources were present such as vehicle emissions, gas appliances and other indoor sources. This

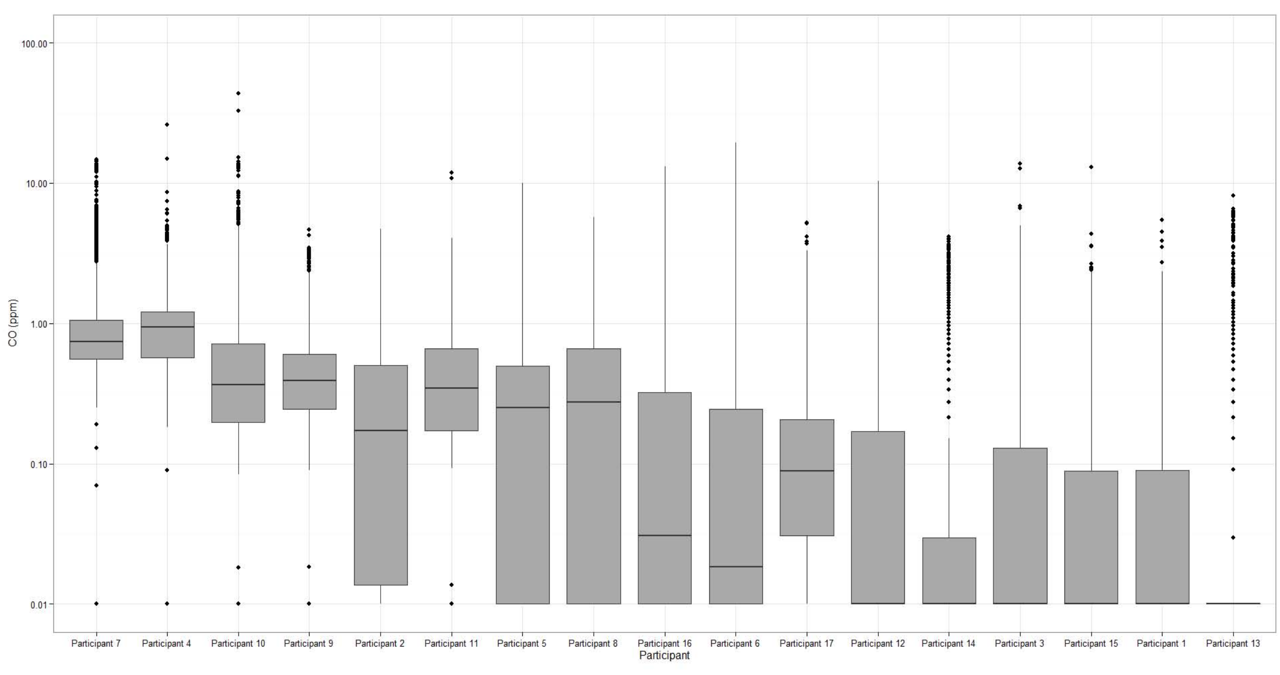

Fig. (1). Box plot of 1-minute CO exposure over a full working week for individual participants, in order of highest mean exposure to lowest. The CO axis is presented as a logarithmic scale.

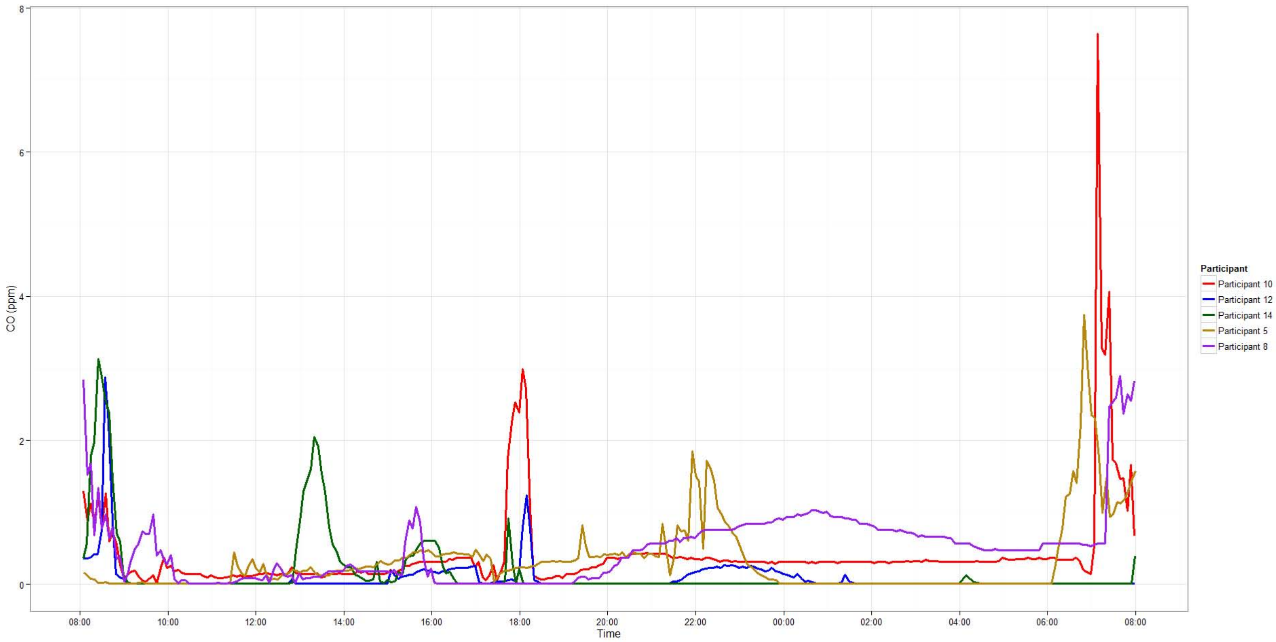

Fig. (2). Time series of five-minute average CO exposures (ppm) from Wednesday 8 am 22 August 2012 to Thursday 8 am 23 August 2012 for five of the study participants.

potentially indicates that background levels of the pollutant are insignificant and that CO exposure can be largely inferred from identifiable sources.

Representativeness of Fixed Monitoring Stations Concentrations to Personal Exposure

The average hourly concentrations at the six FMS ranged from 0.86 ± 0.69 ppm to 0.32 ± 0.39 ppm throughout the observation period with the mean concentrations recorded by the FMS being slightly higher than the mean personal exposure levels reported (Table **1**). While previous studies have suggested that FMS typically underestimate personal exposures [4-6, 27], the levels recorded by the FMS are largely dependent on the microscale characteristics of the location of the FMS, such as their proximity to major emission sources such as busy roads, the urban street design and the prevailing meteorological conditions. In this study, all FMS were situated within 30 metres of roadways which averaged between 13,000 and 40,000 vehicles per day [35]. Therefore, these stations are more likely to be measuring elevated levels of pollution due to traffic and are characteristic of commuter microenvironments rather than background concentrations. This indicates the importance of choosing appropriate FMS when estimating personal exposures. Other studies which reported ambient concentrations from FMS which were similar to personal exposures were also located in close proximity to streets with high traffic flows (Table **1**) [9, 17].

While the mean concentrations observed at the FMS and in the personal exposure study were similar, the FMS data were found to be a poor predictor of personal exposure. The values of the Pearson correlations between the FMS and personal exposure measurements for both hourly and daily averages did not exceed $r = 0.39$, $p>0.05$ (Table **2**). This poor correlation has also been found in a number of previous studies where personal exposures are correlated to FMS concentrations [4, 5, 9, 16, 17]. Overall, it appears that the correlations between the participants' exposure and the measurements made at the FMS were slightly stronger based on daily averages compared to hourly averages. This indicates that FMS are poor representatives of diurnal patterns of exposure, and as such would be a poor predictor of the highest exposures experienced by people. This finding is important as studies have suggested that high exposures are more likely to be detrimental to health [6]. Other studies have found similar results with using FMS to model exposure as mean eight-hour and 48-hour readings were similar to mean personal exposures but hourly means were not [9, 22].

Microenvironment Exposure

Data collection at one-minute resolution enabled the accurate definition of time spent in each microenvironment, particularly where the time spent in a particular microenvironment was short, for example a five-minute commute. A comparison of the mean exposures for the different microenvironments revealed that participants were exposed to the highest levels of CO while commuting (0.65 ± 0.33 ppm) (Table **3**). This was expected as the majority of CO is sourced from traffic emissions, confirming the rationale behind research focussed on the commuting microenvironment [36]. Conversely, mean exposures recorded on the university campus were very low (0.25 ± 0.24 ppm). This was not a surprise as modern heating appliances are used on campus, the campus is smoke free and there is limited vehicle access. Therefore, major sources of CO are absent within this microenvironment. The recreation microenvironment was found to have highly

Table 2. Pearson correlations between FMS and participants hourly and daily average.

FMS Location	Queen Street	Pakuranga	Henderson	Takapuna	Glen Eden	Khyber Pass
Participants Hourly Correlation	0.05	0.20*	0.20*	0.16	0.10*	0.12
Participants Daily Correlation	-0.15	0.38	0.39	0.23	0.24	0.19

* Correlation is significant at 0.05 level (2-tailed)

Table 3. Descriptive statistics of average weekly participants' CO exposure, dose and time spent in each microenvironment.

Microenvironment	Time (Hours)	Standard Deviation (Hours)	Mean Exposure (ppm)	Standard Deviation (ppm)	Dose (%)	Max (ppm)	Minimum (ppm)
Commute	14.2	4.8	0.65	0.33	17.4%	1.28	0.17
Home	71.8	15.6	0.36	0.37	54.5%	1.27	0.01
University	22.8	13.1	0.25	0.24	10.2%	1.01	0.01
Work	13.1	5.3	0.32	0.38	11.6%	1.05	0.02
Recreation	5.5	4.3	0.55	0.71	6.3%	2.70	0.02

variable exposures (0.55 ± 0.71 ppm), in part due to the wide range of environments in which recreational activities take place. A significant difference in mean exposure between microenvironments was observed (ANOVA $F(4,121312)=589.785$, $p<0.05$), although the difference in exposures observed between commuter and recreation microenvironment was not significant when tested with the Games-Howell post hoc test ($p=0.241$).

The highest total CO doses (product of exposure and time) during the monitoring period were found to be in the home and the commuting microenvironment. These two microenvironments accounted for 72% (55% home and 17% commute) of the total dose, suggesting that future research should be focussed on these areas. These microenvironments were also found to result in the highest air pollution dose in other similar microenvironment studies [9, 10, 17]. The CO exposures and doses experienced during work time in this study were very low. However, this may not adequately represent the typical working population as only six of the participants logged work time within the duration of this study, and all employment was on a part-time basis.

Indoor areas had mean exposure of 0.34 ± 0.33 ppm compared to outdoor exposures of 0.49 ± 0.87 ppm. This result is similar to those reported in other studies where indoor exposures were lower than outdoors [9, 10]. However, like findings in other studies, indoor areas had a higher pollutant dose (70% of total CO dose) compared to outdoor areas as up to 85% of time was spent indoors [9, 10, 15, 16, 18]. The amount of time spent indoors again indicates that FMS measuring ambient concentrations are likely to be inadequate for predicting individual personal exposure [17].

Commute

The commuting doses for the week varied between participants, accounting for 4% to 85% of total dose. Participants' average commuting exposures ranged from 0.17 ppm to 1.28 ppm throughout the week. The variability in commuting exposures between participants suggests that merely focussing on reducing personal exposure in this microenvironment may not be beneficial to all individuals. CO exposure was greatest when commuting by car, with participants mean exposures measuring 1.51 ± 0.89 ppm. Conversely, commuting by train (0.32 ± 0.28 ppm) and walking (0.33 ± 0.22 ppm) resulted in the lowest mean exposures (Fig. **3**). The ANOVA test found a significant difference between commuting modes ($F(3,14502)=351.412$, $p<0.05$). Post hoc comparisons found significant differences in exposure between all commuting modes apart from between train and walking commutes ($p=0.581$).

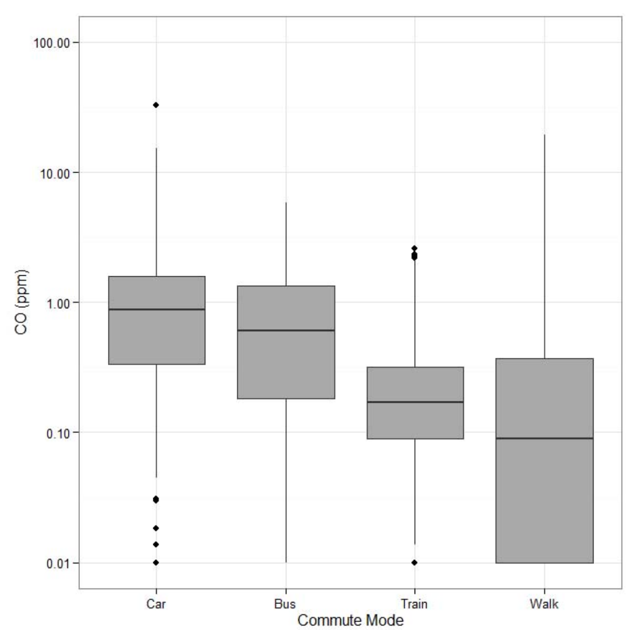

Fig. (3). Box plots of all participants' one-minute averaged CO for different commuting modes, from the highest mean exposure to the lowest. The CO axis is presented as a logarithmic scale.

High exposures in the car microenvironment can be explained by the fact that they are more likely to be in direct line of pollutants compared to other commuting modes and due to residence time of pollutants once they have entered the cabin [5, 9, 8, 14]. Results of the present study showed that participants who had commuting exposures as their highest microenvironment exposure were found to spend four times as much time commuting by car compared to participants who had other microenvironments as their highest mean exposures. Bus commuters experienced comparatively low exposure of 0.79 ± 0.53 ppm on average. The possible reason for lower levels of CO exposure during bus commutes were that the majority of travel was undertaken using a designated bus lane away from the majority of traffic congestion [8, 11, 37]. Low exposures were also seen in train commutes as these too travel on lines away from heavy congestion, resulting in lower exposures compared to other transport modes. Walking resulted in the lowest exposures while commuting, and participants spent the most amount of time using this mode of commuting during the week. This finding differs from similar studies which indicate that this form of commute exhibits high exposure; a study in Milan found average walk commute exposures to be 2.60 ppm [9].

Home

Mean participant exposures in the home environment ranged from 0.01 ppm to 1.30 ppm and varied between 5% and 93% of the total CO dose. CO exposures in the presence of gas heaters were two times, gas stoves three times and environmental tobacco smoke five times higher when compared to an absence of the noted CO sources (Fig. **4**). These results are supported by a number of other studies which suggest that elevated CO levels are caused by gas combustion appliances and tobacco smoke in this microenvironment [9, 10, 19-21]. In the only household in which there was tobacco smoke, the levels of CO were higher than those with gas appliances; this was also observed in the Martinez *et al.* [20] study. Restrictions on items such as unflued gas heaters, gas cooking and tobacco smoke in home locations should be studied further due to their substantial contribution to air pollution levels and the amount of time populations spend in this environment.

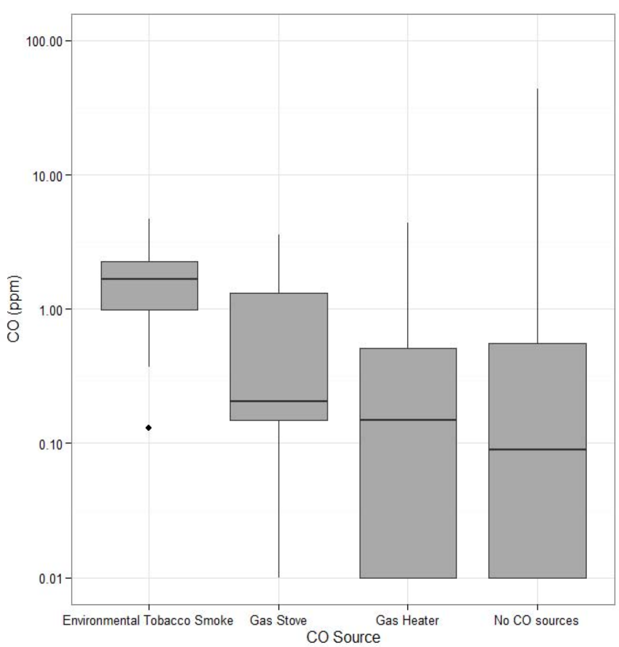

Fig. (4). Box plots of all participants' one-minute CO exposure for CO sources in the home environment, from the highest mean exposure to the lowest. The CO axis is presented as a logarithmic scale.

Other factors which are thought to affect exposure within the home are the design, air tightness and ventilation of the building [15]. A participant during this study exhibited higher levels of CO exposure when family members used hot water, due to the water heating system operated by gas combustion located directly outside the participant's bedroom, potentially indicating issues with the air tightness and ventilation of the household. This was evident as there was a rapid increase in exposure at 6 am daily while the participant was asleep. This finding is consistent with the study of Martinez *et al.* [20] which found that apartments using gas combustion and inadequate ventilation had significantly higher CO concentrations. This in part highlights the complexity and number of differing variables and situations which could influence CO exposure around the home.

CONCLUSION

This study provided insight into the importance of various microenvironments to daily personal CO exposures and investigated the variability between participants exposure in Auckland, New Zealand. The study is the first of its kind conducted in the Southern Hemisphere and the first at one-minute temporal resolution. Overall, individual exposure to CO at a daily scale was lower than that observed in other major cities in the Northern Hemisphere. As with previous personal exposure studies, this study found that the commuting and home environments are the most important microenvironments contributing to individuals' daily air pollution dose [9, 10, 17]. This is due to the majority of time during a day being spent in the home microenvironment, whilst the commuting environment was associated with the highest mean pollutant exposure. FMS were found to be inadequate in predicting the diurnal variation in personal exposures but adequate for predicting mean personal daily exposures.

The study supports findings of other similar microenvironment studies where CO exposures were found to be highest during car and bus commutes compared with other commuting modes, and the presence of gas combustion and tobacco smoke resulted in elevated exposure to CO in indoor locations. Particularly revealing was that participants who were exposed to the highest mean exposures in the commuter microenvironment were found to commute by car four times as often compared to the participants who experienced their highest mean exposures in other microenvironments. Whilst certain trends could be identified, the number of variables and activities which influence personal exposure are vast and complex, highlighting the difficulty surrounding predicting or modelling personal pollutant exposure. This was evident by the significant variability in exposures experienced between participants. This research further reinforced the notion that pollutant concentrations are highly heterogeneous in time, location, and microenvironment, and that further research on the interactions between these variables are needed in order to effectively quantify population exposure.

Further epidemiological studies need to investigate the health effects of short term spikes in exposure (i.e. during commuting) and the effects of lower but consistent exposures as seen in the home microenvironment in this study. Results of these studies would assist in determining which microenvironments have the greatest effect on our health. This would provide a greater understanding of exposure to air pollution at a population scale within different microenvironments, and give further insight into how air quality management could be improved in urban areas.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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