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Article 10. Epidemiology------Comparison between indoor and outdoor air quality at three representative sites in Auckland Center

Author: Liu Huan (1983-), Master of Science (First Class Honours, 2009), The University of Auckland.
Advisor: Jennifer Salmond, School of Environment, Faculty of Science, The University of Auckland.

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Abstract

This field study was carried out at three representative locations in Auckland Center, including Starship Hospital, Shopping Mall, and Food Town. Both indoor and outdoor values of carbon monoxide, carbon dioxide, temperature and humidity were collected at each sampling site. The relation between indoor and outdoor air pollutant concentrations was analyzed in this study. A high correlation (R: 0.8424, $P<0.01$) was found between Roadside CO and Shopping Mall CO without significant difference between them ($P>0.05$). However, in Food Town where there was an additional combustion emission source inside, the average concentration of indoor carbon monoxide was 47.86% higher than Roadside level. Both indoor and outdoor CO concentrations in Starship Hospital were significantly lower ($P<0.01$) than Food Town and Shopping Mall levels. At all locations, the indoor carbon dioxide concentrations were significantly ($P<0.05$) higher than outdoor values, which was perhaps caused by higher occupant density inside. Epidemiology, which studies the causal factors of public health or epidemic disease, mainly includes the transmission pattern and mechanism of causal factors and its impacts on the defined receptors. It is undoubted that indoor exposure assessment becomes an essential part of the epidemiology study of airborne pollutants, which can be measured by the personal exposure monitoring. Additionally, relation between microenvironment monitoring and modeling methods for indoor exposure assessment has also been discussed in this study. Overall, Starship Hospital represented the effective design in terms of its ideal location, filtering function of ventilation system, and sufficiently indoor volume, which led to the most satisfactory air quality among all the sampling sites in this study.

Keywords: indoor air quality, carbon monoxide, carbon dioxide, exposure assessment，epidemiology

病理传播学----奥克兰市中心三个代表性监测点的室内和室外大气污染值比较研究（英文）

摘要：这项课题的大气污染监测点选择在奥克兰市中心的三个代表性地点，分别是医院、购物中心、美食城。每个采样点的监测数据包括室内和室外的一氧化碳、二氧化碳、温度和相对湿度值。课题研究了室内和室外空气污染物浓度之间的关系。路边室外 CO 浓度值与购物中心室内的浓度值之间呈现了很高的正相关性（R：0.8424，P＜0.01），并且二者的平均值之间没有显著差异（P＞0.05）。相比而言，在美食城有一个额外的室内燃烧排放源，使得室内一氧化碳浓度平均值高于路边室外 47.86%。在医院，室内和室外 CO 浓度明显（P＜0.01）低于美食城和购物中心的水平。在所有监测地点，室内二氧化碳浓度显著（P＜0.05）高于室外值，这可能是由高密度的人群造成的。病理传播学，主要研究对危害公共健康或爆发传染性疾病的致病因子在传播途径上的规律和机理，及其对特定受众的危害。室内人群大气污染暴露值评估成为病理传播学研究的一个重要组成部分，一般可以由便携式监测仪器测量。此外，室内微观大气环境监测和模型预测方法之间的关系也在课题中进行了探讨。总体上，医院位置代表了较为理想的工程设计，主要体现为良好的通风系统过滤功能和足够的室内体积，其中各项空气指标在三个采样地点是最为满意的。

关键词：室内空气污染监测、大气污染暴露值、一氧化碳、二氧化碳、病理传播学

1. Introduction

Atmospheric pollution has been increasingly paid attention by the public in urban area, which highlights the importance of air pollution monitoring (Chaloulakou & Mavroidis, 2002). The common ambient air pollutants include: Carbon Monoxide, Particulate Matter, Nitrogen Dioxide, Sulphur Dioxide, Ozone, Lead, Hydrogen Sulphide, Acetaldehyde, Benzene, 1,3-Butadiene, Formaldehyde, Benzoapyrene, Mercury, Chromium, and Arsenic (MfE & MoH, 2002). Local sources of air pollution mainly include vehicular emissions, road/sea salt, crustal materials, biomass burning and industrial emissions (Jeong etc, 2011).

In this study, carbon monoxide and carbon dioxide are selected for air quality assessment. The significance of them is discussed below:

1.1. Carbon monoxide

The excessive CO concentration, which combines with the blood's oxygen-carrying protein called haemoglobin (Hb), is able to form blood carboxyhaemoglobin (COHb), which leads blood to lose the oxygen-carrying capacity. Accurate poisoning can be caused by high exposure to CO. However, relatively lower levels of exposure also adversely affect the heart, brain, and central nervous system. The limit values of CO in Ambient Air Quality Guidelines (2002) in New Zealand are 30 mg/m^3 for 1-hour average, and 10 mg/m^3 for 8-hour average (MfE & MoH, 2002).

The sources of carbon monoxide emission are well-defined. CO is usually produced by incomplete combustion. The dominantly outdoor source is vehicle emission, and the indoor gas-cooking and heating system also generate carbon monoxide. Particularly, CO is usually associated with Environmental Tobacco Smoke (ETS) (Liu Huan, 2014). Carbon monoxide has a low reactivity in indoor atmosphere, which hence represents an ideal unreactive air pollutant for the indoor exposure testing (Liu Huan, 2014).

1.2. Carbon dioxide

Usually, carbon dioxide is not considered as air pollutant in the local and regional scale. However, monitoring indoor carbon dioxide concentrations can be effectively applied to control indoor fresh air supply in lecture theatres, halls, cinemas, and other similar places where occupant density can change rapidly (Zuraimi & Tham, 2008). Carbon dioxide monitoring can be also used to estimate the occupants' comfort in a space and the effectiveness of ventilation system (Hung & Derossis, 1989).

Carbon dioxide concentration can be considered as an indicator of indoor air quality (IAQ) (Hui, Wong, & Mui, 2008). A number of studies indicated the relation between indoor air quality and carbon dioxide concentrations, such as the health effect

associated with excessive indoor CO_2 concentrations, as well as the impact of CO_2 concentration on the people's perception about indoor environment (Hoskins, 2003), the association between CO_2 concentrations and other contaminants (Hui, Wong, & Mui, 2007), and the determination of outdoor air exchange rate (Persily, 1997).

The association between indoor air quality and health problem has been paid great attention by the public (Carson, 1994). The incidence of Sick Building Syndrome (SBS) and Building-related illness (BRI) increased since the 1990s, when the decoration was shifted to carpeted floors, synthetic wall coverings, ceiling tile, and multiple copiers. The interior building materials release unhealthy constituents into indoor air and the ventilation is restricted by the airtight structures (Phoon et al., 1995). Consequently, it is essential to monitor the indoor air quality that represents exposure where people live, work, and play (MfE & MoH, 2002).

A number of studies examined the relation between indoor and outdoor carbon monoxide concentrations. Helmis et al., (2007) reported the I/O ratio of carbon monoxide ranged from 0.67 to 0.83 in a dentistry clinic in Greece. Elsewhere Zuraimi and Tham (2008) identified the outdoor traffic emission became the major source of indoor CO in 91 Child Care Centre in Singapore.

Therefore, the objectives of this study is (a) to assess the indoor and outdoor air quality in selected sampling sites in terms of carbon monoxide and carbon dioxide concentrations, (b) to analyze the relation between outdoor and indoor air pollution, (c) to identify the determinants of indoor air quality, and (d) to discuss the implications for indoor air quality management.

2. Methods

2.1. Study design

In order to study indoor air pollution, three representative sites were selected in Auckland Central, including Starship Hospital, Food Town, and Shopping Mall. Sampling was firstly carried out in Food Town and Shopping Mall on Karangahape Road, Central Auckland (Fig 1). Both Food Town and Shopping Mall were naturally ventilated with the main entrance on the traffic road. Another background site was chosen in a Car Park at the back of Food Town. Sampling was subsequently shifted to Starship Hospital (Fig 2), which was mainly ventilated by air-conditioner and is located at a distance of approximately 500m from the main traffic roads.

It was assumed that the vehicle emission on the Karangahape traffic road contributes significantly to the air pollution in Food Town and Shopping Mall, where there is a high population density inside. Particularly, there may be an additional indoor air pollution source in Food Town, which is caused by indoor combustion, such as cooking and heating. Starship Hospital is located away from the main traffic road and is air-conditioned, which should have 'clean' air inside. However, there is always a quite vulnerable group in Starship Hospital: the sick children. The representative characteristics of each indoor sampling site selection are summarized below (Table 1):

Table 1. Representative characteristics of each sampling location.

	Food Town	Shopping Mall	Starship Hospital
Outdoor pollutant emission	**High**	**High**	**Low**
Indoor pollutant emission	**High**	**Low**	**Low**
Ventilation type	**Natural**	**Natural**	**Air-conditioned**
Exposure risk (depending on the population density and pollutant concentration)	**High**	**High**	**Low but vulnerable group**

2.2. Sampling

Sampling was taken on 13/08/2008, which was a rainy day with the minimum and maximum temperature of 12 ºC and 17 ºC, respectively. The sampling equipment used in this project was Model 8552/8554 Q-TRAKTM Plus IAQ Monitor (TSI). Carbon monoxide (ppm), carbon dioxide (ppm), temperature (ºC), and humidity (%) were recorded. Each sampling was measured at the same height.

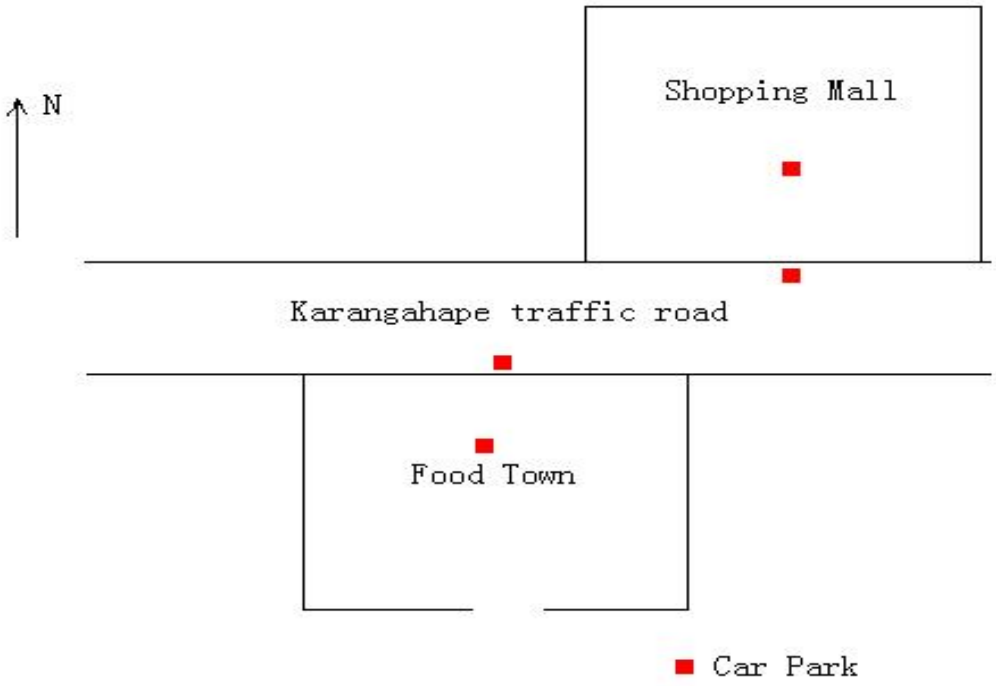


Fig 1. Map of sampling sites in Karangahape Road. ■ indicates the sampling sites

This sampling time in Food Town and Shopping Mall was from 10:20am to 12:50pm. There were five sampling sites selected (Fig 1), and the sampling sequences were: indoor Shopping Mall, Roadside North (in front of Shopping Mall), Roadside South (in front of Food Town), indoor Food Town, and Car Park. Sampling at each site was taken at every 15 minute interval, and was repeated in ten times.

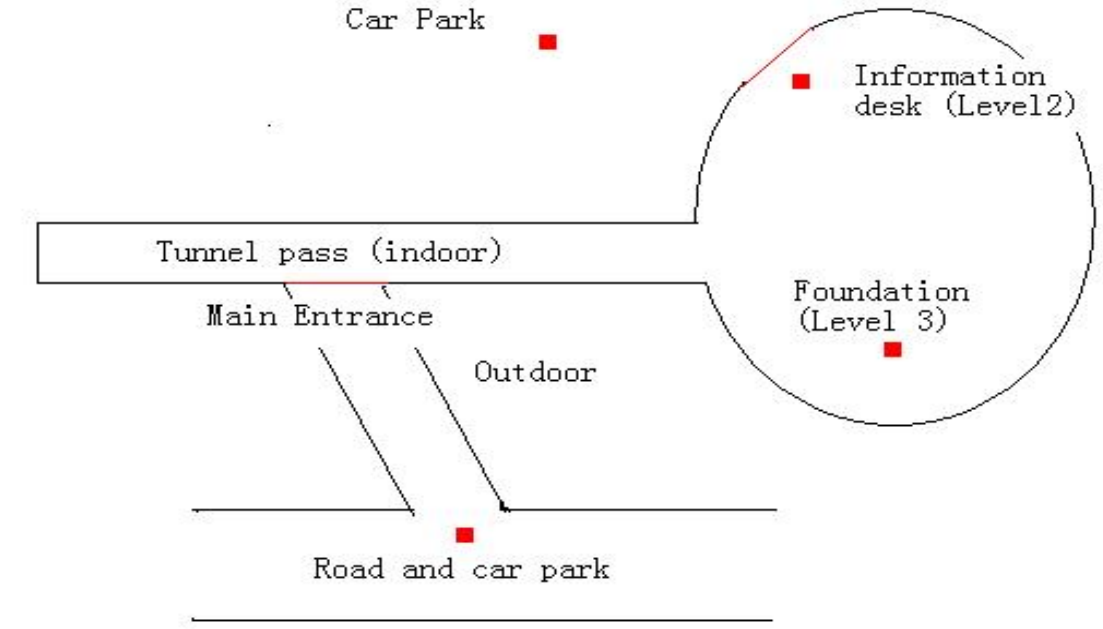


Fig 2. Map of sampling site in Starship Hospital. ■ indicates the sampling sites, and ——— indicates the automatic door.

Sampling in Starship Hospital was taken from 1.30pm to 3:10pm. There were two indoor sites and two outdoor sites selected (Fig 2), and the sequences were: hospital road, indoor Starship Foundation (Level 3), indoor information desk (Level 2), and car park (level 2). Each sampling was taken at every ten minutes, and was also repeated in ten times.

2.3. Data analysis

Mean value and standard deviation (S.D.) of each sampling site data were calculated. Least Significant Difference (Tukey) was calculated using Online Statistical Toolbox in The Chinese University of Hong Kong.

Since I hypothesized that the outdoor air pollution was one of the major sources for indoor air pollutants, Spearman's Rank Correlation coefficient was calculated (using Online IFA Statistical Services) to analyze the correlation of air pollutants between Roadside and Food Town, Roadside and Shopping Mall, and outdoor and indoor Starship Hospital.

3. Results

3.1. Carbon monoxide

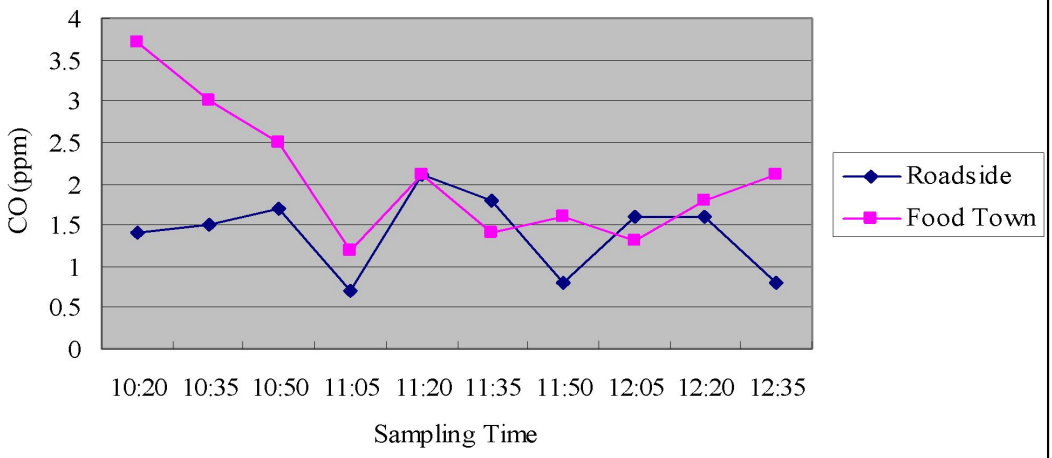


Fig 3. Comparison of CO between Roadside and Food Town.

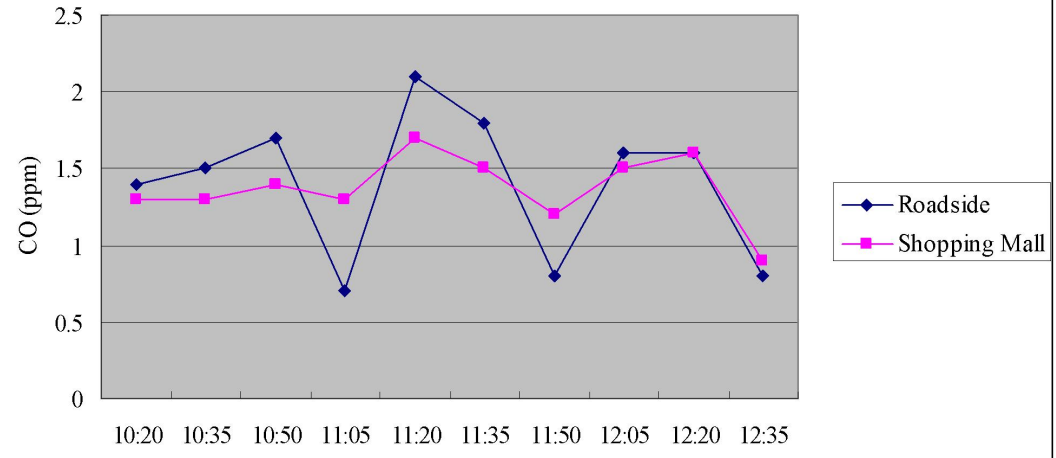


Fig 4. Comparison of CO between Roadside and Shopping Mall.

Table 2. Summary of mean CO concentrations and standard deviation (S.D.) in Roadside, Car Park, Food Town, and Shopping Mall. Roadside concentration is the average of Roadside South and Roadside North concentrations.

	Roadside	Car Park	Food Town	Shopping Mall
Mean CO(ppm)	1.4	0.65	2.07	1.37
S.D.(ppm)	0.452	0.383	0.762	0.215

The mean carbon monoxide concentrations and standard deviation (S.D.) are shown in Table 2. The mean CO concentration of Food Town was significantly higher ($P<0.05$) than CO in Roadside and Shopping Mall. The highest CO level in Food Town was found at the beginning of business hours (at 10:20), then decreased to the Roadside level (Fig 3). However, when the lunch time began at approximately 12:00pm, Food Town CO concentrations started to increase again. The average CO concentration in Food Town was 47.86 % and 51.09 % higher than Roadside and Shopping Mall, respectively. There was poor correlation (R: 0.1455, $P>0.10$) between Roadside [CO] and Food Town [CO]. However, Roadside CO concentration had a high correlation (R: 0.8424, $P<0.01$) with Shopping Mall CO.

No significant difference ($P>0.05$) of CO concentrations were found between Roadside and Shopping Mall (Fig 4). The Car Park CO concentration was significantly lower ($P<0.01$) than Roadside, Food Town, and Shopping Mall.

Table 3. Indoor and outdoor mean of CO concentrations and Standard Deviation (S.D.) in Starship Hospital. Outdoor concentration is the average of Hospital Road concentration and Car Park concentration. Indoor concentration is the average of Foundation concentration and Information Desk concentration.

	Outdoor	**Indoor**
Mean CO (ppm)	**0.32**	**0.06**
S.D.(ppm)	**0.157**	**0.049**

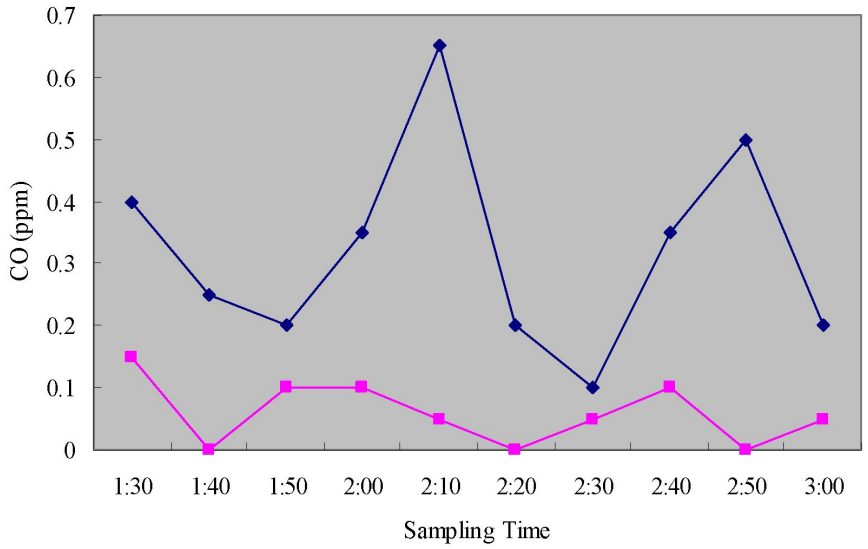


Fig 5. Comparison of indoor and outdoor CO concentrations in Starship Hospital.

In Starship Hospital, outdoor CO concentration was significantly ($P<0.01$) higher than indoor CO concentration (Fig 3). However, there was poor correlation (R: 0.1667, $P>0.10$) between them. Compared with the Roadside and Food Town, both outdoor and indoor CO levels of Starship Hospital were significantly ($P<0.001$) lesser. Mean [CO] of indoor Starship Hospital only accounted for 2.9% and 4.92% of indoor Food Town [CO] and Shopping Mall [CO], respectively.

3.2. Carbon dioxide

Table 4. Summary of mean carbon dioxide concentrations and standard deviation (S.D.) in Roadside, Car Park, Food Town, and Shopping Mall. Roadside concentration is the average of Roadside South concentration and Roadside North concentration.

	Roadside	Car Park	Food Town	Shopping Mall
Mean CO_2 (ppm)	449	435.9	560.8	588.3
S.D.(ppm)	25.29	4.5	37.032	66.133

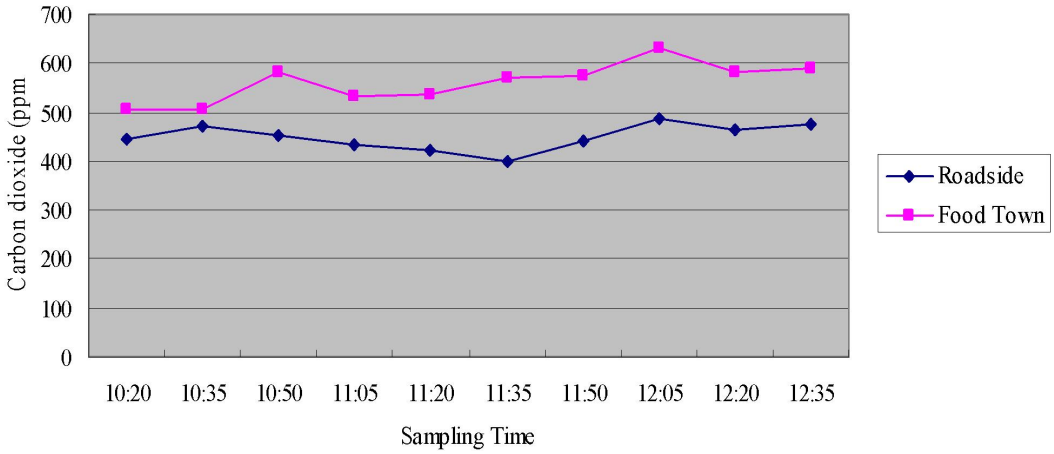


Fig 6. Comparison of carbon dioxide between Roadside and Food Town

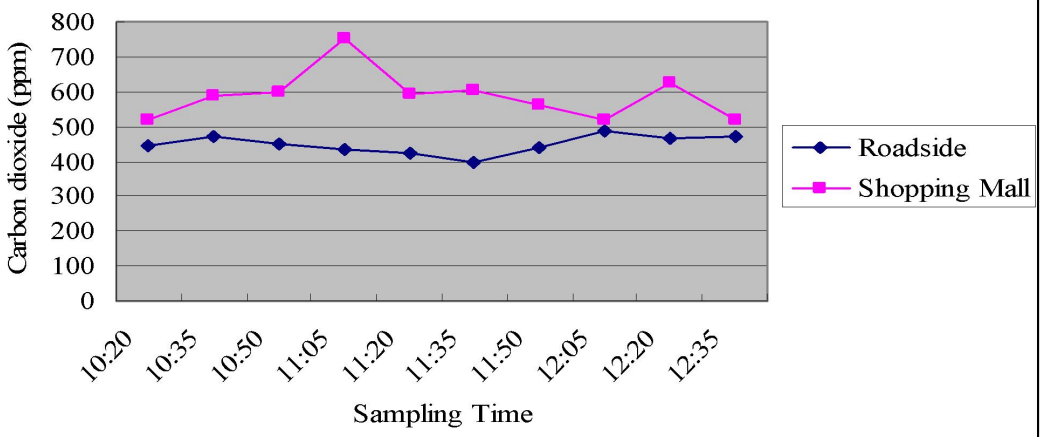


Fig 7. Comparison of carbon dioxide between Roadside and Shopping Mall.

The mean carbon dioxide concentrations and standard deviations (S.D.) in each sampling site are shown in Table 4. Mean CO_2 concentrations of Shopping Mall had the highest value of 588.3 ppm. The indoor CO_2 concentrations of both Food Town

and Shopping Mall were respectively 24.9% and 31.02% higher ($P<0.01$) than Roadside CO_2 concentrations (Fig 6 and Fig 7). However, there was no significant difference ($P>0.05$) between Food Town CO_2 and Shopping Mall CO_2.

Table 5. Mean carbon dioxide concentrations and standard deviation (S.D.) in indoor and outdoor Starship Hospital. Outdoor concentration is the average of Foundation concentration and Information Desk concentration. Indoor concentration is the average of Car Park concentration and Hospital Road concentration.

	Outdoor	Indoor
Mean CO_2 (ppm)	417.8	444.35
S.D. (ppm)	18.986	12.172

Similarly, indoor CO_2 concentration of Starship Hospital was significantly ($P<0.05$) higher than outdoor CO_2 level (Table 5 and Fig 8). However, compared with Food Town and Shopping Mall, the CO_2 level of both indoor and outdoor Starship Hospital was significantly lower ($P<0.01$). No significant correlation ($R<0.5$, $P>0.10$) was found between indoor and outdoor carbon dioxide concentrations at all sites. In addition, indoor CO_2 concentration had no significant correlation with indoor CO level in this study.

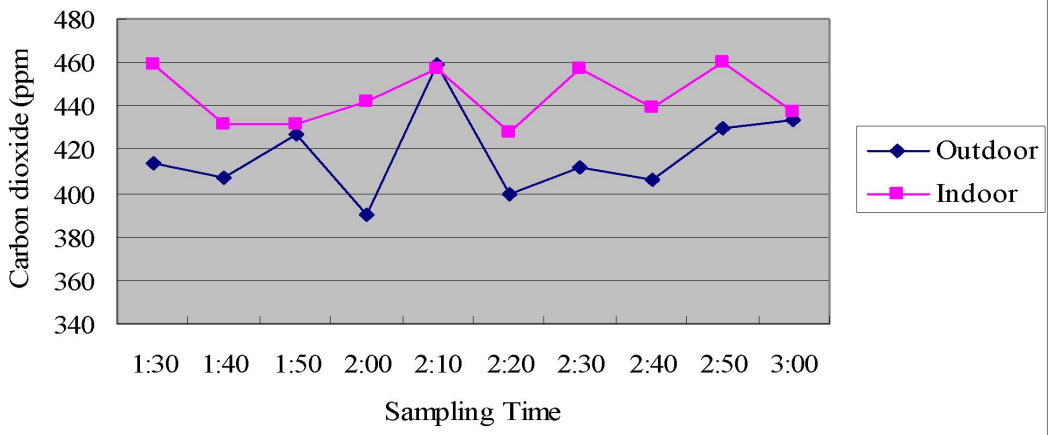


Fig 8. Comparison of carbon dioxide concentrations between indoor and outdoor Starship Hospital

3.3. Temperature and humidity

Mean temperature in Food Town was significantly higher ($P<0.05$) than Roadside and Car Park (Table 6). However, no statistically significant difference ($P>0.05$) were found among Roadside, Car Park, and Shopping Mall temperature. Mean temperature of indoor Starship Hospital was 21.25% higher than ($P<0.05$) outdoor temperature. There were no significant difference ($P>0.05$) between indoor humidity and outdoor humidity at all sites.

Table 6. Summary of mean temperature and humidity and their standard deviations (S.D.).

	Roadside	Car Park	Food Town	Shopping Mall	Outdoor Starship Hospital	Indoor Starship Hospital
Mean Temperature ºC	15.47	14.38	16.77	16.45	13.88	16.83
S.D. ºC	1.54	0.61	1.18	1.22	0.907	2.159
Mean Humidity %	69.03	65.3	73.37	70	64.25	63.3
S.D. %	5.8	4.6	4.1	2.6	5.7	7.7

4. Discussion

4.1. Carbon monoxide

Roadside traffic emission played a significant role in indoor air quality in Food Town and Shopping Mall. This can be reflected by the high correlation between Roadside [CO] and Shopping Mall [CO] (Fig 4), where the outdoor traffic emission became the major source of indoor carbon monoxide (Kukadia & Palmer, 1998). These results can be supported by a number of studies. Chaloulakoua and Mavroidis (2002) reported that indoor and outdoor CO concentrations were highly correlated at a public school in Greece. Elsewhere Hayes (1991) considered outdoor carbon monoxide emission as the only determinant of indoor CO with a determination coefficient (R^2) of 0.69 in his simplified prediction model.

However, compared with Shopping Mall, the carbon monoxide concentrations in Food Town was not only caused by outdoor traffic emission, but also caused by indoor combustion emission. This could be supported by the evidence that the indoor carbon monoxide level was elevated during lunch time (Fig 3), when the indoor combustion was increased. Consequently, the mean level of indoor carbon monoxide in Food Town was significantly higher than Shopping Mall in this study. The impact of indoor combustion on air quality has been demonstrated by a number of studies, such as Tian et al., (2005), Rijal et al., (2005), and Zhang and Smith (2005).

Indoor carbon monoxide level in Starship Hospital was significantly lower than Shopping Mall (Table 3). This was mainly due to two reasons. Firstly, Starship Hospital is located away from the main traffic road, which effectively prevents it from the outdoor traffic emission. Further more, the air-conditioned ventilation system in Starship Hospital was able to filter the outdoor carbon monoxide. This can be supported by the evidence that indoor carbon monoxide concentration in Starship Hospital was significantly lower than the correspondingly outdoor mean value (Fig 5). Beko et al., (2006) also found similar results, who reported that lesser outdoor air amount and lower penetration efficiency were caused by the filter function of air-conditioner in resident homes. Elsewhere Suh et al., (1994) reported a lowered infiltration factor (representing the outdoor air penetration) in air-conditioned homes. This can be considered as an advantage of air-conditioned ventilation system.

However, compared with Starship Hospital, there was no significant difference found between indoor and outdoor carbon monoxide concentrations in Shopping Mall (Fig 4). This indicated a high outdoor air infiltration rate in their ventilation system.

Particularly, in this study, both outdoor and indoor carbon monoxide levels at all locations were always below the limit value of NZ Ambient Air Quality Guidelines (10 mg/m^3 or 8.73ppm for 8-hour exposure).

4.2. Carbon dioxide

Indoor carbon dioxide concentrations were significantly higher than outdoor levels at all locations (Table 4 and 5), which were mainly caused by higher population density inside these buildings. These results were consistent with other studies. For example, Zuraimi and Tham (2008) reported that the mean values of indoor carbon dioxide concentrations were significantly higher than corresponding outdoor concentrations in 104 Child Care Centre (CCCs) in Singapore.

Carbon dioxide, which is metabolic, is closely associated with occupant density (Daneault et al., 1992). This can be supported by Ruotsalainen et al., (1993), who found that indoor carbon dioxide concentration was significantly correlated with occupant density in air-conditioned buildings. Nevertheless, in the naturally-ventilated buildings, this correlation might not be significant (Hanley et al., 1994; Zuraimi & Tham, 2008). However, in this study, less variation in indoor carbon dioxide was found at all locations, regardless of the change of occupant density (Fig 6, 7, and 8), which was possibly due to high air exchange rate, or large inside volume in these buildings.

Usually, compared with naturally-ventilated buildings, air-conditioned ventilation tends to lower air exchange rate (AER), which elevates the level of indoor-generated CO_2 (Zuraimi & Tham, 2008). Nevertheless, in this study, the mean concentration of indoor CO_2 in Starship Hospital (air-conditioned) was significantly lower than Food Town and Shopping Mall (naturally-conditioned) (Table 5). This was possibly due to larger volume inside Starship Hospital and lower outdoor traffic emission of carbon dioxide.

Outdoor carbon dioxide emission also potentially contributed to the indoor CO_2 level. There were no statistically significant correlations between indoor and outdoor carbon dioxide concentrations at all locations in this study (Fig 6 and 7), but Zuraimi and Tham (2008) reported that outdoor carbon dioxide concentrations were significantly associated with indoor levels in naturally-ventilated Child Care Centre (CCCs). However, compared with indoor occupant density, outdoor carbon dioxide infiltration should be less significant in this study.

The mean levels of indoor carbon dioxide in this study (from 400 ppm to 600 ppm) were relatively lower than other research. Helmis et al., (2007) and Daneault et al., (1992) found a mean CO_2 concentration of 2200ppm and 1500ppm, respectively, in a Dentistry Clinic (Greece) and in 91 Child Care Centre (Canada). Particularly, in this study, the mean values of indoor carbon dioxide concentrations at all locations were within the acceptable range. There was no indoor Air Quality Standards for carbon dioxide concentrations in New Zealand. However, compared with the Health Guidelines of Minister of Health (2002) in Singapore, the concentrations of indoor carbon dioxide at all sampling sites were always below the threshold level of 1000

ppm.

4.3. Implications for the indoor air quality management

4.3.1. Indoor air pollution and exposure assessment

In New Zealand, the Ambient Air Quality Guidelines (2002) can be used to assess and regulate outdoor air pollution. However, these Guideline values can be applied only to ambient air outside buildings or structures, but not to air inside a house, tunnel, and vehicle (MfE & MoH, 2002). The framework of air quality monitoring by regional councils emphasizes only on the outdoor air pollution.

Nevertheless, as can be seen from this study, indoor carbon monoxide concentrations can differ significantly from the correspondingly outdoor values. Especially, indoor CO levels in both Food Town and Shopping Mall were significantly higher than outdoor background value (Car Park). People usually spend more time inside the buildings (estimated 70-90%), which leads to potentially significant exposure to indoor air pollution. This is particularly important for the susceptible groups, such as elderly and sick people (Liu Huan, 2014). Further more, indoor air pollutants do not only include the commonly outdoor substances which are pointed out in Ambient Air Quality Guidelines, but also contain the toxic chemicals caused by building interior material emission, such as Asbestos, Radon, Lead, Formaldehyde, and VOCs (Niu & Burnett, 2001). Therefore, it is essential to assess the people's exposure to indoor air pollutants for the epidemiology study (Liu Huan, 2014).

4.3.2. Exposure monitoring methods

In this study, a portable monitoring instrument (Model 8552/8554 Q-TRAKTM Plus IAQ Monitor (TSI)) was used for the sampling, which well measured the personal exposure to carbon monoxide. Cherrie (2002) and Kromhout and Tongeren (2003) demonstrated the importance of personal exposure monitoring in the epidemiology study of air pollutants. In reality, the exposure risk can be caused by multiple sources, including inside houses, vehicles, and generally urban environment. The exposure risks can vary among populations with different life styles. For example, elderly and sick people may have less exposure risk to particulate matter due to their limitation of activity (Liu Huan, 2014). Consequently, the fixed point measurement at some central locations in the city can not represent the variability of personal exposure. Instead, the personal exposure monitoring is required for the epidemiology study of air pollutants (Cherrie, 2002).

However, in practice, the personal sampling method used in this study may be considered to be inconvenient and expensive for more comprehensively personal exposure measurement. Hence, Liu Huan (2014) proposed the microenvironment measurement which used static monitoring method to estimate the personal exposure.

Nevertheless, the correlation between personal monitoring and static monitoring is

still controversial. Lots of historic data indicated that there were no relations between personal and static exposure measurements (N. Esmen & Hall, 2000; Lange, Kuhn, & Thomulka, 2000; Linch & Pfaff, 1971). However, Liu Huan (2014) recently questioned these findings and reported that a high correlation was found between personal exposure monitoring and microenvironment measurement (static monitoring) for carbon monoxide and nitrogen dioxide. According to the results, personal exposure of carbon monoxide was significantly higher in smokers who were associated with Environmental Tobacco Smoke (ETS). Further more, the results showed that the carbon monoxide concentrations measured by personal monitoring were nearly equal to the measurement of static monitoring (Liu Huan, 2014), which differed from Sherwood and Greenhalgh (1960), who firstly suggested that the concentrations of personal samples were usually higher than the static sampling.

Cherrie (2002) supported the findings made by Harrison and his coworkers, and considered the microenvironment monitoring method to be important for the epidemiology study. In order to better understand the correlation between personal exposure and microenvironment measurement (static monitoring), a number of factors should be studied, including the volume of the room, the quantity of general ventilation, the time the person spends in the proximity of sources of hazardous substances, and the presence of other internal or environmental sources of the contaminant (Cherrie, 2004).

Nevertheless, Kromhout and Tongeren (2003) subsequently questioned the methodology used by Harrison and his coworkers, and considered the static monitoring method to be less effective. Instead, the improved instruments for personal sampling, which were smaller, lighter, and inexpensive, should be more accurate and precise than microenvironment monitoring.

4.3.3. Modeling of indoor air pollution

As mentioned above, it is impossible to assess the population exposure accurately without considerations on the indoor air pollution (Hayes, 1989). However, continuously indoor monitoring is considered to be difficult. Hence the modeling of indoor air pollutant which is based on the correlation between indoor and outdoor concentrations becomes essential for the exposure assessment (Chaloulakou & Mavroidis, 2002). For example, the probabilistic National Ambient Air Quality Standards (NAAQS) Exposure Model was developed by the U.S. Environmental Protection Agency (EPA) to estimate the population exposure to carbon monoxide using outdoor monitoring data to estimate CO exposure in homes (Law et al., 1997).

However, all the models are the simplified simulation of air pollution, which inevitably leads to limitations (Chaloulakou & Mavroidis, 2002). Esmen (1978) developed a general mass balance model for indoor air pollutants, but it did not take into account of air pollutant reactivity or air filter loss. Dockery and Spengler (1981) employed a mass-balance based model to estimate the indoor particulate matter and

sulfates. However, this model lacked of mixing factor and recirculation filter loss. Moschandreas et al. (1981) developed an indoor air pollution model, but did not consider the infiltration of outdoor make-up pollutants. Therefore, it is important to validate these models under a range of conditions. For example, Allen and Wadden (1982) validated Shair and Heitner (1974) model, and found a poor correlation (r: 0.19) between predicted CO and measured CO levels under certain conditions. Elsewhere Chaloulakoua and Mavroidis (2002) validated the Hayes (1989 and 1991) model which predicted the indoor carbon monoxide concentrations, suggested that it did not respond rapidly to the sudden peak of CO concentrations (Chaloulakou & Mavroidis, 2002).

Particularly, in this study, Hayes (1989 and 1991) model can be used to predict the carbon monoxide concentrations in Shopping Mall, which gives an accurate estimation of indoor CO value and is quick and easy to run, as suggested by Chaloulakoua and Mavroidis (2002). However, in the Food Town, Hayes model may not be applicable due to lack of consideration on the indoor emission source.

4.3.4. Control of indoor air pollution

In this study, Starship Hospital represents a good design for the indoor air pollutant control. There are several advantages: the location of Starship Hospital leads it away from the outdoor vehicle emission on the main traffic road; the air-conditioned ventilation system filters the outdoor air pollutants; and the sufficient volume inside Starship Hospital further dilutes the indoor air pollution (Niren, Harry, & Michael, 1986).

Usually, the I/O ratio of air pollutant concentration can be reduced significantly in the energy-efficient buildings (Hayes, 1991). Therefore, the air quality in Shopping Mall can be improved by installing mechanical ventilation system. However, in the Food Town where indoor emission source also becomes significant, installation of mechanical ventilation will not be sufficient. In order to better mitigate the indoor air pollution in Food Town, the heating and cooking devices can be replaced by electric appliance or solar-heating system, or pilotless combustion appliances. The combustion devices should also be placed in isolated rooms and special ventilation system is required (Isaac, 1985).

4.4. Limitations of this study

In this study, all the sampling work was undertaken by one person and there was only one sampling instrument, so that it was impossible to compare these monitoring data at the exactly same time. Further, I was not able to collect the air pollutant data at a longer time scale due to time limit. Ideally, the sampling data should cover the whole working hours. The small sampling size may lead the explanations to be cautious.

Although the significant air pollution sources have been identified, it is still difficult

to interpret the direct cause of increased carbon monoxide in Food Town. Population density was not able to be exactly counted in this study, so the explanation about the indoor carbon dioxide level was also vague.

4.5. Implication for future study

As pointed out above, exposure assessment is the essential part of epidemiology study, which will be conducted in future study. The objectives of future research will focus on the monitoring of peoples' cumulative exposure to heavy metal pollution in atmospheric environment, and to in-door airborne microbes by classification and identification (although outdoor airborne microbes are also sometimes paid attention in coast area by Laura et al., (2011)); then the pathological characters of the defined receptors will be recorded concurrently for the analysis of correlation between the exposure dose and incidence of pathological characters. This provides robust evidence for the policy-making of Environmental & Health Standards regulating the atmospheric transmission pathways, which are divided into limit value of pollutants and monitoring methods.

Future research hypothesizes that the heavy metal concentration adhering to the aerosol and its impact on health is source-dependent and particle size-dependent (e.g. The heavy metal impacts differ between PM2.5 and coarser particle due to the different solubility of heavy metal adhering to particles in different size), which will be examined in future research by analyzing the correlation of heavy metal concentration in different particle size to the pathology testing. Further more, the structure of particle is the main factor influencing the accuracy of air quality monitoring (Zimmerman et al., 2014), which should be the consideration in the routine assessment of environmental toxicity of heavy metals as well. Consequently, the structure of particle (e.g. The agglomerate nature of diesel particle) is the determinant of the environmental toxicity of heavy metal pollution adhering to aerosol, which should be examined by the animal test (e.g. The test of heavy metal concentration in urine) as well, and the method is designed in another article of this journal (Liu Huan, 2021 a).

Static monitoring does not well represent the people's exposure dose to air particle, as discussed above. The sampling instruments for atmospheric virus are compared by Chen (2013). Nevertheless, the sampling methods specifically for fugitive and mobile source of virus have not been fully characterized, e.g. virus population density, incidence of relevant illness in the receptors' population, so that it is difficult to correlate the airborne virus density, which is not counted in research, to the receptors' incidence of relevant illness, but this is compulsory to determine the air quality standards (limitation value) against specific airborne virus density. Consequently, future research will aim to measure the cumulative exposure concentration on both the atmospheric heavy metal and airborne virus

pollution by portable samplers, as to compare with the tested static monitoring, which reveal the representativeness of static monitoring so that the optimal sampling protocol of static monitoring is worked out in terms of sampling sites, time and frequency in response to the fugitive pollution source. A novel method of evaluating virus density is designed in my another article (Liu Huan, 2021 b), which is important to monitor the airborne virus density such as COVID-19.

5. Conclusion

In this study, outdoor carbon monoxide emission was one of the major sources for the indoor CO pollution at all locations. However, the I/O carbon monoxide ratio varied among these sampling sites. In the naturally-ventilated Shopping Mall, indoor CO level was approximately equivalent to outdoor concentration. In Food Town where there was an additional combustion emission source, indoor carbon monoxide level was significantly higher. Compared with the naturally-ventilated buildings, air-conditioned Starship Hospital had significantly lower carbon monoxide concentration inside. However, all the CO sampling concentrations were always below the limit value of Ambient Air Quality Guidelines (2002).

Indoor carbon dioxide levels were mainly determined by occupant density, which led the indoor concentrations to be higher than outdoor levels at all sampling sites. However, all the sampling values of carbon dioxide were within the acceptable range (below 1000ppm). Compared with other studies, the indoor carbon dioxide concentrations in this study were relatively lower.

It is necessary to include the indoor exposure assessment for the epidemiology study of airborne pollutants. Microenvironment monitoring can be applied to estimate the personal exposure to indoor air pollution. However, it is expected that the smaller, lighter, and inexpensive personal sampling instruments can be widely applied to give more accurate measurement of personal exposure.

Indoor air quality modeling which is based on the relation between indoor and outdoor air pollutant concentrations can be a more convenient way than continuously indoor monitoring. However, it is essential to understand the limitations of these models before application, which should be validated under a wide range of conditions.

Overall, Starship Hospital had the most satisfied air quality in this study, mainly due to its ideal location, effectively air-conditioned ventilation, and sufficient volume. Air quality in Shopping Mall and Food Town can be improved by installing mechanical ventilation system. However, control of indoor combustion emission is also essential to reduce carbon monoxide level in Food Town.

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