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Personal exposure to black carbon during commuting in peak and off-peak hours in Shanghai

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HIGHLIGHTS

- The exposure level in subway was the highest among the concerned modes.
- The doses by bus and walking were higher compared to those by other modes.
- Diesel vehicles are an important contributor to on-road BC concentrations.

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ABSTRACT

A study on a commuter's exposure to black carbon (BC) in five different traffic modes (taxi, bus, subway, cycling and walking) was conducted in Xuhui District, Shanghai. A commuter's real-time exposure concentrations were recorded by MicroAeth AE51 BC monitors, and the average BC exposure concentration and inhalation dose were analyzed. Data collected by cyclist was applied to characterize the micro-variability in relation to traffic density and street topology. The distance to the traffic and the street topology as well as the volume of heavy diesel trucks were the dominant factors influencing the BC concentrations. In this study, a high variability of BC concentrations between streets and even within streets was observed, and also between days and hour of the day. The average BC exposure concentrations were 5.59 ± 1.02 μg/m^3, 6.58 ± 1.78 μg/m^3, 7.28 ± 1.87 μg/m^3, 8.62 ± 4.13 μg/m^3 and 9.43 ± 2.89 μg/m^3 for walking, cycling, bus, taxi and subway trips, respectively. Exposure levels of in-vehicle microenvironments were 8.66 ± 3.66 μg/m^3, 9.39 ± 6.98 μg/m^3 and 10.96 ± 2.72 μg/m^3 for bus, taxi and subway, respectively. While inhalation doses were 0.68 ± 0.33 μg, 0.95 ± 0.29 μg, 1.36 ± 0.37 μg, 1.50 ± 0.39 μg and 1.58 ± 0.29 μg for taxi, subway, cycling, bus and walking, respectively. BC exposure level of walking was the lowest among all the traffic modes, but its inhalation dose was the highest.

1. Introduction

Particulate matter (PM) can cause respiratory diseases and trigger cardiovascular morbidity and mortality after long-term and short-term exposure (Anderson et al., 2012; Künzli et al., 2010; KuÈnzli et al., 2000). Black carbon (BC), a constituent of fine particles, is a primary particle that is emitted from incomplete combustion as tiny spherules ranging in size between 0.001 and 0.005 μm, and aggregates to particles of larger size (0.1–1 μm) (EPA, 2010). It is a unique primary tracer for combustion emissions, as it has no non-combustion sources, and is stable once released into the atmosphere (Invernizzi et al., 2011). It absorbs light in the visible part of the spectrum, which is the basis of its detection. If inhaled it deposits deep in the lungs, and a dose-dependent inverse association between the black carbon content of airway macrophages and lung function in children has been found (Kulkarni et al., 2006). On road ways without other emission sources, BC is emitted primarily by traffic, which indicates that BC is a highly relevant metric of traffic pollution and is strongly associated with health outcomes in epidemiological studies (Heal et al., 2012; Invernizzi et al., 2011). BC is also considered as a PM metric more suitable than undifferentiated PM mass to identify traffic pollution (Janssen et al., 2012).

Commuting is considered as one of the high-exposure periods among various daily activities, especially in high vehicle-density metropolitan areas (Duci et al., 2003). Pollutant concentrations are often very high in the traffic microenvironment; individuals may gain a significant contribution to their daily exposure when commuting in traffic even though such individuals usually travel for no more than 1.5–2 hours per day (Kaur et al., 2007). Indeed, during their regular journeys commuters can receive up to 30% of their inhaled daily dose of black carbon, and approximately 12% of their daily PM$_{2.5}$ personal exposure (Dons

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et al., 2011, 2012). As concentrations of air pollutants from traffic are elevated along roadways, personal exposure in transportation microenvironments may not be adequately characterized by fixed-site monitoring methods (Apte et al., 2011; Moreno et al., 2009). So a large number of exposure studies apply personal monitoring by equipping the study subjects with portable integrated sampling equipment or real-time monitors to study personal exposure (Behrentz et al., 2005; Dons et al., 2012, 2013; Kingham et al., 2013; Spira-Cohen et al., 2010). Studies concerning personal pollution exposure on the journey to work had determined that, although temporally and spatially variable, individuals may be exposed to very high ambient pollutant concentrations in the transport microenvironment (e.g. Dons et al., 2011; Kaur et al., 2007; Panis et al., 2010). Briggs et al. (2008) reported that car drivers were the least exposed on road ways. Many researchers reported that car commuters are exposed to higher levels of air pollutants than commuters cycling, walking or using public transport (e.g. de Nazelle et al., 2012; Dons et al., 2012; Kaur et al., 2007). To date there is limited consistency in establishing which mode of transport (car, bus, bike, etc.) is associated with the highest exposures (Boogaard et al., 2009). Results vary both between and within studies which have been undertaken in a variety of different urban settings around the world. Besides personal exposure concentrations, the amount of pollutants inhaled into the body is variable significantly due to variable exposure concentrations, inhalation rates, duration in a specific microenvironment and a range of biological factors such as age and body mass (Rodes et al., 2012). When compared to other traffic modes, increased activity rate and time spent during transportation (walking and cycling) can cause higher inhalation doses of pollution for both modes despite lower exposures (Rodes et al., 2012).

The vast majority of these studies has taken place in large urban areas in developed countries (Kingham et al., 2013), while personal BC exposure studies in China are limited. In view of the limited data on this important air quality issue, we undertook an investigation of the road-way and in-vehicle personal exposure concentrations of black carbon (BC) in Shanghai, China. Shanghai is a crowded city with a population of 24.15 million and an annual traffic flow of over 6.3 billion passengers within the Shanghai public transport system in 2013 (SMBS, 2014). Therefore, the air quality conditions during commuting may have a significant impact on a large population of commuters. The traffic modes in Shanghai are mainly composed of private car, bus, taxi, subway, cycling and walking (Yu et al., 2012). The increasing vehicle population as well as a large population of commuters drives our curiosity to know the exposure characteristics for the commuters in the central city of Shanghai. Meanwhile, it is important to understand the factors determining exposure in different traffic modes so that steps can be taken to minimize exposure and promote healthy lifestyles. So this study focused on a commuter's BC exposure characteristics in Shanghai and quantifies personal exposure levels for different traffic modes (bus, subway, taxi, walking and cycling). BC data acquired in this study can provide a reference in establishing traffic restriction policies in Shanghai.

2. Materials and methods

2.1. Site description and experimental design

Studies by the five travel modes (taxi, bus, subway, cycling and walking) were conducted during six non-rainy working days in August, 2014. Our study builds on the methodology employed by Yu et al. (2012) in an investigation of a commuter's exposure to PM_1 in winter time. While personal exposure to BC and $PM_{2.5}$ was monitored in this study. The other differences between our study and the study of Qi are that Xuhui district was chosen as our study area, underground subway line 1 was investigated and spatial and temporal distributions of BC were monitored in summer as well as three different roads with different features (Table 1) were chosen. Xuhui district is located in the southwest of the downtown area of Shanghai. Channels, highways and railways make Xuhui district an important transport corridor connecting the downtown area of Shanghai with other districts and provinces such as Zhejiang and Jiangsu provinces. In the area and routes in this study, traffic emission was the dominant source for BC since there were no other obvious combustion sources except several hotels and restaurants along the routes. At set times (peak (7:00–9:30 am) and off-peak (14:00–16:30 pm) hours) during weekdays, door-to-door journeys were taken along three routes, R1, R2 and R3. These routes linked residential areas and working or education areas. R1 linked Shanghai South Railway Station and Kai Xiang residential area; R2 linked the 8th hospital of Shanghai and Xu Jia Hui; and R3 linked Xu Jia Hui Park and Shanghai US Consulate. The route lengths were designed to be 3–3.5 km long in order to enable comparison between the five travel modes. Fig. 1 shows the average traffic flow rates of these three routes. A bus, taxi or subway trip consisted of walking to the station, waiting at the station, staying in transit and walking to the destination.

Two MicroAeth Black Carbon monitors (model AE-51, Magee Scientific, USA) were applied in order to conduct the measurements in pairs simultaneously. For each monitoring, one volunteer always traveled by bike, and the other volunteer took the other modes in turns as comparison. Each time the two volunteers started their trips at the same time and the same place. Four measurements by bike and the four concurrent measurements by other travel modes along three routes constituted a round of measurements. In this way, the spatial and temporal distributions of BC in peak and off-peak hours on these roads can be recorded with the assistance of a GPS logger and MicroAeth. Finally, 96 trips (48 cycling trips and 48 others) were taken on each route. For further information about this methodology, refer to Yu et al. (2012).

2.2. Instrumentation

2.2.1. Integrated $PM_{2.5}$ measurements

We measured $PM_{2.5}$ with two personal $PM_{2.5}$ samplers. It consisted of a pump (Buck Elite-5, A. P. BUCK, INC., USA) and a $PM_{2.5}$ personal impactor (H-PEM $PM_{2.5}$ Personal Impactor, BGI, INC., USA). Before each sampling, the pumps were adjusted to the specified 4 L/min flow rate. Quartz filters of 37-mm (Pall Quartz, TISSUQRTZ 2500QAT-UP) were pretreated under 600 °C for 5 h and kept for 24 h in a constant temperature and humidity cabinet (25 ± 1 °C, 40% ± 5%) before used in the impactor. Two volunteer commuters were recruited during the sampling process. The sampler was worn on the commuter in one of the vest pockets respectively with the impactors fixed at the typical breathing zone.

In this way, the quartz filter $PM_{2.5}$ samples were collected. Filter-based EC concentrations were analyzed using a thermal optical reflectance (TOR) method (Chow et al., 2001) and compared to the aethalometer BC concentrations.

Table 1
Features of the routes.

Route	Length (km)	Lanes	Intersections	Bus stations	Bus lines	Buildings	Trips
R1	3.2–3.5	8	5	4	7–13	1–5 story residential buildings on both sides	96
R2	3.2–3.4	10 (with 8-lane flyover)	5	4	14–21	High-rise buildings	96
R3	3.0–3.1	2	5	4	1–5	2–5 story buildings with dense shade tree cover along both sides	96