



Effect of time-activity patterns and microenvironments on the personal exposure of undergraduate students to black carbon

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Abstract In this study, the personal exposure to and potential dose of black carbon (BC) of undergraduate students (22–27 years old, nonsmokers) were determined. BC was continuously measured by a portable device (microAeth[®] AE51) for four consecutive days in Istanbul between April and May 2019. The time-activity diaries filled out by each volunteer were assessed to define the activities and microenvironments (home, school, transportation and entertainment) that contributed to daily BC exposure. The overall mean concentration of BC was 2.0 µg/m³, and

the mean concentrations on weekdays and weekends were 3.0 µg/m³ and 1.1 µg/m³, respectively. Transportation made the highest contribution to mean BC exposure (42%) and dose (45.8%) on weekdays, while the contributions of home-based activities to BC exposure (66.1%) and dose (63.2%) were higher on weekends. Students had the most intense exposure to (2.8% and 4.6%) and dose (3.1% and 5.8%) of BC in transportation both on weekdays and on weekends, respectively. Between transportation modes, the mean BC concentration was the highest for mini-buses (14.8 µg/m³), while walking made the largest contribution to BC exposure (16.8%) on weekdays. Students spent 12.8% of their weekdays at school, and the contributions of the school environment to BC exposure and dose were 8.5% and 7%, respectively. Exposure to BC increased during cooking and eating activities in microenvironments such as the kitchen, cafe and dining hall.

Highlight

- The mean BC concentration in transportation was 6.2 times higher than that at home.
- The largest contribution to BC exposure was that of transportation, with 42% on weekdays, and at home with 66.1% on weekends.
- The contribution to BC exposure in schools was 8.5% on weekdays.
- Walking was a significant contributor to BC exposure.

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Introduction

In urban areas, fixed monitoring stations (FMSs) do not fully represent daily individual exposure in different microenvironments. Therefore, in the past decade, personal exposure to air pollutants in different

microenvironments has been measured using portable devices. The measurement of personal exposure to air pollutants is crucial to be able to determine the level and contribution of pollutants in different microenvironments for the purpose of estimating the relationships of these pollutants with health. BC is a particularly notable pollutant in personal exposure studies, as it causes adverse cardiovascular (Gan et al., 2011; Luben et al., 2017; McCracken et al., 2010), respiratory (Lepeule et al., 2014; Lin et al., 2011; Patel et al., 2010) and neurological effects (Chiu et al., 2013; Suglia et al., 2008). Furthermore, BC is the most important contributor to global warming after carbon dioxide (CO₂) (Ramanathan & Carmichael, 2008).

BC is an indicator of diesel emissions from transport (HEI, 2010) and is an important parameter for the assessment of transport-related exposure effects (Buonanno et al., 2013; Cunha-Lopes et al., 2019). Personal exposure to BC is variable depending on factors such as the locations (Cunha-Lopes et al., 2019) and routes (Carvalho et al., 2018; Hankey & Marshall, 2015), daily activities (Buonanno et al., 2013), the mode of transportation (Dons et al., 2011) and timing of trips (Dons et al., 2012). The primary combustion of fossil fuels and biomass (Mousavi et al., 2019; Onat et al., 2019a), diesel engine vehicles (Lamarque et al., 2010), cooking and smoking in indoor environments all contribute to the concentration of BC (Jeong & Park, 2017).

Previous studies showed that the BC concentration in traffic microenvironments was higher than that in other environments (Dons et al., 2011, 2012; Koehler et al., 2019; Lei et al., 2016; Paunescu et al., 2017). Some studies stated that the concentration of BC during home activities and sleeping was lower than that in traffic (Dons et al., 2011). Paunescu et al. (2017) showed that 83.8% of the total BC exposure of 9-year-old students was caused by activities at home and at school. Zhou et al. (2020) observed that home activities and transportation make the greatest contribution (74.5%) to the BC exposure of high school students. Indoor activities (46%) and transportation (12%) are the main contributors to the daily BC exposure of graduate students (Lei et al., 2016). Exposure to BC during commuting by walking to school is associated with the cognitive development of children (7–10 years old) (Alvarez-Pedrerol et al., 2017). Also, exposure to BC is associated with symptoms of

depression in college students (Shen et al., 2021). In Istanbul, the concentration of BC in traffic areas was investigated in previous studies (Kuzu et al., 2020; Ozdemir et al., 2014; Şahin et al., 2020). Depending on the mode of transportation and route taken, passengers are exposed to different levels of BC (Onat et al., 2019b, c). Istanbul is a metropole with a population of 18.6 million and 4.0 million registered vehicles. To the best of our knowledge, while there are a few studies related to the personal exposure of commuters in public transport (Şahin et al., 2012; Onat & Stekeava, 2013, 2014; Onat et al., 2017), the contribution of daily activities in different microenvironments to BC exposure has not been investigated in Istanbul. The daily activity patterns of undergraduate students (aged 22–27 years) are dissimilar from those of adults, meaning that their BC exposures (and the microenvironments contributing to these exposures) are likely to be disparate.

The aims of this study were (1) to measure the personal exposure to BC of undergraduate students who live in different districts of an urban area during their daily activities, (2) to investigate the BC exposure concentration in different microenvironments/activities, such as home, school, transportation, entertainment indoors/outdoors, on weekdays and weekends and (3) to define the contribution of microenvironments/activities to the exposure, inhaled dose and dose intensity.

Material and method

Study area

This study was performed in the city of Istanbul located in northwestern Turkey (41°K and 29°E). Istanbul has many emissions sourced from industry, traffic vehicles and domestic heating. The number of registered vehicles in the city is approximately 4 million. Sixty-nine percent of these vehicles are passenger cars, 16% are vans, 8% are motorcycles, 3% are trucks, 2% are minibuses, 2% are buses and other types of vehicles (special purpose vehicles, tractors, etc.) (TUIK, 2020). The air quality is variable across city districts (Onat et al., 2012, 2013; Şahin et al., 2012, 2016, 2020). The average temperature and humidity in the city are 14.5 °C and 75%, respectively. The dominant winds are north and northeast,

while the second dominant wind directions are south and southwest. The Bosphorus separates the city into two parts (the European side and the Asian side). The university is located in the Avcılar district on the European side of Istanbul. There is a highway (D100) near the university. The students participating in this study reside in different districts of Istanbul. Two of them live in Beykoz and Üsküdar districts on the Asian side, and the others live in Bağcılar, Fatih and Büyükçekmece districts on the European side. The location of the university and the places where students stay are illustrated in Fig. 1.

Study design

A personal measurement study was conducted from April to May 2019. The measurement campaign was performed between Thursday and Sunday for a period of 96 h (24-h measurement for a day) to represent weekdays and weekends. A total of 9 undergraduate students participated in this study, and the data of five volunteers were considered for evaluation because of technical problems (missing data, incomplete time-activity tables, etc.). Undergraduate students were 22–27 years old and nonsmokers.

Personal measurements comprised all daily activities, such as those related to transportation, home, university and the outdoors. Students filled out time-activity diaries defining the microenvironments, periods, types of transportation they used and their activities (cooking, sleeping, social activities, etc.) during the measurement period. Additionally, the location coordinates of the students during their daily activities were recorded with a GPS mobile application. There was no intervention during the measurement study. Students used natural gas for heating and cooking, and their homes used natural ventilation. While four students (U1, U3, U4 and U5) were living at home with family or friends, U2 was staying in a dormitory.

All students were instructed on how to use the aethalometer prior to measurement and were communicated with in case of any problem. During measurement, students carried the aethalometer in a backpack or fixed to their belt. The inlet of the aethalometer was placed at the breathing height. All students placed the instrument on a table next to them when they were sleeping. At the end of the measurement day, a filter change and BC data downloading were carried out by students at home.

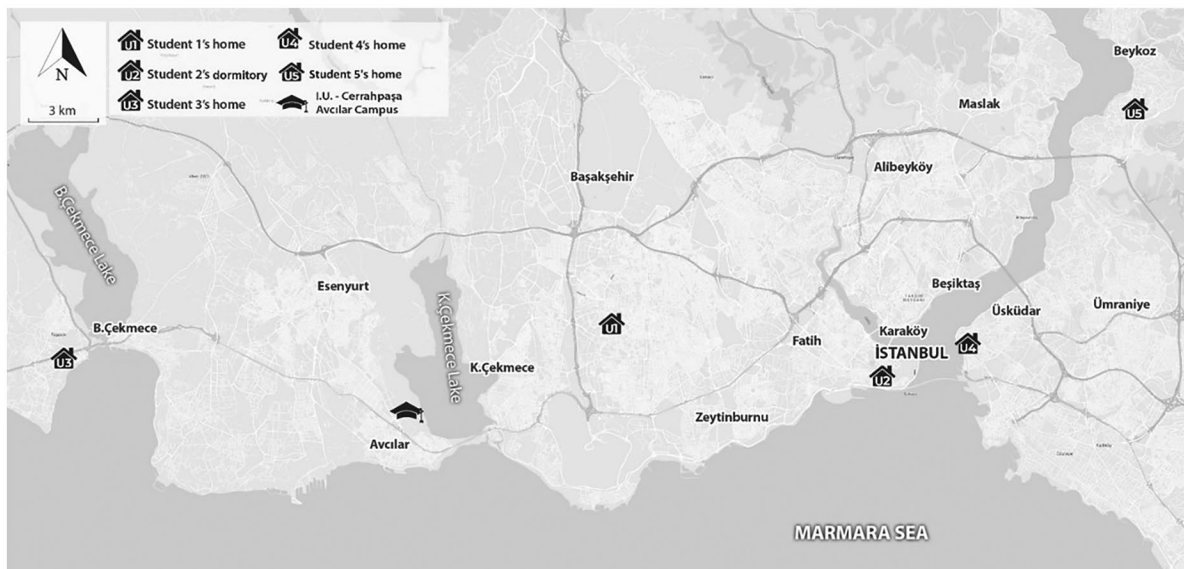


Fig. 1 Study area, university location and student homes

Table 1 Inhalation rates (m^3/h) as a function of activity and age group (Buonanno et al., 2011)

Activities	Age (years)	
	19–40	
Sleeping and resting	0.36	
Sedentary activities	0.45	
School	0.45	
Transportation	0.60	
Entertainment indoors	0.94	
Entertainment outdoors	0.94	

Personal BC measurements

Personal BC measurements were performed using a MicroAeth[®]AE51 portable aethalometer (AethLabs, San Francisco, USA), which was equipped with a 2.5- μm inlet and adjusted to operate at a flow rate of 100 mL min^{-1} with a time average of 60 s. Preparation, configuration and data processing were carried out as defined in previous studies (Onat et al., 2019b, c). The aethalometer was calibrated by the manufacturer and was prepared before the study, which included cleaning, changing the filter strip and controlling the flow measurement. Filter strips were changed when the attenuation factor (ATN) value was approximately 75–80.

Estimation of inhaled dose, contribution and intensity

The concentrations of BC monitored in different micro-environments were considered for the determination of

the daily exposure of each student. The inhaled dose, daily BC exposure contribution, daily BC inhaled dose contribution and BC exposure (inhaled dose) intensity were calculated using the equations of Cunha-Lopes et al. (2019) (Supplementary S1). Table 1 shows the inhalation rates used for the 19- to 40-year-old age group and activities (Buonanno et al., 2011).

Data analysis

The Shapiro–Wilk test indicated that the variables (data) were not normally distributed. Therefore, a nonparametric test was used for data analysis. Differences in BC concentrations on different days of the measurement campaign were compared using the Kruskal–Wallis and Bonferroni tests, adjusted for multiple comparisons. A p -value < 0.05 was considered statistically significant. To conduct the statistical analyses, SPSS v20 was used (IBM Corp., Armonk, NY, USA).

Results and discussion

Time-activity patterns

The time-activity diaries filled out by each student were used to obtain the daily time-activity patterns. Table 2 displays the percentage of time spent on activities in different microenvironments during the measurement study for each student. On weekdays, most of the time was spent at home (18.0–32.7% for sleeping and 22.3–58.0% for performing home

Table 2 Percentage of time spent by students in different microenvironments/activities

Microenvironment/activity	U1		U2		U3		U4		U5		Overall mean			
	Time (%)		Time (%)		Time (%)		Time (%)		Time (%)		Time (%)		N	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b
Sleep	22.3	24.5	26.0	30.1	32.7	20.6	29.5	27.5	18.0	37.7	25.7	28.1	3667	4033
Home activities	35.9	75.5	46.8	69.3	22.3	73.0	34.5	63.5	58.0	51.3	39.6	66.5	5645	9562
Transportation	22.4	NA	10.6	NA	14.3	3.0	17.0	1.9	10.7	3.5	15.0	1.7	2140	242
School	13.0	NA	14.0	NA	6.6	NA	17.2	NA	13.2	NA	12.8	NA	1829	NA
Entertainment indoors	6.4	NA	1.1	NA	24.1	3.4	1.7	7.1	0.1	7.6	6.6	3.6	949	520
Entertainment outdoors	NA	NA	1.4	0.6	NA	NA	NA	NA	NA	NA	0.3	0.1	41	18

a, weekdays; b, weekends

NA not applicable, N number of data

activities), followed by transportation (10.6–22.4%), school (6.6–17.2%) and entertainment indoors (0.1–24.1%). While students spent more time at home (20.6–37.7% for sleeping and 51.3–75.5% for performing home activities), they spent less time on transportation (1.9–3.5%) and entertainment indoors (3.4–7.6%) on weekends. As an overall mean, entertainment outdoors were the least time spent activity (weekday; 0.3% and weekend; 0.1%). These results showed similarities to those given in previous studies. Lei et al. (2016) evaluated the time-activity pattern of graduate students in a similar age group (22–28 years old) in Shanghai and observed that students spent most of their time indoors (86%), followed by transportation (7%). In Portugal, students in the 7- to 10-year-old age group spent most of their time at home (55%), at school (30.3%) and for transportation (5%) (Cunha-Lopes et al., 2019). In Chengdu, it was observed that students in the 17- to 18-year-old age group spent 68.6% of their time at home and 18.7% in the classroom, followed by transportation (8.97%) (Zhou et al., 2020). These studies emphasized that students in various age groups spent most of their time indoors (Cunha-Lopes et al., 2019; Lei et al., 2016; Zhou et al., 2020).

BC concentrations in microenvironments/activities

Transportation

Table 3 shows the descriptive statistical values (mean, standard deviation, min and max) of the personal BC concentrations in different microenvironments/activities during the measurement campaign. The highest mean BC concentration was measured in transportation ($8 \mu\text{g}/\text{m}^3$) and this value was 6.2 times higher than that measured at home ($1.3 \mu\text{g}/\text{m}^3$) (Table S1). Each of the students travelled by different modes of transportation and the most preferred transport mode was walking (41.7%). Approximately 20.7% of students travelled by metrobus, 25.1% by car (16.8% by car with the windows open and air conditioning (AC) off and 8.3% by car with the windows closed and AC on), 6.9% by minibus, 3.3% by tram and 2.3% by bus (Table S2). The highest mean BC concentration among the transportation modes was measured for minibuses ($14.8 \mu\text{g}/\text{m}^3$). In a previous study conducted by Jeong and Park (2017), it was found that the highest BC exposure level of students was that of

those who travelled by minibus ($7.5 \mu\text{g}/\text{m}^3$). In Istanbul, the capacity of minibuses is commonly 6–14 seats and passenger activity is very high because it is the preferred mode of transport for short distances. When the door of a minibus opens, outdoor pollutants can enter the minibus. The mean concentrations of BC in metrobuses and buses were $10.4 \mu\text{g}/\text{m}^3$ and $9.2 \mu\text{g}/\text{m}^3$, respectively. These results were similar to those of a previous study conducted by Onat et al. (2019a) in Istanbul (metrobus: $9.5 \mu\text{g}/\text{m}^3$, bus: $11.1 \mu\text{g}/\text{m}^3$).

U5 travelled with a car in two situations: (1) with the windows open and AC off and (2) with the windows closed and AC on recirculation mode. The lowest average BC concentration ($1.6 \mu\text{g}/\text{m}^3$) was measured when the windows were closed and the AC was in recirculation mode. We observed that the mean BC concentration for cars with the windows open and AC off was 4.4 times higher than that measured for cars with the windows closed and AC on. Similar results were reported in previous studies (De Nazelle et al., 2012; Ham et al., 2017; Onat et al., 2019b).

The daily BC time series for students on weekdays is given in Fig. 2. The peak levels of BC were observed, especially when students were travelling inside a vehicle and walking between transportation modes. The mean BC concentration of U3 when walking was considerably higher than that of the other students ($18.5 \pm 40.2 \mu\text{g}/\text{m}^3$). As seen in Fig. 2, when U3 approached the station to board the bus (10:43 am), the BC concentration reached a high level ($203 \mu\text{g}/\text{m}^3$). An increase in BC was also observed when U3 arrived at the metrobus terminal station (11:19 am, $157.2 \mu\text{g}/\text{m}^3$) and was waiting for a minibus (21:59 pm; $173.2 \mu\text{g}/\text{m}^3$). Carvalho et al. (2018) reported that BC concentrations were higher in terminal stations.

On the busiest streets, proximity to bus terminals, busy roads and congested streets can affect BC concentrations (Liu et al., 2019). We also observed an increase in BC during all weekend/weekday measurement campaigns in traffic microenvironments (Fig. S1).

Home

The lowest mean BC concentration measured at home was $1.3 \mu\text{g}/\text{m}^3$. Similarly, previous studies conducted in Belgium ($1.2 \mu\text{g}/\text{m}^3$), Shanghai ($2.3 \mu\text{g}/\text{m}^3$), Seoul

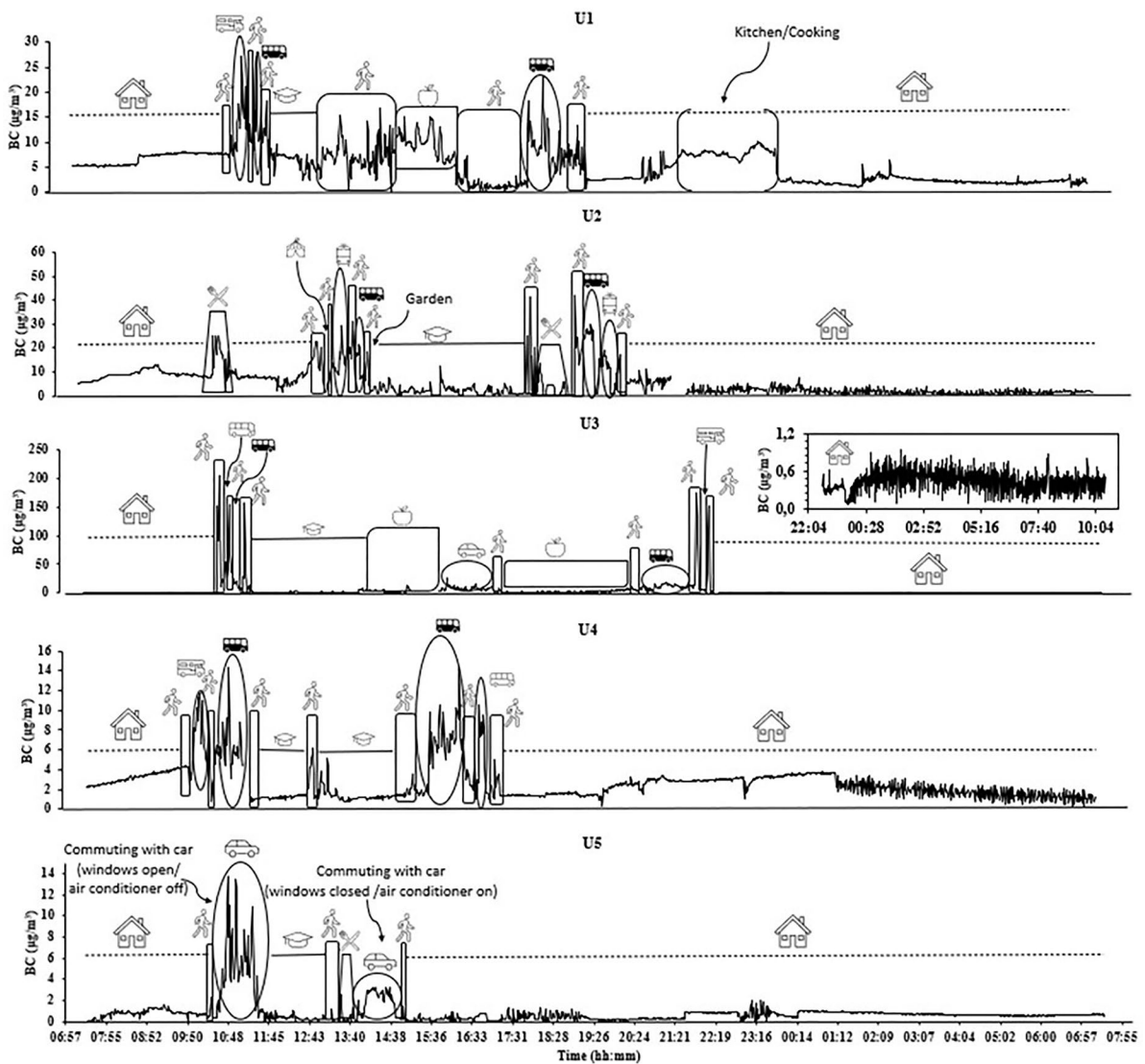


Fig. 2 Daily BC time series for students on 1st day (note: the additional graphic shows the time series in U3’s home environment detail)

($1.4 \mu\text{g}/\text{m}^3$) and Lisbon ($0.89 \mu\text{g}/\text{m}^3$) found that the lowest BC concentrations were observed at home (Dons et al., 2011; Lei et al., 2016; Jeong & Park, 2017; Cunha-Lopes et al., 2019). The mean BC concentrations during sleeping and household activities were $0.9 \mu\text{g}/\text{m}^3$ and $1.5 \mu\text{g}/\text{m}^3$, respectively. The individual exposure at home of U4 ($1.9 \pm 0.6 \mu\text{g}/\text{m}^3$ for sleeping and $2.3 \pm 0.9 \mu\text{g}/\text{m}^3$ for household activities) was higher than those of others. The probable reason for this could

be the level of outdoor concentration of BC. The home of U4 is located near the pier where car ferries and cargo ships usually dock. Additionally, its proximity to the intercity bus terminal is approximately 550 m (Fig. S2). Traffic during marine activities, exhaust emissions during the loading and unloading of vehicles (Onat et al., 2019c) and bus terminals (Kuzu et al., 2020) are the main sources of BC. The proximity of piers and ports to residential areas affects the air quality of a city

(Gobbi et al., 2020), and ship activity in the Bosphorus can contribute to elevated BC concentrations (Şahin et al., 2020).

Generally, BC is not monitored at FMSs in Istanbul. However, to gain insight into outdoor concentrations, the daily mean PM_{10} concentration at the FMSs nearest to the students' homes and the mean BC concentrations measured at home or in dormitories are given in Fig. S3. The concentration of PM_{10} monitored at the fixed monitoring station nearest to U4's home during the campaign was $33.3 \pm 10.3 \mu\text{g}/\text{m}^3$. This value was higher than that measured at the other FMSs (Fig. S3). Previous studies showed that outdoor pollutant sources affect indoor BC concentrations, even if the concentrations in urban settings are lower than those at home (Carvalho et al., 2018; Dons et al., 2011).

Figure 2 displays the daily temporal trend of BC for each student. Overall, the results showed that the concentration of BC measured at home was lower than that measured during outdoor activities. The peak BC concentrations were observed during cooking activities at home ($10.1 \mu\text{g}/\text{m}^3$) and eating in dormitory kitchens ($12.6 \mu\text{g}/\text{m}^3$) (Fig. S1). The concentration of pollutants can reach high levels during cooking in the kitchen (Rupakheti et al., 2019) and the type of kitchen (open, half-open or closed) affects the level of BC (Ravindra, 2019). Dining halls are common areas in dormitories and students can be exposed to high levels of BC during cooking activities in these halls.

School

The concentration of BC in school varied between 0.6 and $3.7 \mu\text{g}/\text{m}^3$, and the mean BC concentration was $2.0 \mu\text{g}/\text{m}^3$ in the classroom. These results were quite similar to those of previous studies; the mean BC concentrations in the classroom were $1.2 \mu\text{g}/\text{m}^3$ in Barcelona (Rivas et al., 2016), $1.2 \mu\text{g}/\text{m}^3$ in Lisbon (Cunha-Lopes et al., 2019), $1.22 \mu\text{g}/\text{m}^3$ in Paris (Paunescu et al., 2017) and $2.3 \mu\text{g}/\text{m}^3$ in Seoul (Jeong & Park, 2017). The highest mean BC concentration was observed in the dining hall ($2.9 \mu\text{g}/\text{m}^3$), followed by the classroom ($1.7 \mu\text{g}/\text{m}^3$) (Table 3). The dining hall is in a separate building on the university campus. Cooking activities in the building may have contributed to the increase in BC concentrations. The studies conducted in school environment showed that BC exposure may vary depending

on factors such as the time of the day, ventilation, traffic density on nearby streets and leakage from outdoors (Buonanno et al., 2013; MacNeill et al., 2016; Rivas et al., 2016; Paunescu et al., 2017; Zhou et al., 2020). Students spent less time in conference halls, student affairs offices and computer rooms, and the mean BC concentrations were $2.2 \pm 1.7 \mu\text{g}/\text{m}^3$, $0.8 \pm 0.8 \mu\text{g}/\text{m}^3$ and $0.6 \pm 0.3 \mu\text{g}/\text{m}^3$, respectively.

Entertainment indoors/outdoors

The mean BC concentration during indoor entertainment activities varied between 0.6 and $5.0 \mu\text{g}/\text{m}^3$. The highest mean concentration of BC was measured in a mosque, at $5.0 \pm 5.3 \mu\text{g}/\text{m}^3$, which is located near a busy street (Fig. S4). Air pollutants can reach high concentrations near roads (Morales Betancourt et al., 2017), and road dust can contribute to BC concentrations (Kuzu et al., 2020). The second highest mean BC concentration was observed in cafes/restaurants ($3.3 \mu\text{g}/\text{m}^3$). Paunescu et al. (2017) showed that the highest BC exposure ($2.4 \pm 1.19 \mu\text{g}/\text{m}^3$) of 9-year-old students was measured during meals at restaurants. Similarly, Koehler et al. (2019) found that the highest BC exposure of those in the 22- to 61-year-old age group was observed at restaurants and bars. Combustion sources such as cooking and smoking may contribute to BC concentrations in restaurants. The mean BC concentration in hair salons and supermarkets was measured as $2.3 \mu\text{g}/\text{m}^3$. The lowest mean BC concentration was measured at a cultural centre ($0.6 \mu\text{g}/\text{m}^3$). The students spent limited time in the entertainment outdoors activities. In the dormitory garden, the mean BC concentration was measured as $3.0 \pm 3.8 \mu\text{g}/\text{m}^3$. The dormitory is located next to the Eurasian tunnel that connects Europe and Anatolia, and this connection road has very dense traffic all day.

Differences across days of the measurement campaign

Figure 3 shows the daily mean concentrations of BC on weekdays (1st and 2nd days) and on weekends (3rd and 4th days) for each student. The differences across the days of the measurement campaign were statistically significant for each student ($p < 0.01$). According to the multiple comparison results, it was observed that the BC concentrations of four students (U1, U2, U3 and U4) on weekdays (1st and 2nd days)

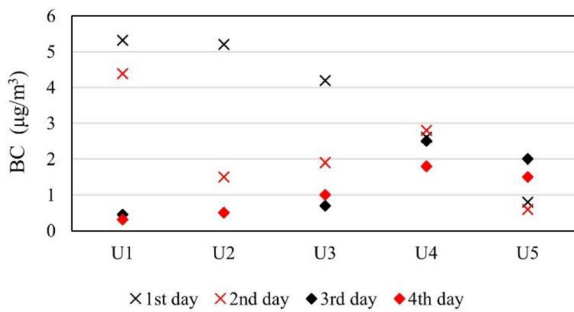


Fig. 3 Daily mean BC concentrations for each student during the measurement campaign (1st and 2nd days: weekdays; 3rd and 4th days: weekends)

were significantly higher than those on weekends (3rd and 4th days); however, the difference between the BC concentrations of U3 on the 2nd and 4th days was not significant ($p = 1.00$). Jeong and Park (2017) stated that students may be exposed to a higher concentration of BC on weekdays than on weekends due to the increasing traffic volume during the former. With reduced traffic density, lower BC concentrations can be seen on weekends (Quang et al., 2021). In contrast to other students, the BC concentration of U5 on the 3rd and 4th days was higher than that on the 1st and 2nd days ($p < 0.01$); the probable reasons for this might be that U5 travelled by car with the windows closed and AC on (less exposure) on the weekday and spent time in cafes/restaurants (more exposure) on the 3rd day.

The BC concentrations of U2 and U3 measured on the 1st day of the campaign were significantly higher than those measured on the 2nd day ($p < 0.01$). The BC concentrations for U2 on the 1st and 2nd days of the campaign were $5.2 \pm 5.6 \mu\text{g}/\text{m}^3$ and $1.5 \pm 1.8 \mu\text{g}/\text{m}^3$, respectively. U2 preferred similar modes of transport and route during the 1st and 2nd days of the measurement campaign, but they were at different times of the day. Furthermore, the time spent by U2 in the transport microenvironment was variable. For U3, the BC concentrations on the 1st and 2nd days of the campaign were $4.2 \pm 6.3 \mu\text{g}/\text{m}^3$ and $1.9 \pm 3.1 \mu\text{g}/\text{m}^3$, respectively. U3 travelled by metrobus on day 1, while he preferred a private car for travelling on the 2nd day. The preferred transport mode can affect exposure concentration. BC exposure may vary depending on the preferred transportation mode and the time of day spent in the microenvironment (Dons

et al., 2011; Paunescu et al., 2017). High concentrations can be observed in transport environments, especially during rush hour (Dons et al., 2012; Rivas et al., 2016).

Contribution to exposure, dose and dose intensity

The mean BC exposure and dose, and the contribution and intensity calculated according to the exposure and dose are given in Table 4 for each activity/microenvironment (sleep, home-based activity, transport, school, entertainment indoors and outdoors). The exposure, contribution and dose values for each student are given in Table S4 (Table S4).

The overall mean BC exposure on weekdays and weekends was $3.0 \mu\text{g}/\text{m}^3$ and $1.1 \mu\text{g}/\text{m}^3$, respectively. Consequently, students spent most of their time during home-based activities (weekdays: 39.6%; weekends: 66.5%), and the highest contribution to BC was observed for home-based activities on weekends (BC exposure: 66.1%, BC dose: 63.2%). On weekdays, the highest mean BC exposure ($8.3 \pm 13.1 \mu\text{g}/\text{m}^3$) and BC dose ($177.4 \pm 293.2 \mu\text{g}$) were measured in the transport microenvironment. Consequently, transport made the largest contribution to the overall mean BC exposure (42%) and dose (45.8%) on weekdays. On weekends, the highest BC exposure was found for transport ($5.0 \pm 8.4 \mu\text{g}/\text{m}^3$), while the highest BC dose was found at home ($78.4 \pm 64.5 \mu\text{g}/\text{m}^3$).

Previous studies indicated that the contributions of different microenvironments/activities in several cities to BC exposure and doses were quite variable. In Seoul, the contribution of home-based activities (sleeping, general activities and cooking and eating) to BC exposure for students in the 10- to 12-year-old age group was 49.9% on weekdays and 58.4% on weekends. The BC dose contribution was determined to be the highest, with 38.4% on weekdays and 50.3% on weekends (Jeong & Park, 2017). The BC exposure and dose on weekends for home-based activities were similar to those reported in Seoul.

The contribution of home-based activities to BC concentration on weekdays was 58% for 9-year-old students in Paris (during school periods: 53%, during vacation periods: 77%) (Paunescu et al., 2017) and 52% for the 8- to 11-year-old age group in Casino (Buonanno et al., 2013). Other previous studies showed that the contributions of home-based activities to BC concentration and BC dose on weekdays

Table 4 Percentage of contribution to exposure, dose and dose intensity in microenvironments/activities on weekends and weekdays

Microenvironment/activity	BC exposure ($\mu\text{g}/\text{m}^3$)		BC dose (μg)		Contribution time (%)		Contribution exposure (%)		Contribution dose (%)		Intensity (dose)	
	a	b	a	b	a	b	a	b	a	b	a	b
Sleep (N_a : 3667, N_b : 4033)	1.1±0.9	0.8±0.7	24.3±19.8	19.6±16.9	25.7	28.1	9.6	20.7	6.3	15.8	0.4	0.7
Home-based activities (N_a : 5645, N_b : 9562)	2.3±2.6	1.1±0.9	97.2±110.1	78.4±64.5	39.6	66.5	30.6	66.1	25.1	63.2	0.8	1.0
Transport (N_a : 2140, N_b : 242)	8.3±13.7	5.0±8.4	177.4±293.2	12.1±20.3	15.0	1.7	42.0	7.7	45.8	9.8	2.8	4.6
School (N_a : 1829)	2.0±2.4	-	27.1±32.9	-	12.8	-	8.5	-	7.0	-	0.7	-
Entertainment indoors (N_a : 949, N_b : 520)	4.0±4.6	1.7±3.9	58.9±68.4	13.7±9.0	6.6	3.6	8.9	5.5	15.2	11.1	1.3	1.5
Entertainment outdoors (N_a : 41, N_b : 18)	4.1±4.1	0.5±0.2	2.6±2.6	0.1±0.2	0.3	0.1	0.4	0.1	0.7	0.1	1.4	0.4
Overall mean for activities	3.0	1.1	-	-	49.8	50.2	72.8	27.2	-	-	1.5	0.5

a, weekdays; b, weekends; N_a , no. of weekdays; N_b , no. of weekends; -, this data is not available

for the 7- to 10-year-old age group in Lisbon were 38% and 27%; for the 7- to 10-year-old age group in Barcelona, they were 50% and 35% (Rivas et al., 2016), respectively. The total BC dose contribution was 74.5% in Chengdu for the 17- to 18-year-old age group at home (Zhou et al., 2020).

In previous studies on children’s BC exposure, the contribution of transportation to daily BC exposure ranged from 11 to 21%, while the contribution of BC dose ranged from 12 to 23% (Buonanno et al., 2013; Rivas et al., 2016; Paunescu et al., 2017; Jeong & Park, 2017; Cunha-Lopes et al., 2019). Zhou et al. (2020) reported that the BC dose contribution of transportation was 13.5% for the 17- to 18-year-old age group. Some studies involving adult age groups showed that transport made a greater contribution to BC exposure than did other microenvironments (Carvalho et al., 2018; Dons et al., 2011; Koehler et al., 2019). Our findings are similar to the results of previous studies involving adults; however, we observed that the contribution of transportation to BC exposure (42%) and dose (45.8) on weekdays was higher in our study than in those studies. In this study, students spent more time (mean: 15.0% on weekends) on transportation on weekdays (Table S3), and transportation had the highest BC intensity exposure (weekdays: 2.8 $\mu\text{g}/\text{m}^3$, weekends: 4.6 $\mu\text{g}/\text{m}^3$) and intensity dose (weekdays: 3.1 μg , weekends: 5.8 μg) (Table 4). These results were similar to those of the previous study conducted by Jeong and Park (2017). Studies on personal exposure to BC showed that high BC exposure and BC doses in the transportation microenvironment could be seen (Cunha-Lopes et al., 2019; Jeong & Park, 2017; Rivas et al., 2016), further supporting BC as an important pollutant in the monitoring traffic-related pollution (Janssen et al., 2012). The differences in activity, inhalation rates (Rivas et al., 2016) and time spent in microenvironments (Carvalho et al., 2018) affect the exposure differences between children and adults. On weekdays, walking made the greatest contribution to BC exposure (16.8%) for transport, followed by metrobuses (12.1%), minibuses (5.8%), cars with windows open and AC off (4.3%), trams (1.4%), buses (1.2%) and cars with windows closed and AC in recirculation mode (0.4%) (Table S3). Outdoor entertainment activities made the lowest contribution to overall BC exposure and dose.

Previous studies indicated that the contribution of the school to BC exposure in children varied between 20 and 33% (Buonanno et al., 2013; Cunha-Lopes et al., 2019; Paunescu et al., 2017; Rivas et al., 2016). In this study, the contribution of the school to BC exposure for undergraduate students was found to be lower than that of children indicated in previous studies. The undergraduate students participating in this study spent less time at school because of the differences in lesson days and times.

The contributions of indoor entertainment to BC exposure and BC dose were 8.9% and 15.2% on weekdays and 5.5% and 11.1% on weekends, respectively. The greatest contribution to BC exposure and dose of indoor entertainment was cafe/restaurant activity (8.5% and 14.6% on weekdays, 4.2% and 8.3% on weekends) (Table S3). The contribution of sleep to BC exposure was 9.6% on weekdays and 20.7% on weekends, while sleep had the lowest BC dose intensity on weekdays (0.2) and on weekends (0.6).

Conclusions

The personal exposure to BC of undergraduate students in Istanbul was investigated considering time-activity/microenvironment patterns. Students spent most of their time at home (65.3%) followed by transportation (15.0%) and school (12.8%) on weekdays. On the weekends, the time spent reached 94.6% at home.

The mean BC concentration measured for transportation was 6.2 times higher than that measured at home. The time spent in the transport microenvironment and the mode of transport were considerable determinants of BC exposure and BC dose intensity. The use of air conditioning in the recirculation mode decreased BC exposure in cars. The highest contribution to BC exposure and dose was in the transportation environment on weekdays and at home on weekends. Through transportation, students received the most intense exposure to and dose of BC on both weekdays and weekends, and the mode of walking made the most contribution to BC exposure (16.8%) and dose (18.3%) on weekdays. Cafes, restaurants and dining halls also were important indoor entertainment microenvironments that contributed to exposure.

The results of this study reveal the importance of the contribution of microenvironments, especially in terms of transport, to the daily BC exposure of undergraduate students. Outdoor BC pollution in the urban areas of Istanbul should be monitored in the future and BC should be considered by local governments as an important pollutant parameter in the transport environment.

Study limitations

This study was a preliminary follow-up study of daily exposure of undergraduate students in a metropole city and was conducted with a limited number of participants because we had only one portable device. Furthermore, it should be considered that we only made measurements in spring. Because the average BC concentrations can be different between seasons, the measurement campaign can be developed in the future by obtaining more instruments and measuring more students at the same time in different seasons.

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Author contributions Burcu Uzun: data curation, writing—original draft preparation; Burcu Onat: conceptualization, writing—reviewing and editing; Coşkun Ayvaz: formal analysis; Özcan Akın: resources; Ülkü Alver Şahin: visualization, editing.

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Data availability The datasets are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Informed consent was obtained from all participants in the study.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

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