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Assessment of indoor air pollution exposure in urban hospital microenvironments

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Abstract

Hospitals are microenvironments containing populations with potentially enhanced sensitivity to air pollution. The objectives of this study were to characterize the concentration of indoor and outdoor size-fractionated particulate matter (PM) at two urban hospital sites in Kashan, Iran, and to evaluate the relationship between indoor and outdoor PM levels. $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations were measured over a 3-month period outside each hospital with parallel sampling at four indoor locations in patient wards. The results indicated that mean indoor concentrations at the sampling sites ($PM_{1.0} = 17.8$ μg/m^3, $PM_{2.5} = 45.5$ μg/m^3, and $PM_{10} = 162.7$ μg/m^3) were found to be lower than outdoors levels ($PM_{1.0} = 20.6$ μg/m^3, $PM_{2.5} = 62.1$ μg/m^3, and $PM_{10} = 300.6$ μg/m^3). Outdoor and indoor PM mass concentrations were associated with $PM_{1.0}$, $PM_{2.5}$, and $PM_{10.0}$. Ambient wind speed also influenced the indoor/outdoor relationship for $PM_{1.0}$ and $PM_{2.5}$ but not for PM_{10}. The average I/O ratios for $PM_{2.5}$ in the intensive care unit (ICU) and children's ward at Shahid Beheshti Hospital were close to or above 1.00. Indoor $PM_{1.0}$ and $PM_{2.5}$ concentrations were found to be positively associated with outdoor $PM_{1.0}$ and $PM_{2.5}$ concentrations, but no relationship was observed with PM_{10}. The present findings may inform policymakers in implementing evidence-based efforts for the aim of improving the indoor air quality in closed and confined spaces.

Keywords Indoor air quality · $PM_{2.5}$ · PM_{10} · Hospitals · Iran

Introduction

Particulate matter (PM) exposure has been positively associated with adverse health. Enhanced PM sensitivity has been reported for children (less than 15), the elderly (over 65), and those with compromised immune systems and/or pre-existing health conditions (Park et al. 2013; Mohammadyan et al. 2017b; WHO 2004, 2006, 2007, 2009; Zereini and Wiseman 2010). Surveys of human activity patterns indicate a person spends on average 87% of their day in enclosed buildings (Klepeis et al. 2001). Consequently, personal exposure is primarily attributable to indoor PM

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concentrations rather than the outdoor environment. In particular, indoor exposure to PM has been consistently associated with increased risk of lower respiratory infection in children and respiratory diseases among other vulnerable people such as the elderly (Campbell 1997; Ezzati and Kammen 2001; Ghozikali et al. 2016a, b; Gurley et al. 2013; Smith et al. 2000; Pope et al. 2017). Gurley et al. (2013) reported that increased exposure to indoor PM was associated with enhanced incidence of acute lower respiratory infection in children. In another study, Smith et al. (2000) reviewed acute lower respiratory infection and pneumonia in children under the age of 2 years. They found that elevated indoor PM emitted from combustion of biomass fuels was associated with a higher incidence of acute lower respiratory infection and pneumonia.

The indoor-to-outdoor (I/O) ratio of PM mass concentrations has been widely explored in the literature (Chen and Zhao 2011; Wang et al. 2016; Zhao et al. 2015; López-Villarrubia et al. 2016). Indoor/outdoor (I/O) ratio of PM mass concentrations can vary due to a larger number of factors including locations, building design, and human activities. The results of these previous studies showed that an important background contribution to indoor PM from penetration of outdoor PM, and indoor sources (e.g., cooking, smoking, cleaning, and general activity) contributed to indoor concentrations of PM less than 10 μm (PM_{10}). While cleaning and general activity have been reported to have minimal influence on concentrations within this size range, cooking and smoking (Vu et al. 2017) have been suggested to be major indoor sources of PM less than 2.5 μm ($PM_{2.5}$) and PM less than 1 μm ($PM_{1.0}$).

Indoor air quality in hospitals and health facilities requires particular attention for the potentially high sensitivity of occupants to PM exposure (Chamseddine and El-Fadel 2015; Eames et al. 2009; Slezakova et al. 2012). The main objectives of this study were to assess the indoor and outdoor PM mass concentrations and to evaluate the I/O ratio of PM mass concentrations (if indoor PM levels were attributable to indoor sources or the result of penetration of outdoor PM) at two large public hospitals in the city of Kashan, Iran.

Materials and methods

Study location

The study was conducted at two hospitals in Kashan, Iran (latitude 33°98′59″N, longitude 51°41′27″E). This city has a population of 275,000 and is located in the province of Isfahan, situated in central Iran at an elevation of 924 m above sea level. A number of industrial facilities are located in the south-east region of Kashan, including sand and gravel manufacturing, steel factories, textile industries, plastic production factories, and car manufacturing companies. This industrial activity, which is approximately 10 km from the city center, is a major source of the ambient air pollution.

Participating hospitals

Ambient PM concentrations were measured at indoor and outdoor sites at two public hospitals in Kashan (Fig. 1). Naghavi Hospital (latitude 33°59′13″N, longitude 51°26′39″E) is located in the city center, while Shahid Beheshti Hospital (latitude 33°00′46″N, longitude 51°24′24″E) is 10 km away from the Kashan city center. Both hospitals had a similar building design with ceramic flooring. No mechanical ventilation or air conditioning was in use during the study period (March to May 2014). However, some windows were opened, particularly during warm weather period (temperature > 25 °C), which is 90% of days during the sampling period. All wards were heated through a central heating system (radiators) when the temperature dropped below 15.5 °C. The boiler was located in a separate room in the basement of the hospitals' building.

Air pollution sampling

For indoor and outdoor measurements, a GRIMM dust monitor (GRIMM Aerosol Technik Gmbh & Co. KG, Ainrig, Germany, model 1.108) was used to measure $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations. An instrument flow rate of 1.2 L/min was used for all sample collection. The GRIMM monitor (GRIMM Aerosol Technik GmbH & Co. KG) contains a teflon filter to collect PM during real-time monitoring. Following manufacturer's protocols, PM loaded on this filter is used for the gravimetric calibration of optical measurements. During the present study, PM was collected onto the filter in the GRIMM monitor over a 10-day monitoring period. Filters were weighted on a microbalance (Fa-2104 Analytical Electronic Balance) in a humidity- and temperature-controlled room located at the Mazandaran University of Medical Sciences. The total PM mass loaded on filters was divided by the calculated total volume of air sampled during the monitoring period to determine the mean gravimetric PM mass concentrations. Average gravimetric concentrations were then divided by the mean particle concentrations downloaded from respective instruments to obtain gravimetric calibration factors. All real-time data were multiplied by the *C*-factor to calculate the corrected concentrations.

Real-time monitoring was carried out at indoor and outdoor sites over 31 days (from March 8, 2014 to May 9, 2014) with 9 days in March, 17 days in April, and 5 days in May. The indoor monitor was placed in the center of corridors or rooms in three wards (operation room and children and ICU wards) at the Shahid Beheshti Hospital and in the center of the corridor in the operation room at the Naghavi Hospital. The PM sampling unit was positioned 1.5 m above the floor,

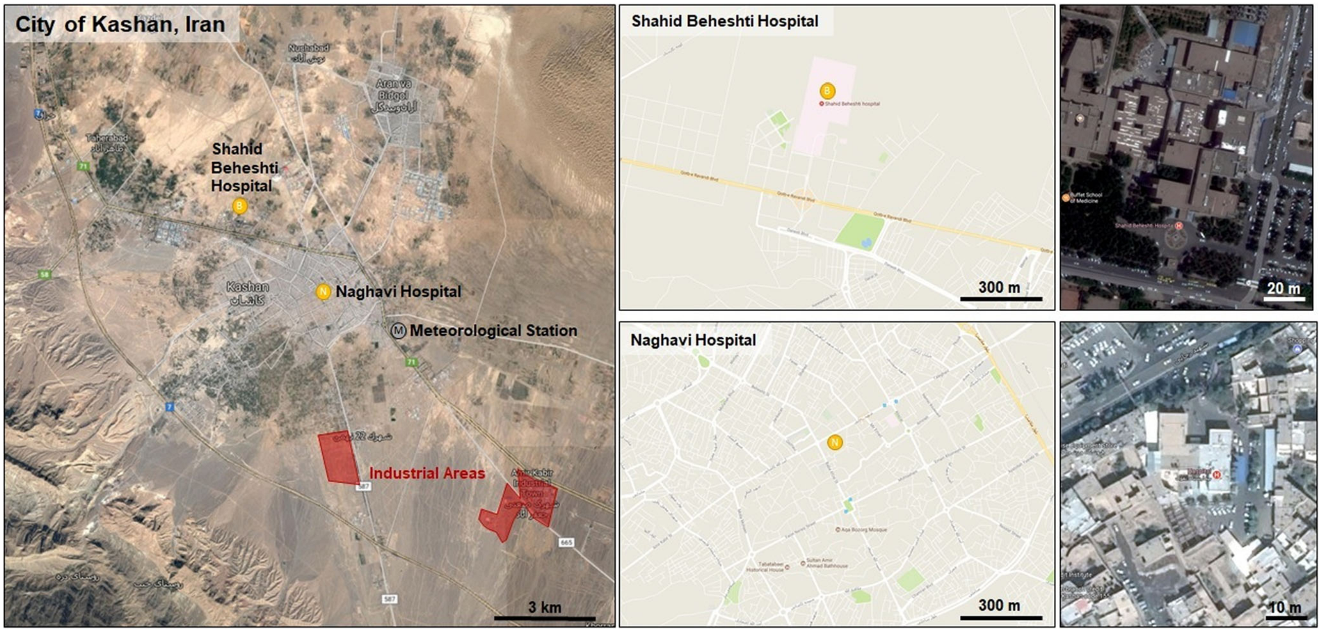
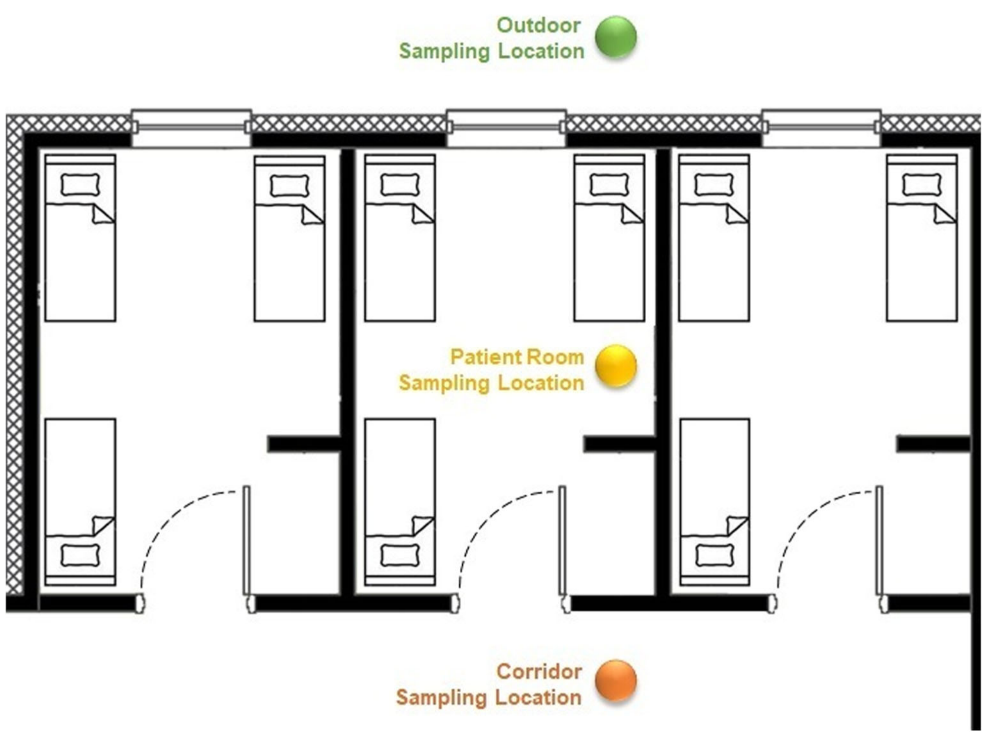


Fig. 1 Study locations of Naghavi and Shahid Beheshti hospitals in the city of Kashan

corresponding to the breathing zone of an adult. Outdoor monitoring was conducted in the hospital yard. The PM monitor was positioned 1 m away from any obstacle and 1.5 m above the ground (Fig. 2).

Limited availability of PM instrumentation restricted sampling to a single location at one time. To minimize the effects of any diurnal variation across sites, 1-min averaged PM mass concentrations were collected over a 5-min period at each sampling site, alternating between indoor and outdoor locations. PM was evaluated at each sampling location twice a day, once in the morning (08:00 to 12:00) and in the afternoon (13:00 to 15:00) at each hospital over 31 days. The total monitoring time at each sampling location across the sampling campaign was 51 min for each monitoring location. The

Fig. 2 Sampling locations of the hospitals and the monitor location



sampled air was collected by a sampling pump and passed through the instrument continuously. This flow configuration prevented the contamination of the sample.

Determinants of indoor PM concentrations

Factors that were deemed to be potential determinants of indoor PM concentrations were characterized for each sampling location during the monitoring period. These factors included the number of people in the vicinity of the monitoring location and air ventilation. A technician operating the PM instrument completed questionnaires to quantify these factors for each sampling location and interval. The technician also noted operation of the heating system in door and room areas. Information on hourly wind speed, temperature, and relative humidity were obtained from a nearby meteorological station (latitude 33°58′59″N and longitude 51°26′11″E) (Fig. 2).

Statistical analyses

All size fractions of PM concentration are presented as the mean with the associated standard deviation (SD). The normality of PM mass concentration measurements was graphically assessed using quantile-quantile plots and also formally using the Kolmogorov–Smirnov test. Differences between paired PM indoor and outdoor measurements were assessed using the Kruskal–Wallis test for each hospital wards (operation room, pediatrics, and intensive care units). The association for each indoor and outdoor PM size fraction and I/O PM mass ratios with environmental variables (door and room areas, hourly wind speed and wind direction, temperature, relative humidity, and number of people) was further evaluated individually using linear regression models, in which the independent variables were the indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations. A p value < 0.05 was considered to be significant at 95% confidence level.

Results

Descriptive analysis of indoor and outdoor hospital environments

Within the framework of the sampling campaign, temperatures ranged from 6.9 to 27.8 °C in the city of Kashan. The average temperature was 20.5 °C (SD = 12.5 °C, where SD denotes standard deviation). Table 1 summarizes the

Table 1 Descriptive statistics of indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations (μg/m^3) in hospital wards and paired outdoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations

	Ward	Location	Size fraction	Mean	Standard deviation	Median	Interquartile range	Range
Naghavi Hospital	Operation room	Indoor	PM_{10}	145.5	176.4	100.5	78.7	26.3–1398.3
			$PM_{2.5}$	45.3	56.4	28.1	26.0	10.3–439.5
			$PM_{1.0}$	17.0	14.7	12.6	10.2	5.3–119.2
		Outdoor	PM_{10}	304.4	287.6	191.4	227.1	64.3–1327.3
			$PM_{2.5}$	62.7	49.9	44.8	39.0	16.8–228.4
			$PM_{1.0}$	21.5	11.9	18.1	14.6	6.3–58.5
Shahid Beheshti Hospital	Operation room	Indoor	PM_{10}	166.5	167.7	114.2	111.9	22.3–995.2
			$PM_{2.5}$	42.0	42.4	29.4	29.4	8.0–227.7
			$PM_{1.0}$	16.1	10.9	13.3	10.9	4.3–53.7
		Outdoor	PM_{10}	265.7	372.2	164.2	146.3	22.1–2353.6
			$PM_{2.5}$	57.4	66.9	38.6	30.4	6.8–416.4
			$PM_{1.0}$	19.8	14.7	16.3	14.8	2.5–86.6
	Pediatric	Indoor	PM_{10}	227.1	311.9	144.1	92.2	20.0–2395.6
			$PM_{2.5}$	55.8	76.7	36.1	22.4	11.5–496.9
			$PM_{1.0}$	19.3	18.0	15.1	9.9	4.5–113.4
		Outdoor	PM_{10}	429.3	1225.6	136.5	130	35.4–7541.5
			$PM_{2.5}$	79.9	176.2	36.6	29.7	12.5–1036.4
			$PM_{1.0}$	23.5	34.9	15.8	9.9	5.0–210.6
	Intensive care unit	Indoor	PM_{10}	112.5	84.9	89.5	73.5	5.0–442.3
			$PM_{2.5}$	38.6	42.0	26.9	27.2	4.3–341.1
			$PM_{1.0}$	18.7	30.4	11.5	14.3	2.0–293.9
		Outdoor	PM_{10}	200.4	255.0	124.6	117.4	26.6–1291
			$PM_{2.5}$	48.1	47.4	31.7	26.4	9.5–231.2
			$PM_{1.0}$	17.5	10.8	15.3	12.0	3.8–47.7

descriptive statistics and cumulative frequency results of the outdoor and indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations measured in each of the hospital wards.

The mean outdoor $PM_{1.0}$ concentrations in operation rooms (Beheshti, 19.8 μg/m^3, SD = 14.7 μg/m^3; Naghavi, 21.5 μg/m^3, SD = 11.9 μg/m^3) and children ward (23.5 μg/m^3, SD = 34.9 μg/m^3) were higher than the mean of indoor $PM_{1.0}$ concentrations in operation rooms (Beheshti, 16.1 μg/m^3, SD = 10.9 μg/m^3; Naghavi, 17.0 μg/m^3, SD = 14.7 μg/m^3) and children ward (19.3 μg/m^3, SD = 18.0 μg/m^3), respectively ($p \leq 0.01$). The mean outdoor $PM_{2.5}$ concentrations in operation rooms (Beheshti, 62.7 μg/m^3, SD = 49.9 μg/m^3; Naghavi, 57.4 μg/m^3, SD = 66.9 μg/m^3), children ward (79.9 μg/m^3, SD = 176.2 μg/m^3), and ICU (48.1 μg/m^3, SD = 47.4 μg/m^3) were higher than the mean of indoor $PM_{2.5}$ concentrations in operation rooms (Beheshti, 42.0 μg/m^3, SD = 42.4 μg/m^3; Naghavi, 45.3 μg/m^3, SD = 56.4 μg/m^3), children ward (55.8 μg/m^3, SD = 76.7 μg/m^3), and ICU (38.6 μg/m^3, SD = 42.0 μg/m^3), respectively ($p \leq 0.01$).

Moreover, the mean outdoor PM_{10} concentrations in operation rooms (Beheshti, 265.7 μg/m^3, SD = 372.2 μg/m^3; Naghavi, 304.4 μg/m^3, SD = 287.6), children ward (429.3 μg/m^3, SD = 1225.6 μg/m^3), and ICU (200.4 μg/m^3, SD = 255 μg/m^3) were higher than the mean of indoor PM_{10} concentrations in operation rooms (Beheshti, 166.5 μg/m^3, SD = 167.7 μg/m^3; Naghavi, 145.5 μg/m^3, SD = 176.4 μg/m^3), children ward (227.1 μg/m^3, SD = 311.9 μg/m^3), and ICU (112.5 μg/m^3, SD = 84.9 μg/m^3), respectively ($p \leq 0.01$).

The maximum PM concentrations measured in the present study were observed in the children's ward at Shahid Beheshti Hospital in a warm (26.8 °C) but highly windy (26.0 m/s) day in April ($PM_{1.0}$, 19.3 μg/m^3; $PM_{2.5}$, 2396 μg/m^3; and PM_{10}, 497 μg/m^3) (Table 1). These elevated concentrations were primarily observed when a large number of occupants with a high movement and activity were inside the patient's room and the door was left open to outside.

Table 2 summarizes building characteristics of indoor hospital spaces as well as meteorological parameters. The hospital rooms characterized in this study accommodated between 5 and 13 patients for areas ranging from 18.0 to 50.0 m^2. The mean door areas open to other spaces and opening window areas to outdoor were 3.3 m^2 and 0.88 m^2, respectively. Relative humidity varied from 18 to 69%, and the average wind speed was 8.6 m/s during the monitoring period (ranging from 0 to 26 m/s). Significant differences were found between concentrations of indoor and outdoor size-fractionated particulate matter ($PM_{1.0}$, $PM_{2.5}$, and PM_{10}) in all patient wards at the two hospital sites ($p < 0.001$).

Indoor-to-outdoor ratios of size-fractioned PM measured

The I/O PM mass ratios for the different wards of two hospitals are shown in Fig. 3 and Fig. S1–4. The average I/O $PM_{2.5}$ mass ratio (0.92, SD = 0.43) in the operation ward at Shahid Beheshti Hospital was greater than that obtained for Naghavi Hospital (0.7, SD = 0.13). The I/O PM mass ratio of the ICU ward for $PM_{2.5}$ mass (0.84, SD = 0.50) was lower than that of the other wards at Shahid Beheshti Hospital. The highest I/O $PM_{2.5}$ mass ratio was 2.28 (SD = 0.57) in the children's ward at Shahid Beheshti Hospital. No difference was found between the average I/O ratios across all size-fractioned PM mass on weekends (0.93, SD = 0.50) compared to weekdays (0.88, SD = 0.43).

Determinants of indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentration

Indoor $PM_{2.5}$ concentration in all wards was found to be positively associated with outdoor $PM_{2.5}$ concentration and ambient wind speed (Table 3). These two variables accounted for 83% of the variation in indoor $PM_{2.5}$ concentrations. Other variables, such as number of occupants, ambient temperature, door area, windows area, and room area, were not found to be significant predictors of indoor $PM_{2.5}$ concentrations. Indoor $PM_{1.0}$ concentration was also associated with outdoor $PM_{1.0}$ and ambient wind speed (Table 3). These variables accounted for 81% of variation in indoor $PM_{1.0}$ concentrations. In contrast to the other PM size fractions measured, indoor PM_{10} was only found to be associated with only outdoor PM_{10} but not with ambient wind speed. Outdoor PM_{10} mass concentrations accounted for 72% of variation in indoor PM_{10} concentration. When evaluating I/O PM mass ratios, wind speed was found to be associated with I/O ratios of $PM_{1.0}$ and $PM_{2.5}$

Table 2 Descriptive statistics of the hospital building characteristics and meterological variables across the 31-day study period

Variable	Mean	Standard deviation	Minimum	Maximum
Room's area (m^2)	27.7	14.5	18.0	50.0
Door area (m^2)	3.3	0.9	1.5	4.0
Opening area to outdoor (m^2)	0.88	0.8	1.5	3.0
Number of people indoor	7.6	1.3	5.0	13.0
Ambient temperature (°C)	19.8	4.6	7.3	26.8
Ambient relative humidity (%)	34.8	12.5	18.0	69.0
Ambient wind speed (m/s)	7.6	5.8	0.0	26.0

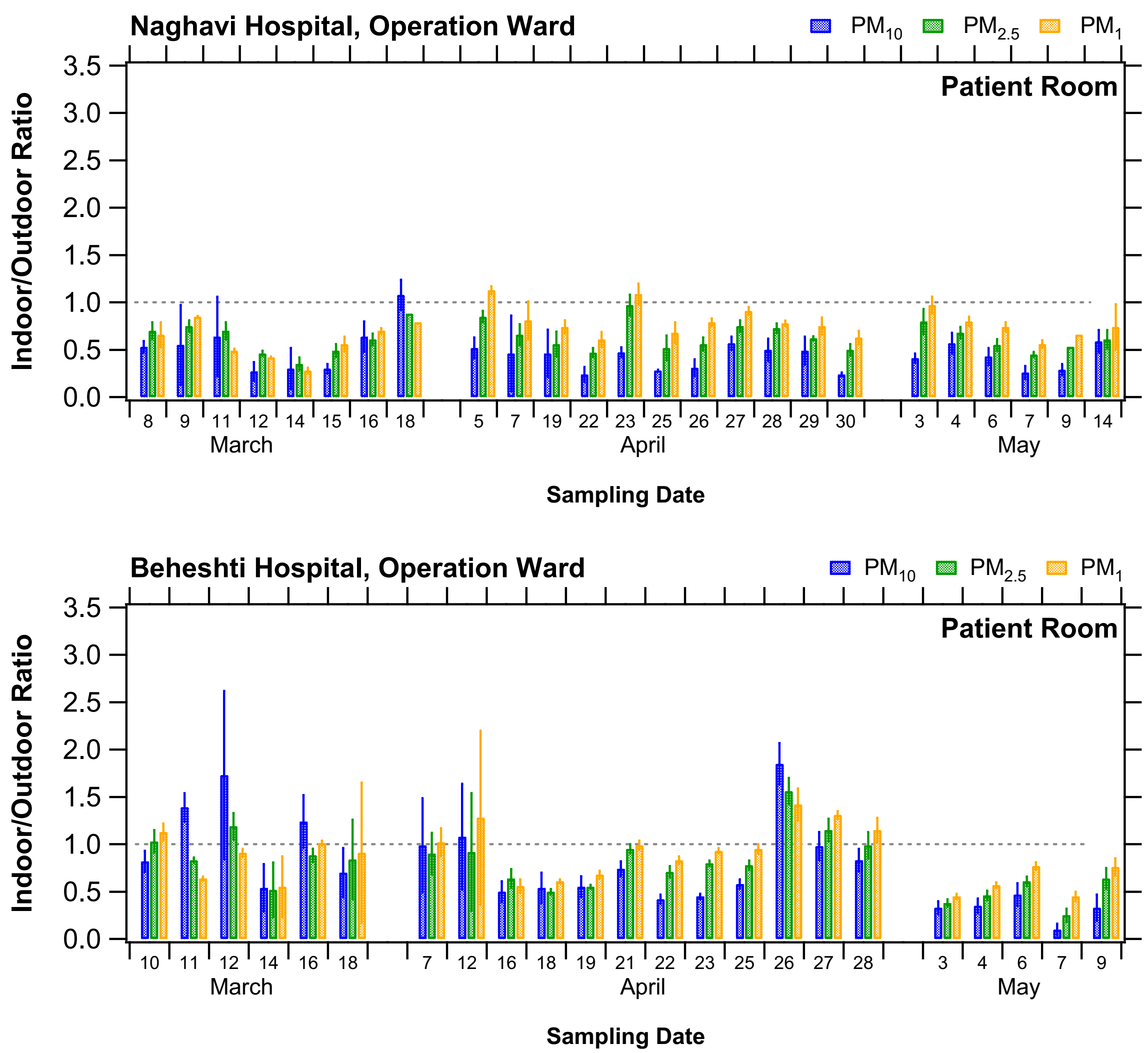


Fig. 3 Indoor/outdoor ratios across different sampling months

mass concentration across all wards at both hospitals (Table 4).

Discussion

Hospitals are microenvironments for highly susceptible occupants who are exposed to health risks associated with indoor PM. Thus, the objective of this study was to characterize indoor and outdoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} collected in operation rooms at Naghavi Hospital and in an operation room, ICU, and children wards at Shahid Beheshti Hospital in Kashan, Iran. Both hospitals were located in urban areas, and PM sampling was conducted over a 3-month period. $PM_{2.5}$ outdoor concentration together with ambient wind speed best predicted indoor $PM_{2.5}$ and $PM_{1.0}$ mass

Table 3 Multiple regression results of the best-fit models for indoor $PM_{2.5}$, PM_{10}, and $PM_{1.0}$ mass concentrations predicted by the respective outdoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} mass concentrations (log-transformed) and meterological variables

Models	Unstandardized coefficients		95% confidence interval		*p* value
	B	Standard error	Lower bound	Upper bound	
Log outdoor $PM_{1.0}$	0.93	0.080	0.756	1.102	0.001
Ambient wind speed (m/s)	− 0.01	0.004	− 0.017	− 0.002	0.010
Log outdoor $PM_{2.5}$	0.87	0.070	0.721	1.024	0.001
Ambient wind speed (m/s)	− 0.01	0.004	− 0.018	− 0.002	0.010
Log outdoor PM_{10}	0.62	0.070	0.471	0.763	0.001
Ambient wind speed (m/s)					

Table 4 Model results for I/O PM mass ratios predicted by the respective (log-transformed) and meterological variables

Models	Unstandardized coefficients		95% confidence interval		*p* value
	B	Standard error	Lower bound	Upper bound	
Log I/O $PM_{1.0}$					
Ambient wind speed (m/s)	− 0.009	0.003	0.972	1.087	< 0.001
Log I/O $PM_{2.5}$					
Ambient wind speed (m/s)	− 0.007	0.003	− 0.012	− 0.002	0.008

concentrations. Only outdoor PM_{10} concentrations were associated with indoor PM_{10}, and no meteorological determinant was found to be a predictor for indoor PM_{10} concentrations.

The mean outdoor $PM_{2.5}$ (62.7 μg/m^3) and PM_{10} concentrations (262.8 μg/m^3) in the hospitals were found to be elevated compared to $PM_{2.5}$ and PM_{10} standards recommended by US EPA (35 μg/m^3 and 150 μg/m^3, respectively) (Esworthy 2015). In the present study, the mean indoor $PM_{2.5}$ concentration (45.3 μg/m^3) was lower than outdoor $PM_{2.5}$ concentrations. Re-suspension of PM due to cleaning and general activity, such as movement in the indoor environments, may have led to the elevated $PM_{2.5}$ concentrations (Lomboy et al. 2015; Mohammadyan et al. 2017a). High outdoor $PM_{2.5}$ concentrations due to open windows and doors, activities/movements of the staff, and visitors could also contribute to the measured indoor $PM_{2.5}$ concentrations.

Indoor $PM_{2.5}$ concentrations measured in the present study in all wards of both hospitals (45.3 μg/m^3, SD = 56.6 μg/m^3) were higher than indoor $PM_{2.5}$ concentrations reported by other studies conducted in Tehran, Iran, at the Children Hospital (35.7 μg/m^3, SD = 46.3 μg/m^3) and Sina Hospital located in a densely populated residential area in Tehran (41.1 μg/m^3, SD = 11.9 μg/m^3) (Kermani et al. 2015; Rezaei et al. 2013). However, considerably lower indoor PM concentrations were observed at hospitals in smaller Iranian cities such as Shiraz (Hafez Hospital, $PM_{2.5}$ = 4.1 μg/m^3 and PM_{10} = 36.1 μg/m^3; Dena Hospital, $PM_{2.5}$ = 10.2 μg/m^3 and PM_{10} = 0.9 μg/m^3) (Dehghani et al. 2012, 2015). Use of high-efficient ventilation systems at Hafiz and Dena Hospitals in Shiraz may be attributable to lower indoor $PM_{2.5}$ in these hospitals compared to those in Tehran and Kashan.

Indoor PM concentrations in hospital setting have also been evaluated in a number of cities outside Iran, which are similar in terms of climate and economy, including Lahore (Pakistan), Istanbul (Turkey), and Guangzhou (China). All concentrations reported for those regions were found to be above PM levels measured in the present study in Kashan and also exceeded the 24-h $PM_{2.5}$ standard (35 μg/m^3) recommended by the US EPA and World Health Organization (WHO) (Yurtseven et al. 2012). In Lahore, the Sheikh Zayed Hospital consists of 99 wards with 713 beds and receives about 50,000 patients visiting the hospital annually. The building was constructed in 1986 and has an indoor ventilation. The authors reported hourly mean indoor $PM_{2.5}$ concentrations of 78 ± 37 μg/m^3 in the medical ward, 86 ± 46 μg/m^3 in the pulmonology ward, 94 ± 48 μg/m^3 in the surgical ward, 169 ± 122 μg/m^3 in the pediatric ward, and 488 ± 314 μg/m^3 in the nephrology ward. These indoor measurements were higher than outdoor $PM_{2.5}$ concentrations for the same wards (69 ± 27 μg/m^3, 81 ± 49 μg/m^3 and 178 ± 85, 282 ± 164 μg/m^3, respectively). These indoor and outdoor measurements were found to be higher in comparison with the results of the present study. The differences among the wards were due to cracks in buildings, indoor particle sources, outdoor environments, and ventilation patterns. For Lahore, the authors reported that the highest I/O PM mass ratio was found in the nephrology ward. This was likely attributable to the high number of room occupants.

Indoor $PM_{2.5}$ concentrations have also been explored at a medical faculty in Istanbul, Turkey, that uses a combination of natural ventilation and air conditioners (Yurtseven et al. 2012). No smoking is allowed at the hospital, and cleaning activities are carried out in the mornings. The average indoor $PM_{2.5}$ mass concentration in patient rooms was 50.2 μg/m^3 (SD = 16.1 μg/m^3), with episodic peaks (maximum = 389 μg/m^3) measured as the number of occupants in a room increased (Yurtseven et al. 2012), which were higher compared to the present study.

Additional studies have further evaluated the indoor air quality at the People Hospital of Shijing, People Hospital of Liwan, Phthisic Hospital, and Pediatric Hospital in Guangzhou, China (Wang et al. 2006). These hospitals are located in densely populated residential areas adjacent to heavy traffic roadways. The mean indoor $PM_{2.5}$ concentration measured at these four hospitals was 99.0 μg/m^3, while the mean outdoor $PM_{2.5}$ concentration was 65 μg/m^3, which were also higher in comparison with the results of the present study. The elevated mean indoor concentration was attributed to outdoor PM sources with positive associations reported between indoor and outdoor $PM_{2.5}$ and PM_{10} concentrations.

Outdoor $PM_{2.5}$ and $PM_{1.0}$ mass concentration and ambient wind speed were found to be predictors of indoor $PM_{2.5}$ and $PM_{1.0}$ concentration measured in the various hospital wards within the framework of the present study. This finding suggests filtration of outdoor PM to the indoor environment. Another study by Massey et al. (2009), which is in line with the present results, considered the influence of outdoor wind speed on PM concentrations in indoor environments. The authors measured $PM_{2.5}$ concentrations inside and outside the homes located in roadside, rural and urban area, along with the field survey study done in the same region in Agra, India. The highest average $PM_{2.5}$ and $PM_{1.0}$ indoor concentrations were found for the rural homes (173.03 μg/m^3 and 133.26 μg/m^3, respectively) followed by roadside homes (137.93 μg/m^3 and 117.09 μg/m^3, respectively), and then by urban homes (135.55 μg/m^3 and 102.92 μg/m^3, respectively). The elevated mean indoor concentrations compared to outdoor were consistent with the fact that indoor $PM_{1.0}$ and $PM_{2.5}$ were not only from outdoor environment through infiltration but also from indoor sources/activities. The average I/O ratios for $PM_{2.5}$, $PM_{1.0}$, $PM_{0.5}$, and $PM_{0.25}$ concentrations in roadside areas were close to 1 (0.98, 0.96, 0.98, and 0.98), for rural areas were 1 or larger than 1 (1.11, 1.08, 1.00, and 1.17), and for urban areas were smaller than 1 (0.92, 0.87, 0.80, and 0.95), respectively. The authors reported that these ratios were related to indoor activities using occupants' diary entries. A positive correlation was further found between indoor and outdoor PM concentrations (Massey et al. 2009).

Indoor/outdoor (I/O) concentrations can vary largely due to a larger number of factors, including locations, building design, different activities, and the time. I/O ratio is an indicator for evaluating the difference between indoor concentrations and the corresponding outdoor levels (Massey et al. 2009). These ratios calculated in the present study are shown in Fig. 3. Elevated I/O PM mass ratios were observed on weekends compared to weekdays in the present study. These elevated I/O PM mass ratios may be attributable to activity patterns which could have lead to resuspension of PM. In contrast to weekends with little activity, more clinicians and nurses observed patient rooms on weekdays at the hospital. In addition, the average I/O ratio in operation room was greater than 1 on some days in April (05, 21, 26–28), which could be attributed to an outdoor PM emission source (Chen and Zhao 2011).

Limitations

Due to logistic limitations, we were not able to conduct the outdoor and indoor measurements simultaneously at both hospitals. One instrument was used to sequentially measure indoor and outdoor PM concentrations across sampling sites. For this reason, 1-min averaged PM mass concentrations were collected over a 5-min period at each sampling site, alternating between indoor and outdoor locations. This may have affected our comparison of indoor and outdoor PM concentrations. In addition, we were not able to measure air exchange rate in the present study as I/O ratios depend on this factor. It should be evaluated as a part of future work.

Conclusions

Indoor and outdoor size-fractionated PM concentrations were evaluated at two public urban hospitals in Kashan, Iran. Indoor PM concentrations were found to be lower than outdoor PM levels. The association between the indoor and outdoor PM levels was assessed to identify predictors of the indoor levels. Outdoor $PM_{2.5}$ and $PM_{1.0}$ concentrations were found as the primary predictors for indoor $PM_{2.5}$ and $PM_{1.0}$ concentrations, respectively. Ambient wind speed variable was also among the predictors for indoor $PM_{2.5}$ and $PM_{1.0}$ concentrations but not for indoor PM_{10} concentrations. The present study evaluating the relationship between indoor and outdoor PM levels in hospital settings in Iran has several implications for local epidemiological studies that can use outdoor $PM_{2.5}$ and $PM_{1.0}$ concentrations to predict levels of PM measured indoors. Most of these studies rely on the effect of outdoor concentrations on the occupants' health. On the other hand, the present findings regarding the predictors of indoor air pollution concentrations can inform policy makers when implementing targeted interventions to improve the air quality, such as using high-efficient ventilation systems at the hospitals. In addition, seasonal and temporal variations of particles in the wards also are required to be considered to investigate the influence of background activities and meteorological factors on the variation of indoor dust.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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