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VOCs concentrations and emission rates in hospital environment and the impact of sampling locations

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In this study, volatile organic compounds (VOCs) were measured from 47 hospital rooms to determine the most suitable sampling location for VOCs indoors. Another goal was to find out the most predominant VOCs and their emission per floor area in a hospital environment. Three samples were taken from each room simultaneously: one from the center of the room, one from the floor near the wall, and one from the exhaust air terminal. Concentrations of the VOCs were relatively low in all the cases, and the most abundant compounds were decamethylcyclopentasiloxane, *d*-limonene, xylenes, and 2-methyl-2-propanol. The average emission rates of the main compounds per floor area varied between 49 and 81 μg/m^{2}h. Statistical analyses showed that room area and volume affected differently the total volatile organic compounds (TVOC) concentrations among the sampling locations. Concentrations were higher at the exhaust air terminal than in samples at the floor and middle of the room. VOC levels were the same at the different sampling locations when the size of the room was below 10 m^2. However, field measurements and statistical analyses showed that when the size of the room increased, the most evenly distributed VOCs can be measured most reliably in the vicinity of the exhaust terminal device or in the exhaust air.

Introduction

The ventilation of modern buildings is typically implemented mechanically. Mixing ventilation is the method most used in public buildings. It brings filtered fresh air into the occupied zone, and indoor air is removed by exhaust air devices, which are often located at the other end of the ceiling. Airflow patterns inside a room are affected by multiple factors. For example, the volume of the supply air, the location of the terminal devices, and the model of supply air diffusers have significant effects on the airflow patterns inside a room. Ventilation guidelines for hospitals have been provided in many countries. For example, the air in the hospital patient room should change at least 6 times per hour, in the operating room 15 times per hour, and in corridors 2 times per hour (American Institute of Architects 2006). For instance, in hospitals in Finland, patient rooms should have either 10 L/s/person or 1.5 L/s/m^2 of supply air, operation rooms should have 14 to 22 L/s/m^2 of supply air, and corridors 0.5 L/s/m^2. Seppänen et al. (1999) analyzed in their extensive review paper ventilation rates and health effects, and they concluded that a supply air rate less than 10 L/s/person was statistically significantly associated with health outcomes or degradation of perceived air quality. When supply air was increased up to 20 L/s/person, symptoms related to sick building syndrome (SBS) (Environmental Protection Agency 1991) decreased. Eye and upper respiratory tract symptoms were the most common. However, multiple confounding factors, such as the age of the building, indoor temperature and relative humidity, outdoor conditions (temperature, pollen, daylight hours), and psychosocial workload factors, hindered the investigation of causality between indoor air quality and health effects. Even for those uncertainties linked to the ventilation studies, there is growing evidence about the influence of ventilation on productivity, well-being, and health effects (Hellgren et al. 2011; Hellgren 2012; Salonen 2009; Seppänen et al. 1999). For example, Hellgren et al. (2011) noticed in their study that workers in

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hospital spaces in which the ventilation required readjustment had more symptoms compared to those workers in spaces with ventilation performing well. In a recent study, Babaoglu et al. (2019) found that hospital workers suffered mainly nonspecific, upper respiratory tract, and skin symptoms. One of the main factors affecting the previously mentioned symptoms was low supply airflow rate. Furthermore, Apte et al. (2000) studied the importance of ventilation and found that good ventilation and control of impurities decreased SBS symptoms by 70–85%. On the other hand, in rooms that had high air exchange rate, occupants experienced eye or mucous membrane irritation that can be linked to the dry indoor air (Seppänen et al. 1999). This might be related especially to the hospital environment, where patients are dressed in hospital clothing and are facing high supply airflow rates. Furthermore, unnecessarily high ventilation rates lead to increased energy costs.

In a cold climate, rooms are usually under slightly negative pressure between the room and its adjacent areas. Thus, supply and exhaust airflow rates should be in balance and set to their designed values. However, in some buildings, supply and exhaust air volumes are unbalanced, which can cause too high negative or positive pressure compared to outdoor air and/or between a room and its surrounding areas. This can lead to leakage and the passage of chemical impurities from the base floor or structures of the building to the living quarters (Leivo et al. 2015).

A hospital environment can in many cases be exceptional; for example, depending on the use of the room, it can deliberately have either negative or positive pressure compared to surrounding areas (Hyttinen et al. 2011). For example, airborne infection isolation rooms (AIIRs) need to have negative pressure versus surrounding areas. Although some harmonization of the ventilation requirements for hospitals worldwide has been carried out, a consensus has not yet been reached for ventilation guidelines for the specific rooms (e.g., isolation rooms) in the hospitals. Furthermore, besides the different guidelines, field studies have revealed that there are deficiencies in the performance of these rooms when comparing them to the ventilation reference values given in the national guidelines (Pavelchak et al. 2000; Saravia et al. 2007; Sutton et al. 1998).

Volatile organic compounds (VOCs) are contaminants commonly found in the indoor environment. In some cases, decreased indoor air quality and SBS symptoms have been linked to elevated VOC levels (Apte and Daisey 1999; Lu 2017; Nakazawa et al. 2005; Smedje et al. 1997; Takigawa et al. 2004). VOCs are emitted into the indoor air from, for example, fragrances, hygiene and cleaning products, building structure, furniture, and materials. In the hospital environment, the use of hand sanitizers is common, leading to an increased VOC concentration in indoor air. Typically, ethanol and propanol (e.g., 2-methyl-2-propanol) concentrations increased when using hand sanitizers (Bessonneau et al. 2013). Furthermore, other special chemicals are also used in the patient and operating rooms, such as alcohol- and chlorine-based cleaning chemicals, anesthetic gases, pharmaceutical and laboratory chemicals, and medication.

Traditionally, it has been assumed that indoor air pollutants are evenly distributed inside a room (Drescher et al. 1995). Thus, in a well-mixed situation, concentrations of the pollutants are the same at any point inside the room. However, this is not always true in real-world situations. The distance from the source, chemical and physical properties of pollutants, airflow patterns, and time are important factors in predicting the complete mixing of air pollutants. In a previous study, we found that source location affected the distribution of released VOCs inside the rooms studied (Rautiainen et al. 2021). The concentration of model compounds decreased inversely with the distance from the source point. Depending on the location of the emission source and the strength and direction of the supply airflow, the concentration was at least halved by midway through the room. When the emission source was protected from incoming air—for example, under a desk or a chair—the concentration of the model compound was more evenly mixed throughout the room.

In the previous study (Rautiainen et al. 2021), the samples taken near the exhaust air unit revealed most efficiently the presence of compounds inside the room. If the supply airflow rate was sufficient and well mixed, the concentrations at the exhaust air unit matched with the samples collected near the emission source (Rautiainen et al. 2021). If there are constant emission sources inside the room and the ventilation is turned off during the nights or weekends to conserve energy, the VOC concentrations in workspaces increase temporarily (Daisey et al. 2003). However, in buildings that are in use all the time, such as hospitals, the ventilation system cannot be turned off. Besides, good ventilation dilutes the concentrations of total volatile organic compounds (TVOC) indoors (Salonen 2009). Therefore, VOC concentrations are relatively low in these public buildings. However, it seems that odor thresholds for many VOCs are considerably lower than previously reported, and it has been speculated that even unrecognizable levels of odors can cause annoyance and mental distraction, which causes deterioration of productivity (Wargocki et al. 1999; Wolkoff et al. 2006).

The study aimed to find an optimum sampling site for chemical impurities inside the room and explain the factors that influence the VOC concentrations inside the room. The VOCs most typically found in operation rooms and offices of a hospital were also evaluated.

Methods

VOC measurements were done in the Kuopio University Hospital's office and treatment rooms. Rooms were chosen based on symptoms reported by the personnel. All together, 47 rooms were measured: two service, five meeting, 12 treatment, and 28 reception rooms. Rooms were sparsely decorated, containing mainly two chairs, a table, a hospital medical instrument cabinet, and a general examination bed.

VOC samples were collected in each room from three measuring points, located in the middle of the room, at the exhaust air terminal, and at the edge of the floor next to a wall. Tenax TA tubes connected to SKC pumps (SKC AirChek 3000 and

222; SKC, Inc., Eighty Four, PA) were used to collect the VOC samples. The flow rate of the pumps was 140–160 ml/min and the sampling duration in the rooms was 60 min. All three samples inside the room were taken simultaneously. Doors and windows were closed during sampling. Tenax tubes were analyzed with a gas chromatograph (Agilent 7890 A; Agilent Technologies, Inc., Santa Clara, CA) equipped with a mass selective detector (Agilent 5975 C) after thermal desorption (TD) (Markes TD-100, Markes International Ltd., United Kingdom) according to the ISO 16000-6:2011 standard. TVOC was determined by addition of all individual compounds in the retention time interval for C6–C16 as described in ISO 16000-6. More detailed information about VOC analysis was given in the previous study (Rautiainen et al. 2021).

Airflow rates of the rooms were measured from terminal devices (supply and exhaust air) using a Swema 3000 universal instrument connected to a SwemaFlow 125 or 420 airflow hood (Swema AB, Farsta, Sweden), or by pressure difference readings over the exhaust terminal using the same universal instrument. The airflow rate was calculated using Equation 1, where q is the rate of flow (L/s), k the metric equivalent factor given by the manufacturers of variable air unit terminals, which depends on the size and shape of the terminal unit, and Δp the differential pressure (Pa) across the device:

$$q = k\sqrt{\Delta p} \quad (1)$$

We used a linear mixed model in SAS 9.4 statistical software for the analysis of TVOC data. The measurement location was treated as a fixed factor and the room identity was used as a random variable, and the Kenward–Roger method was used to compute denominator degrees of freedom. Pairwise differences were analyzed using Tukey's test.

Size, volume, air exchange rate, function of the room, location of the terminal devices, and VOC emission area were considered in statistical analyses when estimating TVOC concentrations at different locations inside the room. The floors of the room under study were made of concrete with filler and a PVC mat above it. Suspended ceilings were made of gypsum hung from the ceiling joists with a metal grid. Above the suspended ceilings were ventilation ducts and electrical and data cables. The roof was made of concrete with filler. The walls were made from concrete or gypsum board, and they were considered to be low-emitting materials. Wall areas of the rooms were not measured. For the reasons mentioned earlier, emission calculations were done according to the floor and ceiling area. Emission was calculated using Equation 2, where E is the emission rate [μg/(hm^2)], C is the measured concentration of VOC or TVOC (μg/m^3), n is the air exchange rate (1/h), V is the volume of the room (m^3), and A is the surface area of the floor (m^2):

$$E = C \times n \times V/A \quad (2)$$

The emission rate was calculated with C obtained from every sampling location and was normalized to the floor area.

Results and discussion

Table 1 shows the most notable VOC concentrations from the three measurement locations inside the tested hospital rooms. Area-specific emission rates for individual VOCs are also given in the table. The VOCs in the table are the predominant compounds in TVOC calculations as well. The highest single VOC concentrations were most often detected close to the exhaust air terminal. The average TVOC concentration was likewise highest near the exhaust air terminal (42% of the cases). The floor and middle of the room had the highest concentrations in 22% of the cases. The mean concentration of TVOC in all the cases was less than 55 μg/m^3, indicating a low VOC concentration level in the rooms studied. Decamethylcyclopentasiloxane, *d*-limonene, xylenes, and 2-methyl-2-propanol were the most abundant VOCs found in the present study, and their emission rates per floor area varied in between 49 and 81 (μg/m^{2}h). The average emission rate for all the main individual VOCs was 23 μg/m^{2}h.

The TVOC emission rate per floor area (μg/m^{3}h) is given in Table 2. Typically, specific emission rate is calculated from the C inside the room, divided by the emission area and air exchange rate. In the present study, three sampling locations were used in the calculations. As seen in the results, the exhaust air is the most reliable for sampling when estimating the total emission rates of the room. Outlet airflow is typically the sampling point in the chemical emission tests of building material when using test chambers as well (RTS 2017). The average TVOC emission rate per floor area based on the measured flow rate and concentration at exhaust was 521 μg/m^{2}h. Järnström et al. (2007) measured somewhat lower emission rates in new residential buildings compared to present study. However, Järnström and colleagues used the field and laboratory cell (FLEC) technique (ISO 16000-10, 2006) while in the present study the whole floor area and VOC sampling at different locations were considered. Their mean TVOC emission measured from the new PVC floor structure varied from 100 to 930 μg/m^{2}h, the same level as in the current study. However, their emissions decreased during follow-up, so that at 1 year they were below the Finnish Indoor Classification, M1 target TVOC value 200 μg/m^{2}h, in all the cases. In the present study the emission rate was calculated per floor area of the room, and this gives some uncertainty to the results, because walls, ceiling, and furniture were excluded from the calculations. This is also the reason why the emission rates are higher than compared to the M1 target value. However, as described in the Methods section, walls and ceiling were considered to be low-emitting materials, and decoration of the rooms was minimal. Thus, only floor area was used in the calculations.

Table 2 shows the maximum TVOC concentrations of each sampling location as well. The exhaust air terminal had the highest concentrations in 21, the floor in 6, and the middle of the room in 6 of the rooms. In 14 of the rooms, no difference in the TVOC concentration between the sampling locations was found. When examining TVOC concentrations, less than 10% difference in measurement results was not considered to be a difference between the concentrations at

Table 1. The average concentrations of the main VOCs in three sampling locations and their emission rate per floor area, based on the measured flow rate and concentration at the exhaust ($n = 47$)

Compound groups: most common compounds	Middle of the room (average (minimum–maximum)) ($\mu g/m^3$)	Floor (average (minimum–maximum)) ($\mu g/m^3$)	Exhaust air terminal (average (minimum–maximum)) ($\mu g/m^3$)	Emission (average (minimum–maximum)) ($\mu g/m^2h$)
Aromatic hydrocarbons				
Benzene	0.9 (0.2–2.0)	0.9 (0.3–3.4)	1.3 (0.4–4.8)	14 (4–51)
Toluene	2.0 (0.3–6.0)	1.5 (0.3–4.5)	1.7 (0.4–3.9)	18 (4–42)
p-Xylene	1.5 (0.3–4.5)	1.7 (0.3–5.6)	1.8 (0.2–4.8)	19 (2–51)
o-Xylene	4.8 (1.1–8.5)	1.9 (0.2–4.0)	3.6 (0.5–8.4)	20 (4–42)
Alcohols				
Benzyl alcohol	1.2 (0.2–2.3)	1.5 (0.3–4.3)	1.4 (0.3–2.9)	15 (3–31)
Ethanol*	1.4 (0.5–4.4)	1.1 (0.3–3.4)	1.1 (0.3–3.4)	12 (3–36)
2-Propanol, 2-methyl-	4.2 (0.2–20)	4.3 (0.1–24)	5.0 (1.0–18)	53 (11–192)
Phenol	0.8 (0.2–1.5)	0.8 (0.2–1.2)	0.7 (0.3–1.1)	7 (3–12)
1-Hexanol, 2-ethyl-	0.8 (0.1–2.9)	1.0 (0.2–2.9)	0.9 (0.3–2.7)	10 (3–29)
Aliphatic hydrocarbons				
Undecane	2.7 (0.5–4.2)	2.5 (1.2–3.5)	2.5 (0.2–4,0)	27 (2–43)
Dodecane	0.9 (0.5–1.2)	0.8 (0.3–1.3)	0.9 (0.5–1.2)	10 (5–13)
Tetradecane	0.9 (0.6–1.2)	1.0 (0.6–1.4)	1.1 (0.8–1.3)	12 (9–14)
Pentadecane	0.2 (0.0–0.3)	0.9 (0.9–0.9)	0.8 (0.5–1.1)	9 (5–12)
Hexadecane	1.2 (0.1–7.6)	1.1 (0.6–1.4)	1.9 (0.4–3.3)	20 (4–35)
Aldehydes				
Hexanal	1.0 (0.1–3.0)	1.0 (0.2–2.8)	1.0 (0.2–3.2)	11 (2–34)
Benzaldehyde	1.5 (0.6–4.2)	1.5 (0.8–3.1)	1.7 (0.7–4.0)	18 (7–43)
Octanal	0.5 (0.2–1.6)	0.6 (0.2–1.3)	0.7 (0.3–1.8)	7 (3–19)
Nonanal	2.3 (0.6–6.7)	2.2 (0.6–5.0)	2.9 (0.6–8.2)	31 (6–87)
Decanal	2.4 (0.6–8.3)	2.1 (0.7–4.7)	3.2 (0.8–9.1)	34 (9–97)
Glycols				
Ethanol, 2-(2-butoxyethoxy)-, acetate	0.5 (0.1–1.5)	0.9 (0.0–2.3)	0.7 (0.1–1.7)	7 (1–18)
Terpenes				
Alpha-pinene	1.0 (0.2–2)	1.0 (0.0–2.7)	1.2 (0.2–2.7)	13 (2–29)
d-Limonene	7.9 (0.7–49)	7.1 (0.1–47)	7.3 (0.0–51)	78 (0–544)
Silicon compounds				
Cyclopentasiloxane, decamethyl-	8.1 (0.3–140)	7.3 (0.4–120)	7.6 (0.4–110)	81 (4–1173)
Cyclotrisiloxane, hexamethyl-	4.1 (0.4–150)	2.3 (0.7–5.1)	4.1 (0.9–20)	44 (10–213)
Cyclotetrasiloxane, octamethyl-	2.7 (0.4–12)	1.4 (0.3–5.3)	2.7 (0.3–13)	29 (3–139)
Organic acids/ carboxylic acids				
Acetic acid	2.2 (0.1–9.6)	0.9 (0.0–5.0)	2.1 (0.1–12)	22 (1–128)
Esters				
TXIB (pentanoic acid, 2,2,4-trimethyl-3-carboxyisopropyl, isobutyl ester)	0.5 (0.1–2.1)	0.5 (0.1–3.2)	0.5 (0–2.6)	5 (0–28)
Ketones				
5-Hepten-2-one, 6-methyl-	0.3 (0.1–0.7)	0.4 (0.1–0.7)	0.4 (0.2–0.7)	4 (2–7)
TVOC	48 (9.2–180)	44 (13–170)	53 (14–170)	–

*Out of TVOC range, method not valid for reliable analysis.

Table 2. TVOC emission rate per floor area (μg/m^{2}h), and maximum TVOC concentrations in the three sampling locations.

	Floor	In the middle	Exhaust	The same values	All
TVOC emission (μg/m^{2}h)	435 (142–1531)	424(114–1566)	521 (127–1495)	–	–
TVOC (μg/m^3)	44 (17–84)	66 (39–92)	50 (21–110)	67 (21–170)	53 (14–170)
Measured airflow rate (L/s)	47 (20–110)	27 (27–29)	67 (16–290)	37 (15–66)	52 (15–290)
Designed airflow rate (L/s)	45 (16–100)	22 (20–25)	66 (11–300)	31 (20–60)	49 (11–300)
Floor area (m^2)	16 (9.6–25)	14 (12–17)	20 (9–48)	14 (9–20)	17 (8.8–48)
Volume (m^3)	40 (24–64)	41 (33–47)	51 (22–130)	35 (22–56)	44 (22–130)
Calculated ventilation coefficient (1/h)	3.9 (2.4–6.3)	2.3 (2–3)	4.5 (1.8–8)	3.4 (1.8–6.1)	3.9 (1.8–8)
Designed ventilation coefficient (1/h)	3.7 (1.9–5.6)	2.1 (1.9–2.2)	4.3 (1.6–8.4)	3.1 (2.2–4)	3.7 (1.6–8.4)
Number of cases	6	6	21	14	47

Note. The number of cases is the number of rooms where the TVOC concentration was highest in the sampling location. For measured and designed supply airflow rates, room volume, and calculated air exchange rate, the results are presented as an average, and in parentheses are the minimum and maximum values.

different sampling locations. This is because of the low TVOC concentrations and uncertainty related to the VOC measurements during the sampling (e.g., pump calibration, variation in sampling flow rate) and analysis (gas chromatography–mass spectroscopy [GC-MS] analysis). The TVOC concentrations were low due to the high ventilation rates inside the rooms studied and low emission of VOCs from the materials. Previous studies have pointed out that TVOC concentrations in offices are low, generally below 100 μg/m^3 (Salonen et al. 2009; Sundell et al. 1993).

Room area and volume had a different effect on the TVOC concentrations among the sampling locations (room area: $F_{2,\ 67.4} = 7.77$, $P = 0.0009$; room volume: $F_{2,\ 66.3} = 6.18$, $P = 0.0034$; Figure 1A,B).

The effect of air exchange on the TVOC concentrations was the same between the sampling locations ($F_{2,\ 67.9} = 2.46$, $P = 0.093$). The air exchange rate affected TVOC concentrations significantly ($F_{1,\ 40.3} = 7.82$, $P = 0.0079$; Figure 1C) and the concentrations differed between the sampling locations ($F_{2,\ 69.7} = 4.34$, $P = 0.017$; Figure 1D). Concentrations were higher at the exhaust air terminal than at the floor and middle of the room, whereas the concentrations at the floor and middle of the room did not differ from each other (Tukey's pairwise tests, exhaust air terminal vs. FLOOR: $P = 0.034$; exhaust air terminal vs. middle: $P = 0.046$; floor vs. middle: $P = 0.95$).

Room area, room volume, and air exchange rate affected the TVOC emissions among the sampling locations differently (room area: $F_{2,\ 65.8} = 4.76$, $P = 0.012$; room volume: $F_{2,\ 65.8} = 3.93$, $P = 0.024$; air exchange rate: $F_{2,\ 66} = 5.19$, $P = 0.0081$; Figure 2). The TVOC concentrations and emissions of rooms were similar regardless of the location of the terminal devices inside the room (concentration: $F_{2,\ 39.3} = 2.20$, $P = 0.124$; emission: $F_{2,\ 37.6} = 0.50$, $P = 0.612$). Regression functions and coefficients of determination (r^2) for modeled prediction lines (Figures 1 and 2) are presented in Table 3. The coefficients of determinations were not very strong, with many of them below 10% ($r^2 < 0.10$) which indicates a high level of unexplained variation.

One possible source of unexplained variation is the different room types. However, the function of the room did not make a statistically significant difference in the TVOC concentrations ($F_{3,\ 37.8} = 2.10$, $P = 0.12$). This can be at least partly attributed to the minimal decoration, low-emitting materials, high ventilation rates of the rooms, and thus overall low concentrations of VOCs in every studied rooms.

The concentrations of single VOCs were low, and detected compounds were typical VOCs found in houses, offices, and public buildings. The main exceptions are ethanol, 2-methyl-2-propanol, and benzyl alcohol, which are more common in the hospital environment than in offices (Mazzola et al. 2003; Scheepers et al. 2017; Su et al. 2018). In addition, isopropyl alcohol, hydrogen peroxide, iodopovidone, polyhexanide, chloramine, and sodium hypochlorite are other common antibacterial agents or disinfectants used in Kuopio University Hospital. Alcohols are generally used in cleaning chemicals, disinfectants, and hand sanitizers. However, the concentration of measured alcohols in present study was lower compared to other studies related to the hospital environment (Baurès et al. 2018; Bessonneau et al. 2013).

TVOC was low in all the cases (average 53 μg/m^3), and even the highest TVOC concentration was below 200 μg/m^3. This is consistent with other studies (Baurès et al. 2018; Scheepers et al. 2017). Based on the results of this and our previous study, a VOC sample taken from the exhaust air terminal gives, in general, the most reliable information about the concentrations of chemical pollutants inside the room; see Figure 1 (Rautiainen et al. 2021). However, in smaller rooms (area ≤ 10 m^2 and volume ≤ 30 m^3), the difference in the VOC concentrations between sampling locations is only marginal. This might be due to shorter distances from walls and furniture to sampling point in

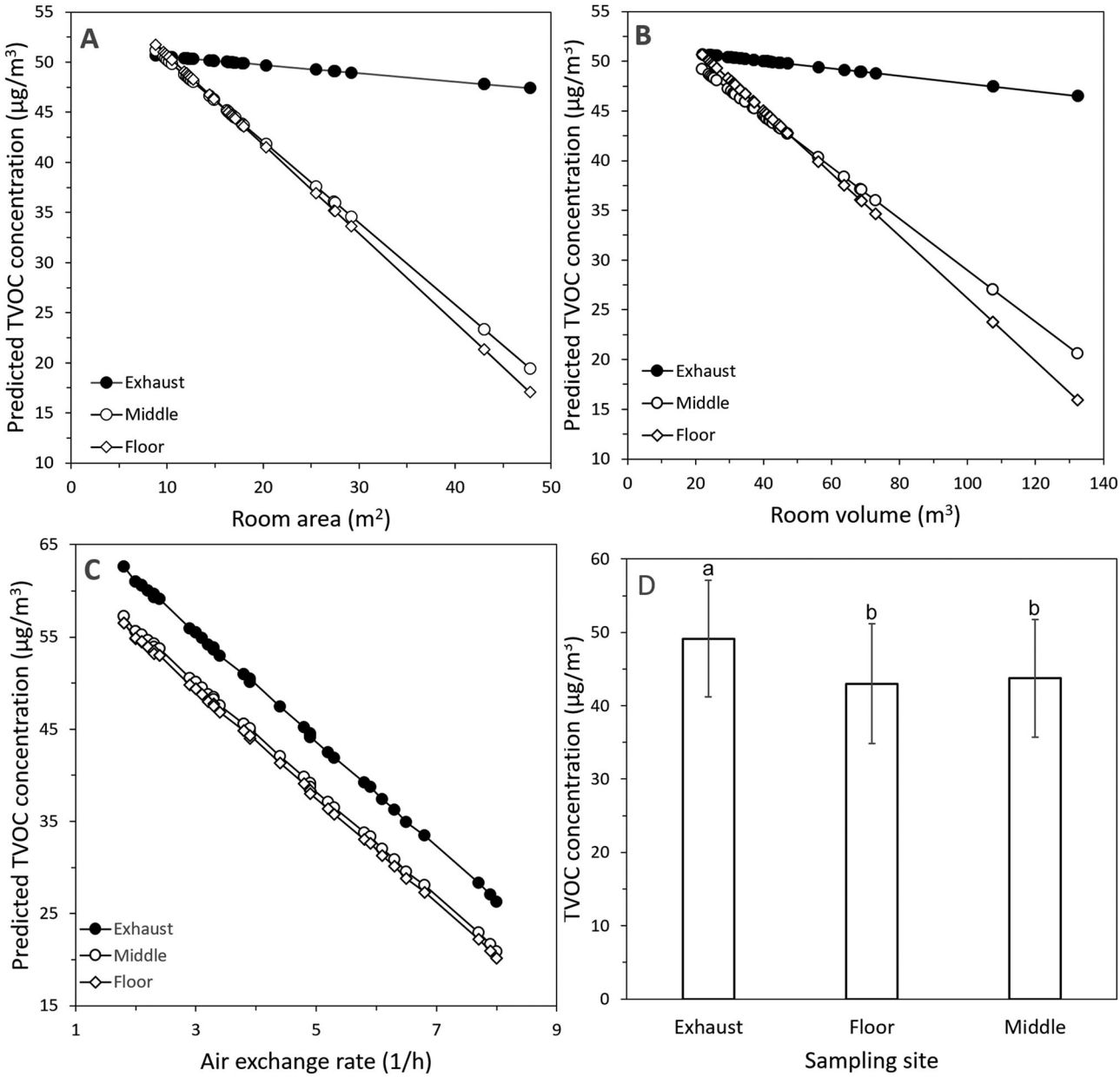

Fig. 1. Predicted TVOC concentrations associated with (A) room area, (B) room volume, and (C) air exchange rate modeled with linear mixed models. (D) Estimated marginal means (±95% confidence interval [CI]) TVOC concentrations of sampling sites in studied rooms. Different letter above error bars indicates significant pairwise difference (Tukey's test, $P < 0.05$).

smaller rooms, so the emitted VOCs distributed more evenly than in bigger rooms. The spatial distribution of VOCs inside a room is affected by several factors, including the distribution of contaminant sources, room size, ventilation (efficiency, airflow patterns, location and design of terminal devices), sinks, internal barriers to airflow (screens, furniture, etc.), thermal gradients, and pressure conditions (Yang and Chen 2001).

As expected, air exchange rate did correlate inversely with the TVOC concentrations. High ventilation rates dilute the VOC concentrations, which are already at low levels because of sparse decoration of the rooms and low-emitting building materials.

VOC measurements and statistical analyses showed that the qualities of exhaust air describe extremely well the general indoor air quality of the room. It can thus be considered and is already commonly used as the sampling and monitoring site for other parameters and chemical impurities (e.g., CO_2, fine particles, temperature, and relative humidity) as well.

Conclusion

The main emitted compounds found in samples from hospital rooms were alcohols (2-methyl-2-propanol), xylenes, *d*-

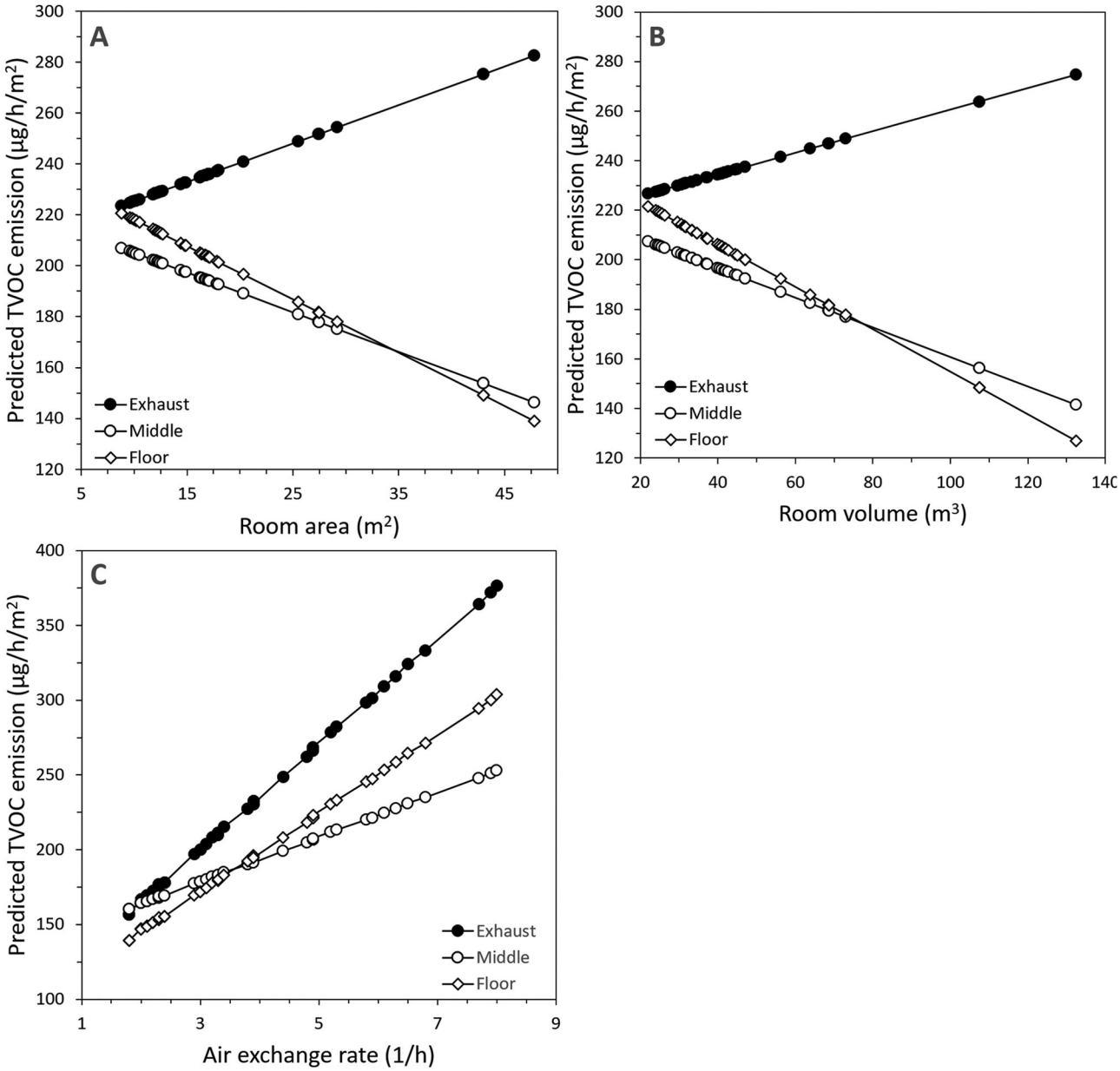

Fig. 2. Predicted TVOC emissions associated with (A) room area, (B) room volume, and (C) air exchange rate modeled with linear mixed models.

Table 3. Linear mixed model-derived regression model functions ($y = bx$) and coefficient of determinations (r^2, in parentheses) for VOC concentrations and emissions in different sampling locations in studied rooms.

Models	Location	Floor area (m^2)	Room volume (m^3)	Air exchange rate (1/h)
Concentrations	Exhaust	$y = 51.38 - 0.08x$ (0.001)	$y = 51.56 - 0.04x$ (0.049)	$y = 72.85 - 5.80x$ (0.241)
	Middle	$y = 58.37 - 0.81x$ (0.067)	$y = 54.89 - 0.26x$ (0.078)	$y = 67.46 - 5.80x$ (0.054)
	Floor	$y = 59.57 - 0.89x$ (0.074)	$y = 57.60 - 0.31x$ (0.001)	$y = 66.72 - 5.80x$ (0.101)
Emissions	Exhaust	$y = 210.16 + 1.51x$ (0.008)	$y = 217.03 + 0.43x$ (0.005)	$y = 95.02 + 35.10x$ (0.175)
	Middle	$y = 220.63 - 1.56x$ (0.001)	$y = 220.47 - 0.60x$ (0.189)	$y = 134.10 + 14.84x$ (0.040)
	Floor	$y = 239.06 - 2.09x$ (0.027)	$y = 240.43 - 0.86x$ (0.029)	$y = 93.37 + 26.21x$ (0.133)

Note. The prediction lines are presented in Figures 1 and 2.

limonene, and silicon compounds. The average emission rates of the main compounds per floor area varied between 49 and 81 $\mu g/m^2h$. Overall, total concentrations of the VOCs were relatively low in all cases. One reason for this is the relatively high ventilation rates and modest decoration of the rooms. Alcohols used in disinfectants and organic silicon compounds originating from occupants are the most common VOCs in the hospital environment. There were no significant differences in VOC levels between the sampling locations with size lower than 10 m^2 or for volume of the room lower than 30 m^3, respectively. However, field measurements and statistical analyses showed that when the size of the room increases, the most evenly distributed VOCs can be measured most reliably in the vicinity of the exhaust terminal device or in the exhaust air.

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Authors' contribution

All the authors contributed equally to the preparation of this article.

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