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Evaluation of Indoor Air Pollution during the Decorating Process and Inhalation Health Risks in Xi'an, China: A Case Study

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ABSTRACT

$PM_{2.5}$, formaldehyde, and 8 volatile organic compounds (VOCs) were observed in 6 newly decorated apartment units to evaluate the effects of the decorating process on the indoor air quality in Xi'an, China. The comparison of indoor and outdoor formaldehyde and VOCs concentrations showed that the outdoor $PM_{2.5}$ concentration exceeded the indoor one during the monitoring process, whereas the indoor formaldehyde and VOCs concentrations exceeded the outdoor ones. The levels of formaldehyde and VOCs in different rooms were investigated, and the concentrations in the bedroom were found to be the highest. Furthermore, the formaldehyde and VOCs concentrations were measured in 200 other rooms decorated within a 2-year period in Xi'an, and the results indicated that wallpapering, wooden flooring, and furniture were the major decorating processes emitting these compounds. In addition, a health risk assessment of the monitored formaldehyde and VOCs in the rooms 1 year after decorating showed that benzene posed the greatest health risk among the assessed VOCs.

Keywords: Indoor air quality; Decorating process; Inhalation health risks; Xi'an.

INTRODUCTION

Indoor air quality is considered to be a major environmental issue given that indoor air pollution has significant detrimental health effects (Batterman *et al.*, 2012a; Verriele *et al.*, 2016; Zorpas and Skouroupatis, 2016). Indoor air quality is important because of the following two reasons. On the one hand, people spend almost 90% of their days in enclosed living spaces (Gong *et al.*, 2017). On the other hand, indoor air pollutants accumulate more easily because the indoor environment contains many pollution sources and indoor air flows slowly (Pei *et al.*, 2013; Bourdin *et al.*, 2014). Among the indoor air pollutants, formaldehyde and volatile organic compounds (VOCs) have been recognized as detrimental constituents because of human health effects, including their non-cancer or cancer risks. The dominant non-cancer chronic effects of formaldehyde and VOCs are headache, cough, nausea, severe liver poisoning, asthma and other respiratory effects (Rumchev *et al.*, 2007; Dai *et al.*, 2017), whereas cancer affects mainly include the brain, liver, lung, blood (leukemia and non-Hodgkin lymphoma), kidney, and biliary tract cancers (WHO, 2000; He *et al.*, 2015). Formaldehyde and VOCs can be taken up by the human body through inhalation, ingestion, and via the dermis, with inhalation being a predominant uptake route (Guo *et al.*, 2004; Lee *et al.*, 2006; Rumchev *et al.*, 2007). Of the wide variety of indoor sources, building materials, decorative materials, and furniture constitute important sources for indoor air pollution (Zhang *et al.*, 2016; Cheng *et al.*, 2017). Many countries have established labeling schemes to reduce indoor emissions from building products (Kephalopoulos *et al.*, 2006). In addition, fine particulate matter (PM) also comprises a large group of indoor air compounds, which mainly harm the respiratory and cardiovascular systems (Batterman *et al.*, 2012b; Mehta *et al.*, 2013; Petkova *et al.*, 2013; Song *et al.*, 2015; Dickerson *et al.*, 2017; Tong *et al.*, 2018).

Extensive investigations have been conducted on the indoor $PM_{2.5}$, formaldehyde and VOCs concentration, especially for formaldehyde and total volatile organic compounds (TVOC) concentrations (Afshari *et al.*, 2003; Chang *et al.*, 2017). Recent studies have shown that formaldehyde and the VOCs concentrations in new homes

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were higher than that in older homes (Park and Ikeda, 2006). Han *et al.* (2015) reported that outdoor $PM_{2.5}$ concentrations influenced indoor $PM_{2.5}$ concentrations significantly. Chi *et al.* (2016) reported that TVOC and formaldehyde originated mainly from volatile sources by pollution generation during decoration. Tao *et al.* (2015) proposed that the formaldehyde and TVOC concentrations were inversely proportional to indoor air velocity and in direct proportion to the indoor temperature and relative humidity. Sofuoglu *et al.* (2011) measured the VOCs concentrations and estimated associated health risks in schools, and formaldehyde was found to be the main concern with high chronic toxic and carcinogenic risk levels followed by naphthalene, benzene, and toluene among the measured VOCs. However, almost all previous studies focused on pollutant concentrations at a laboratory scale or in rooms that had been decorated several years previously. Limited studies exist on the $PM_{2.5}$ concentration, formaldehyde and VOCs emission characteristics during decorating. It is necessary to identify the formaldehyde and VOCs emission sources to obtain a better understanding of their emission characteristics during the decorating process. The inhalation-related health risks of formaldehyde and VOCs in newly decorated apartment units have not been well studied in Xi'an. Thus, a deeper understanding of the potential adverse health effect of formaldehyde and VOCs in newly decorated apartment units is required urgently.

This study was designed to investigate the $PM_{2.5}$, formaldehyde and VOCs (including benzene, toluene, *o*-xylene, *p*-xylene, *n*-butyl acetate, ethylbenzene, styrene, and *n*-undecane) emission characteristics during the decoration process of 6 residential apartment units (24 rooms) in Xi'an. Eight compounds were selected as the target VOCs, including benzene, toluene, *o*-xylene, *p*-xylene, *n*-butyl acetate, ethylbenzene, styrene, and *n*-undecane. The purpose of our study was to (1) compare the indoor and outdoor $PM_{2.5}$, formaldehyde and VOCs concentrations, (2) obtain formaldehyde and VOCs concentrations variations as a function of the decorating process, (3) explore the influence of decorating materials on formaldehyde and VOCs emissions, and (4) estimate the health risk of formaldehyde and the selected VOCs (benzene, toluene, *o*-xylene, *p*-xylene, styrene and ethylbenzene) in rooms 1 year after decoration.

MATERIALS AND METHODS

General Information of Sampling Sites

Air sampling was conducted in Xi'an, China, from March 2014 to November 2017. 6 apartment units that were decorated with different materials were selected and their air quality was monitored at different decorating stages. 4 rooms, including the bedroom, living room, kitchen, and bathroom were selected from each house. The detailed characterizations of the selected apartment units were presented in Table 1. For a more precise investigation of the influence of decoration materials and the health effect of formaldehyde and the selected VOCs, formaldehyde and the given VOCs concentrations were measured in 200 other rooms in this study. These rooms were decorated within 2 years.

Sampling and Analytical Methods

Air pollutants, including formaldehyde, benzene, toluene, *o*-xylene, *p*-xylene, *n*-butyl acetate, styrene, ethylbenzene, *n*-undecane, and respirable suspended particulate ($PM_{2.5}$) matter were studied. Indoor and outdoor air samples were collected simultaneously in the selected homes and outdoor sampling sites were located near the monitored apartment units during the decorating process. The sampling and analysis methods of formaldehyde and VOCs were based on China's GB/T 18883-2002 indoor air quality standard. Before sampling, the flow of the sampling instrument was calibrated by a mass flowmeter (Model 4140, TSI Inc., USA). The stainless steel tubes for VOCs sampling were activated by the thermal desorption unit for 1 h at 350°C in the pure N_2. Also of note was that all the monitored rooms were closed for 12 h before sampling to make sure each room was independent relatively. All the samples were collected using a sampler (QC-2, Beijing Municipal Institute of Labour Protection, China) equipped with a bubble tube for formaldehyde sampling and stainless steel tube for VOCs sampling. The stainless steel tube was filled with 200 mg Tenax-TA absorbents (60–80 mesh). The sampler was fixed on a tripod approximately 1.5 m above the ground level, close to the breathing height of human. The sample flow rate and time were set as 0.5 L min^{-1} and 20 min, respectively. After sampling, all the samples were

Table 1. Characteristics of sampling sites in Xi'an.

Site no.	Number of floors	Area (m^2)				[e]Frequency of Ventilation				[f]Traffic flow
		a	b	c	d	a	b	c	d	
1	7	12	30	7	4	Daily	Daily	Infrequent	Daily	Low
2	10	12	30	7	4	Weekly	Daily	Weekly	Infrequent	Low
3	11	12	30	7	4	Weekly	Daily	Infrequent	Infrequent	Low
4	13	15	42	8	5	Daily	Daily	Daily	Daily	Low
5	11	18	45	8	6	Daily	Daily	Infrequent	Infrequent	Moderate
6	28	18	45	8	6	Weekly	Daily	Infrequent	Infrequent	Moderate

Note: a, bedroom; b, living room; c, kitchen; d, bathroom.
[e] *daily* means opening windows every day; *weekly* means opening windows once a week; and *infrequent* means the frequency of opening windows is less than once a week.
[f] *low* means that the apartment is not adjacent to a trafficked road; *moderate* means that the apartment is adjacent to a trafficked road; and *high* means that the apartment is adjacent to a heavily trafficked road.

immediately transported to the laboratory for analysis. It was worth noting that the influence of SO_2 was excluded by making the air samples pass the manganese sulfate paper filter before entering the formaldehyde absorption tube as described in GB/T 18204.2-2014. The $PM_{2.5}$ concentrations were measured using a Dust-Trak Handheld Aerosol Monitor (Model 8520, TSI Inc., USA) at 3.0 L min^{-1}. Before sampling, the Dust-Trak monitor was calibrated by gravimetric methods. The Dust-Trak monitor was located away from the exhaust ducts during sampling. On the testing day, field blanks were conducted for each house. The general descriptions of sampling parameters including home type, indoor temperature, pressure, relative humidity, decoration stage, and decoration materials were recorded during sampling collection.

Phenol reagent spectrophotometry was used to measure the formaldehyde concentration of the samples (GB/T 18204.2-2014). First, phenol reagent dissolved in deionized water was used to collect formaldehyde sample based on their reactions to form azine. Then, ammonium ferric sulfate dissolved in hydrochloric acid (0.1 mol L^{-1}) was added into the above liquid to react with azine to form blue-green compounds. Subsequently, the above solution was allowed to stand for at least 15 minutes to react thoroughly. Finally, the formaldehyde concentration was determined by colorimetric method using a spectrophotometer (UV-2600AH, Unico, USA). VOCs concentrations of the samples were determined by a gas chromatography (GC9790, Fuli Instruments, China) equipped with a flame ionization detector, thermal desorption unit (JX-3) and quartz capillary column (SE-30, 50 m × 0.32 mm). For the determination of VOCs, the injector temperature was set as 240°C. The initial temperature of GC oven is 50°C, holding for 10 min, and then increased to 260°C at a rate of 10°C min^{-1}, then hold for 2 min.

Risk Calculation

The risk assessment for indoor VOC inhalation exposure was based on published toxicity data and exposure concentrations measured in this study. Formaldehyde, benzene, toluene, *o*-xylene, *p*-xylene, styrene and ethylbenzene were selected as the target toxic chemicals.

Cancer risks from the formaldehyde and VOCs cannot be ignored because we spend most of our daily life indoors. We investigated the cancer risks for formaldehyde and the selected VOCs using Eqs. (1)–(2) (Guo *et al.*, 2004; Lee *et al.*, 2006; EPA, 2011):

$$\mathrm{CR} = \mathrm{EC} \times \mathrm{SF} \tag{1}$$

$$\mathrm{EC} = \frac{\mathrm{CA} \times \mathrm{IR} \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{UCF}}{\mathrm{BW} \times \mathrm{AT} \times 365} \tag{2}$$

where CR, EC, SF, CA, IR, ET, EF, ED, UCF, BW and AT denote the cancer risk, exposure concentration, cancer slope factor (kg d mg^{-1}), contaminant concentration (mg m^{-3}), inhalation rate ($m^3 \cdot day^{-1}$), exposure time (h day^{-1}), exposure frequency (days y^{-1}), exposure duration (y), unit conversion factor (say, $1 \cdot 24^{-1}$), exposed body weight (kg), and average time (70 y) (Guo *et al.*, 2004), respectively. As referenced to the *Exposure Factors Handbook* of the Chinese population and previous reports (MEPC, 2013; Dai *et al.*, 2017), the exposure frequency and exposure duration were estimated as 354 days y^{-1} and 5 years, respectively, and the exposure time was estimated as 15 h (living room, 3 h; bedroom, 8 h; kitchen, 3 h; and bathroom, 1 h) for adults and 20 h (living room, 4 h; bedroom, 12 h; kitchen, 0 h; and bathroom, 1 h) for children (< 3 years) (U.S. EPA, 2011; Pei *et al.*, 2013; Dai *et al.*, 2017). The U.S. EPA suggests that the standard IR values for man, woman and children are 20, 18 m^3 day^{-1} and 5 m^3 day^{-1}, respectively (U.S. EPA, 1994; Gratt, 1996; Guo *et al.*, 2004; U.S. EPA, 2011), for average body masses of 70 kg for men, 60 kg for women, and 10 kg for children (Guo *et al.*, 2004; Bu *et al.*, 2016). Based on the Integrated Risk Information System (IRIS) of the EPA, the SFs of the assessed formaldehyde and VOCs were listed in Table 2.

The non-cancer risk and hazard index can be calculated by Eqs. (3)–(4) (He *et al.*, 2015; Gong *et al.*, 2017):

$$\mathrm{HQ} = \frac{\mathrm{EC}}{RfD} \tag{3}$$

$$\mathrm{HI} = \textstyle\sum_{\mathrm{i}} HQ_{\mathrm{i}} \tag{4}$$

where HQ, *Rf*D, HI, and i represent the non-cancer risk, reference dose (mg kg^{-1} day^{-1}), hazard index, and pollutant *i*. The *Rf*D is defined as a numerical estimate of the daily exposure to the human population, which is unlikely to cause harm during a lifetime (U.S. EPA, 1989). For a given airborne toxic contaminant, exposures below the reference level (HI = 1) are unlikely to be connected with adverse health effects (Durmusoglu *et al.*, 2010). The potential for adverse health effects is correlated positively with the HI when exposures exceed the reference dose.

RESULTS AND DISCUSSION

The Difference of $PM_{2.5}$, Formaldehyde, and VOCs Concentrations of Indoors and Outdoors during Different Decorating Steps

Concentrations of indoor $PM_{2.5}$ and outdoor $PM_{2.5}$, formaldehyde, and VOCs in different decorating stages (hydropower finished, tile finished, putty finished, wallpaper/painting finished, wooden floor finished, door finished, and furniture finished; 1 month after decoration, 3 months after decoration, 6 months after decoration, and 12 months after decoration) were shown in Fig. 1. The outdoor $PM_{2.5}$ concentration exceeded the indoor concentration in nearly all of the decorating processes. The indoor $PM_{2.5}$ concentration exceeded that of outdoors after tiling had been finished, which could imply that cement and putty were stacked in the rooms used for tiling and puttying, respectively. For formaldehyde and VOCs, the indoor concentrations were similar with or higher than the outdoor concentrations before wallpapering (painting) commenced, and these increased significantly after wallpapering (painting) was concluded. The indoor formaldehyde and VOCs concentrations exceeded the outdoor concentrations significantly, which indicated that formaldehyde and VOCs evaporated primarily from many decorating materials, furniture, and other household products. Among the target outdoor VOCs concentrations, toluene was the most abundant in all selected rooms, followed by benzene, ethylbenzene, *o*-xylene, *p*-xylene, styrene, *n*-butyl acetate, and *n*-undecane. However, the order of indoors differed from that of outdoors, with the concentrations of ethylbenzene tending to be higher than those of benzene after wallpapering (painting) had been completed. All above-mentioned phenomena revealed that the indoor $PM_{2.5}$ was derived mainly from outdoors and that the VOCs originated mainly from decorating materials, which agreed with previous reports (Yrieix *et al.*, 2010; Han *et al.*, 2015; Tao *et al.*, 2015).

Emission Characteristics of Formaldehyde and the Selected VOCs from Different Decorating Steps in Rooms with Different Functions

The emission characteristics of formaldehyde and VOCs were further investigated in rooms with different functions as they are the main cause for the detrimental quality of the indoor air environment (Wang *et al.*, 2007). As shown in Fig. 1, indoor formaldehyde and VOCs concentrations differed significantly between rooms with different functions. Initially, the trends in indoor formaldehyde and VOCs concentrations were similar during the first three decoration stages, and then diverged gradually after wallpapering (painting) had been completed. Regardless of the decorating stage, the indoor formaldehyde and VOCs concentrations of the bedroom were consistent with or slightly higher than those of the living room, followed by kitchen and bathroom. This phenomenon could have resulted from the species and

Table 2. Related toxicity values of target health-related VOCs.

VOCs	CAS no.	Group ([a]IRAC)	[b]SF (kg d mg^{-1})		[c]RfD (mg kg^{-1} d^{-1})	
			Value	Source	Value	Source
formaldehyde	50-00-0	1	-	-	0.2	IRIS
benzenze	71-43-2	1	0.055	IRIS	0.004	IRIS
toluene	108-88-3	3	-	-	0.08	IRIS
o-xylene	95-47-6	3	-	-	0.2	IRIS
p-xylene	108-38-3	3	-	-		
styrene	100-42-5	2B	0.0035	IRIS	0.2	IRIS
ehylbenzene	100-41-4	2B	0.0087	IRIS	0.1	IRIS

[a]IARC, International Agency for Research on Cancer; [b]SF, Slope factor (obtained from IRIS); [c]RfD, Reference dose for chronic oral exposure.

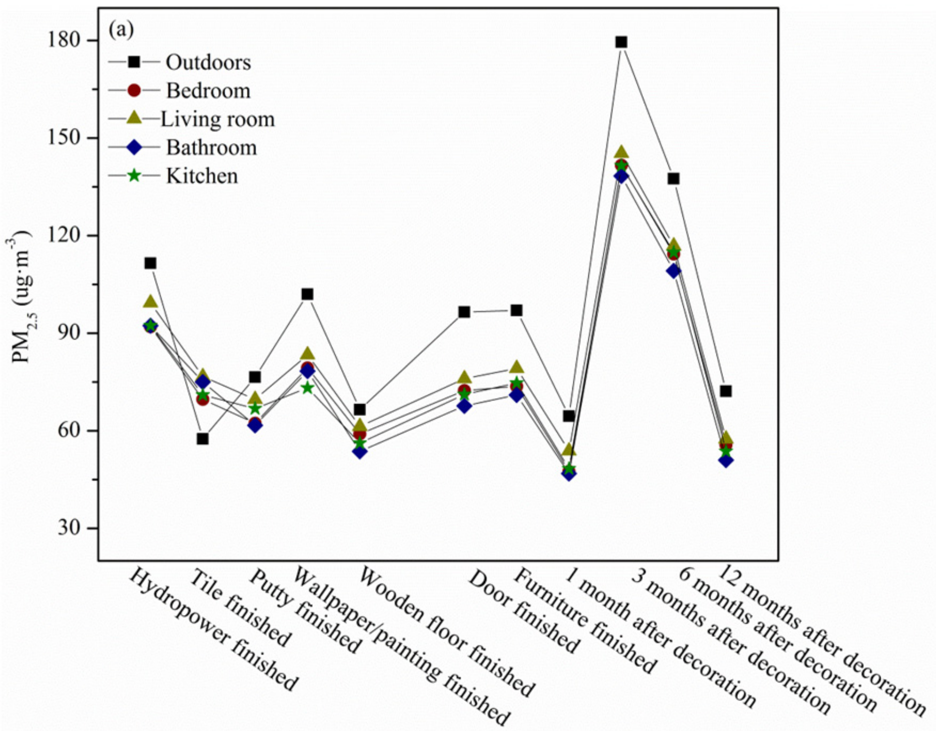

Fig. 1. Concentration of (a) $PM_{2.5}$, (b) formaldehyde, and (c) VOCs in indoor and outdoor ((c): a: outdoors; b: bedroom; c: living room; d: kitchen; e: bathroom).

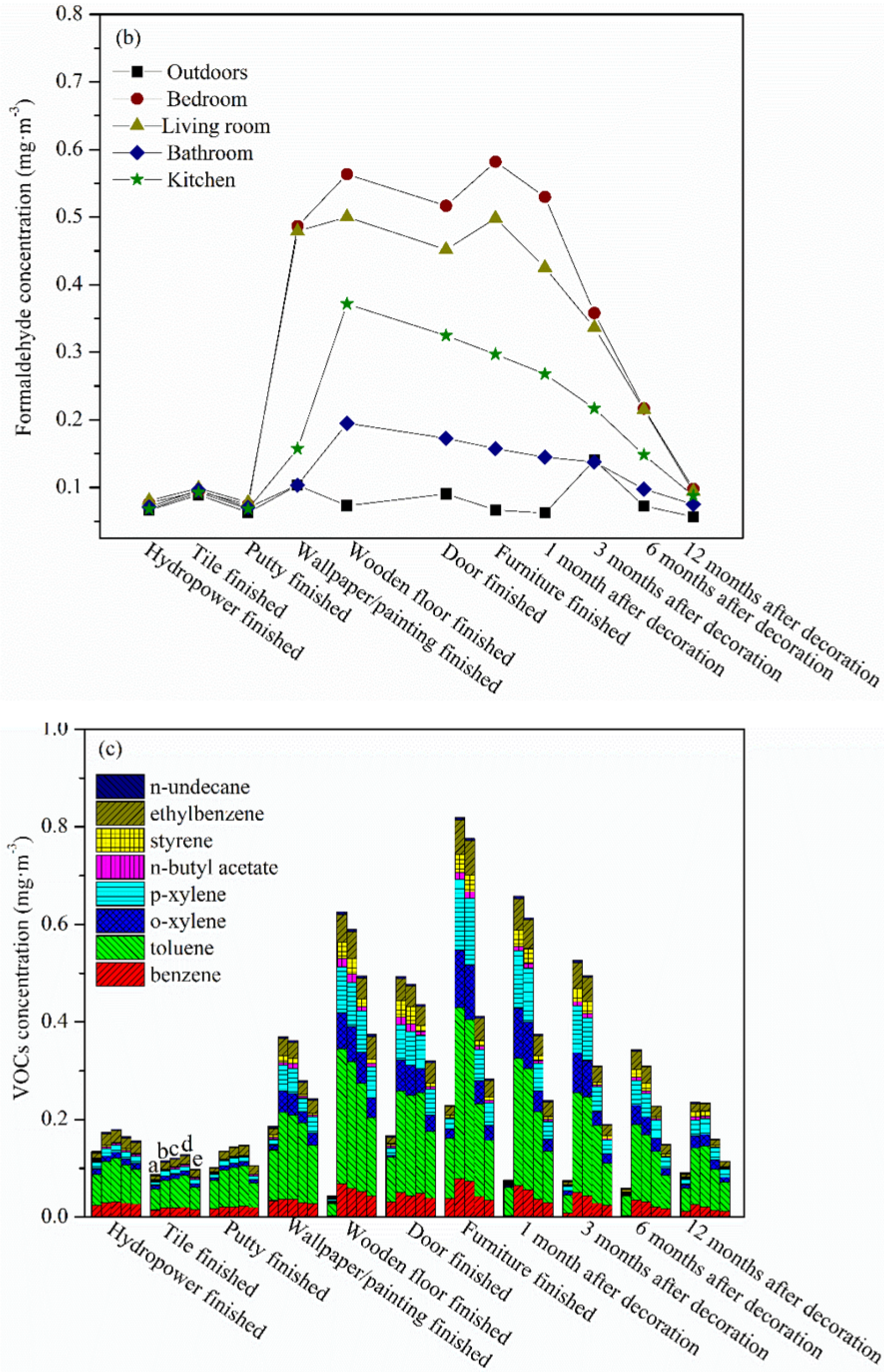

Fig. 1. (*continued*).

quantity of decorating materials in the living room and bedroom exceeding that of the other 2 rooms. Thus, the variations of formaldehyde and VOCs concentrations during different decorating steps were further investigated as follows.

As shown in Figs. 2–3, both the indoor formaldehyde and VOCs concentrations displayed a big difference in the different decorating stage. The indoor formaldehyde concentrations in all 4 kinds of rooms showed a sharp increase after wallpapering (painting) had been completed, especially for the living room and bedroom, whereas the indoor VOCs showed a slight increase. This phenomenon indicated that the main harmful gas releasing from wallpapering (painting) was formaldehyde. The VOCs concentrations in the living room and bedroom presented two peaks after the wooden flooring and furniture had been finished, whereas formaldehyde changed within a relatively

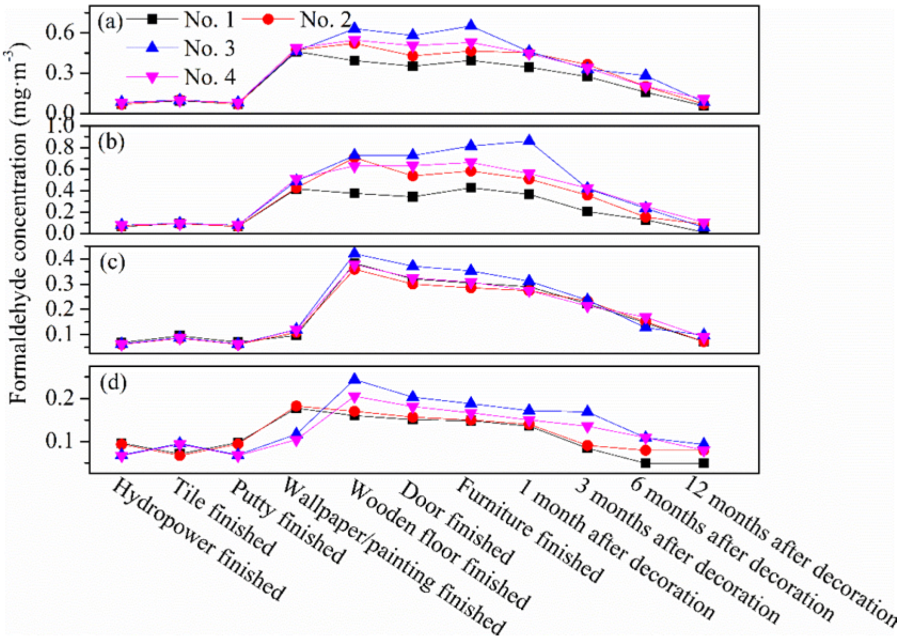

Fig. 2. Concentration of formaldehyde in (a) living room, (b) bedroom, (c) kitchen, and (d) bathroom.

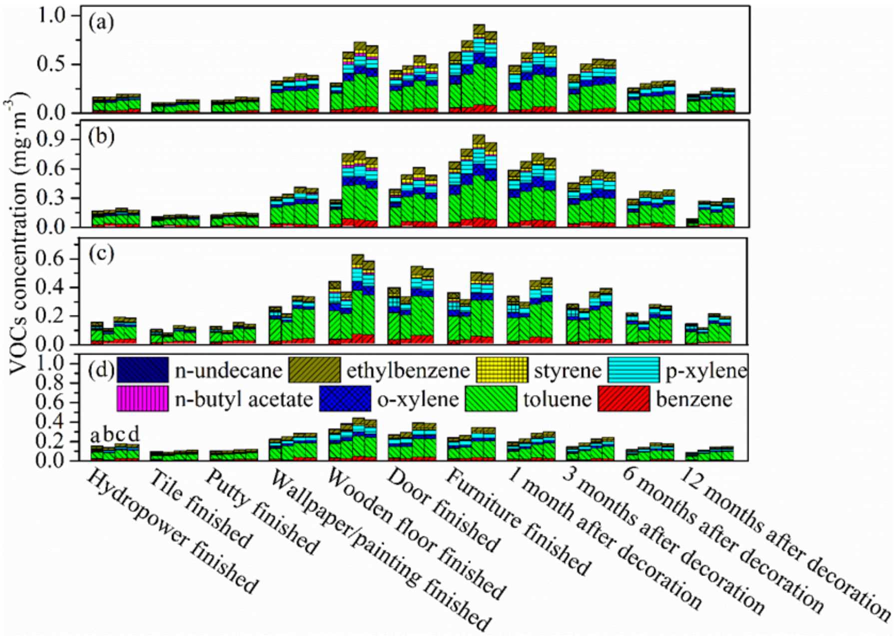

Fig. 3. Concentration of VOCs in (a) living room, (b) bedroom, (c) kitchen, and (d) bathroom (a: No. 1; b: No. 2; c: No. 3; d: No. 4).

narrow range. This manifested that wooden products were the main source of VOCs and formaldehyde. For the kitchen and bathroom, the indoor formaldehyde and VOCs concentrations increased continually after the cupboard installation and then decreased gradually as a function of time. In addition, it was noteworthy that the indoor formaldehyde and VOCs concentrations presented a downward trend after the decorating had been completed. The indoor formaldehyde concentration decreased to limits of 0.1 mg m^{-3} (GB/T 18883-2002) when the decoration was completed after 1 year, and the indoor VOCs concentration fell below the limits of 0.6 mg m^{-3} (GB/T 18883-2002) when the decoration was completed within 6 months. This phenomenon revealed that the indoor elevated VOCs were related to decorations and could last for a long period, which was in accordance with previous studies (Dai *et al.*, 2017).

Based on the above analysis, it could be concluded that the influence of different decorating stages might be mainly attributed to different decorating materials. Thus, the effect of different materials on the variation in indoor formaldehyde and VOCs concentrations of selected apartment units (Nos. 1–4) were investigated further. The first 3 apartment units were of the same size and layout and the fourth was larger. The different decorating materials (wall coverings, flooring, and furniture) were listed in Table 3. Table 3, Fig. 2, and Fig. 3 showed that the pollutant concentrations of the 4 room types in No. 1 house were lower than those of the same room types in other apartment units, because of the usage of diverse decorating materials. Conversely, rooms in No. 3 house showed the highest pollution levels because of the usage of diverse decorating materials. Similar decorating materials were used in the rooms in No. 3 and No. 4, but the pollution levels of No. 4 house were lower than those of No. 3 house, which could be attributed to the excellent ventilation of No. 4. All rooms of the same size and with decorating materials possessed a similar variation for the indoor formaldehyde and VOCs concentrations.

Formaldehyde and TVOC Concentrations in 200 Rooms: A Further Investigation on the Effect of Decorating Materials

As mentioned above, wallpaper, wooden floor and furniture were the main sources of formaldehyde and VOCs. To verify this, formaldehyde and TVOC concentrations were measured in 200 other rooms with different decorating materials. These rooms were decorated within 2 years. The TVOC concentration was referred to the summation of benzene, toluene, *o*-xylene, *p*-xylene, *n*-butyl acetate, ethylbenzene, styrene, and *n*-undecane concentrations. These rooms were sorted into 4 types by decorating materials: a: rooms with emulsion varnish, tile and solid wood composite board; b: rooms with wallpaper, tile and solid wood composite board; c: emulsion varnish, wood floor and solid reinforced composite board; and d: rooms with emulsion varnish, tile and solid wood composite board. As shown in Fig. 4, the formaldehyde concentration followed the sequence: b > c > d > a, while the TVOC concentration followed the sequence: c > b > a > d. This was in accordance with the above results.

The above results showed that the indoor formaldehyde and VOCs concentrations of rooms with wallpaper or wooden flooring exceeded those of the same room type with emulsion varnish or tiles, respectively. The introduction of furniture increased the indoor formaldehyde and VOCs concentrations significantly, especially for solid wood furniture. Formaldehyde was the most ubiquitous pollutant during the decorating process and was released mainly from the decorating materials, such as wall paint, furniture, and adhesives (Liu *et al.*, 2017). Moreover, formaldehyde was used widely to strengthen the plate hardness due to its strong adhesive properties (Huang *et al.*, 2016). Among the determined VOCs, toluene was most frequently detected during decorating, which could be attributed to its wide application in decorating materials, solvents, and household products. Our results also showed that decorating may induce a significant increase in indoor concentrations of xylene and ethylbenzene, which was in line with previous studies (Dai *et al.*, 2017).

In summary, indoor pollution sources played a dominant role over outdoor sources, with the bedroom contributing the highest pollution levels among the 4 monitored room types during decorating. Wallpaper, wooden floors, and wooden furniture were important indoor air pollutant sources. The concentration of the most common indoor VOCs decreased dramatically with time. Given this, we used 1-year data to determine human inhalation exposure levels, assuming that these levels would be stable for 5 years.

Exposure Risks

We investigated the health risks of indoor formaldehyde and VOCs in rooms 1 year after decorating. 6 quantified VOCs (benzene, toluene, *o*-xylene, *p*-xylene, styrene, and ethylbenzene) were selected to assess non-cancer effects. The concentrations of these selected VOCs were shown in Fig. 5. The average individual concentrations of formaldehyde

Table 3. Characteristics of decoration materials.

Site No.		Wall covering		Flooring		Furniture	
		Emulsion varnish	Wallpaper	Tile	Wood floor	Solid wood composite board	Solid reinforced composite board
No. 1	living room	√	-	√	-	√	-
	bedroom	√	-	√	-	√	-
	kitchen	√	-	√	-	-	√
	bathroom	√	-	√	-	-	√
No. 2	living room	-	√	-	√	√	-
	bedroom	√	-	-	√	√	-
	kitchen	√	-	√	-	√	-
	bathroom	√	-	√	-	√	-
No. 3	living room	-	√	-	√	-	√
	bedroom	-	√	-	√	-	√
	kitchen	√	-	√	-	-	√
	bathroom	√	-	√	-	-	√
No. 4	living room	-	√	-	√	-	√
	bedroom	-	√	-	√	-	√
	kitchen	√	-	√	-	-	√
	bathroom	√	-	√	-	-	√

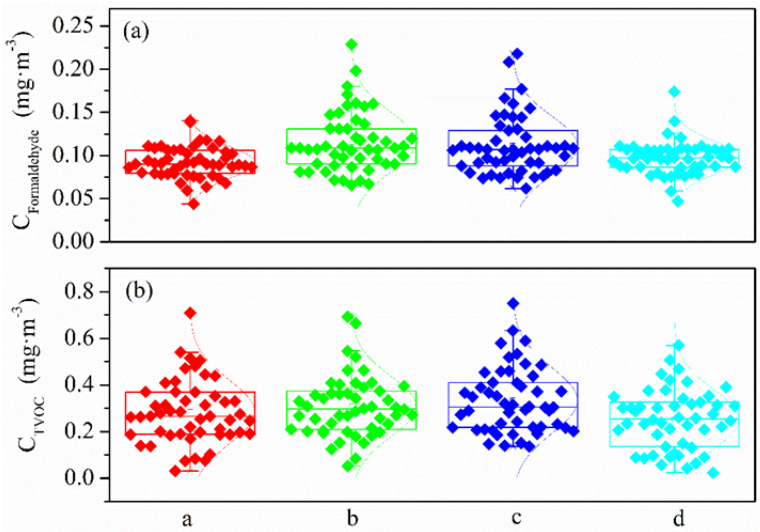

Fig. 4. (a) Formaldehyde and (b) TVOC concentrations in rooms with different decorating materials (a: rooms with emulsion varnish, tile and solid wood composite board; b: rooms with wallpaper, tile and solid wood composite board; c: emulsion varnish, wood floor and solid reinforced composite board; d: rooms with emulsion varnish, tile and solid wood composite board).

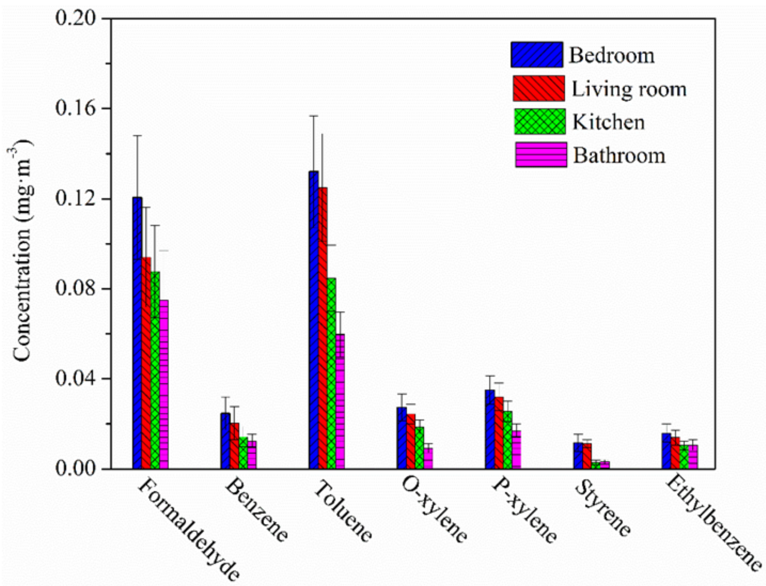

Fig. 5. Concentration of VOCs in rooms 1 year after decoration.

and these 6 VOCs ranged from 0.003 mg m^{-3} for styrene to 0.13 mg m^{-3} for toluene. The average concentration of formaldehyde in the living room exceeded the limit specified by national standard GB/T 18883-2002, whereas those in other 3 room types were lower than the limit. The average concentrations of the selected VOCs were lower than the limit specified by national standard GB/T 18883-2002. The results of the non-cancer effects were displayed in Fig. 6. The results showed that all the HQ and HI of the formaldehyde and VOCs were far less than the threshold (HQ = 1, HI = 1) (He *et al.*, 2015; Bu *et al.*, 2016), which indicated that the correction between the non-cancer risk and formaldehyde and the selected VOCs was negligible. The HQ and HI of formaldehyde and the selected VOCs in the bedroom were higher than those in the living room. The HQ and HI of formaldehyde and the selected VOCs were highest for children, followed by women and men. The maximum HI with a value of 0.15 was obtained for children in the bedroom and revealed that children were more susceptible than adults in the same environment.

This study also evaluated the CR that was associated with 3 selected VOCs (benzene, styrene, and ethylbenzene) for newly decorated apartment units 1 year after decoration. As shown in Table 4, the CR value of the selected VOCs in newly decorated apartment units varied as bedroom > living room > kitchen > bathroom. All styrene cancer risk values were lower than the acceptable risk level of 1 × 10^{-6} (proposed by the U.S. EPA), which indicated the unlikely

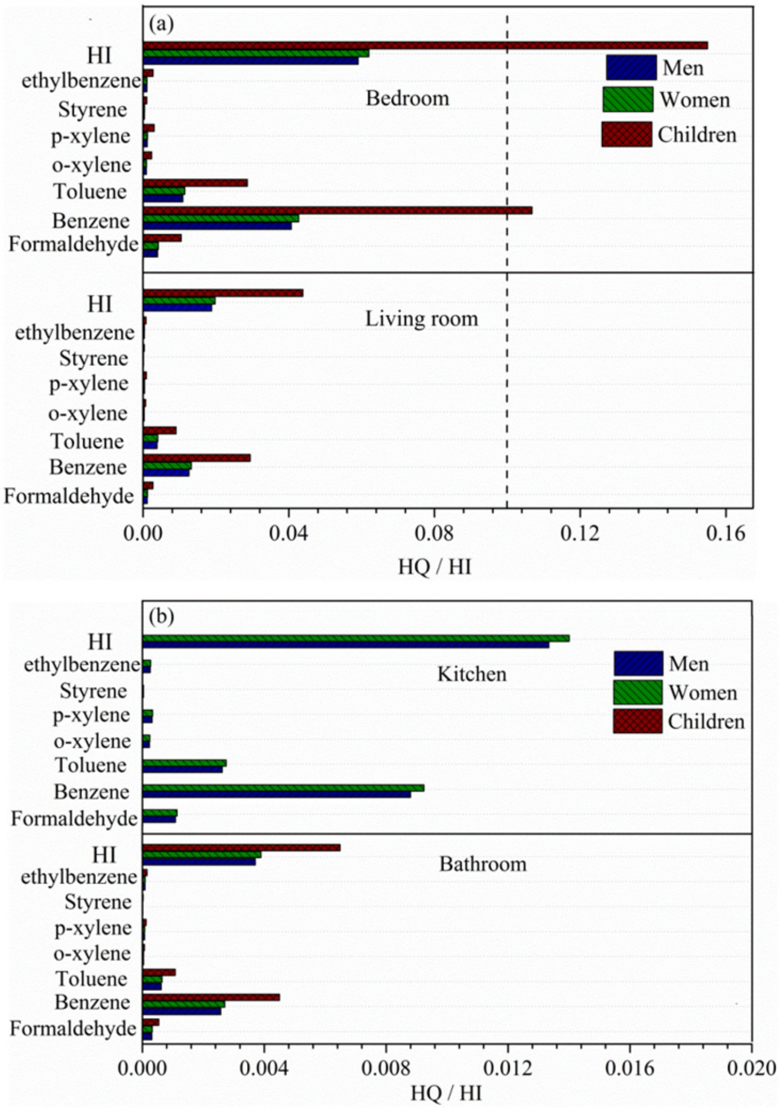

Fig. 6. Indoor VOC non-cancer hazard indexes for the residents in (a) living room and bedroom and (b) kitchen and bathroom.

Table 4. Risk cancer assessment of men, women and children.

VOCs		Men			Women			children		
		benzenze	styrene	ethylbenzene	benzenze	styrene	ethylbenzene	benzenze	styrene	ethylbenzene
Risk ($\times 10^{-6}$)	Bedroom	8.95	0.26	0.91	9.40	0.28	0.96	23.49	0.70	2.39
	Living room	2.77	0.10	0.30	2.91	0.10	0.31	6.46	0.23	0.70
	kitchen	1.94	0.02	0.22	2.03	0.03	0.24	-	-	-
	bathroom	0.57	0	0.08	0.60	0.01	0.098	0.99	0.02	0.13

association with harmful health risks. The CR value of partial ethylbenzene exceeded 1×10^{-6}, but was less than 1×10^{-5}, which indicated a probable cancer risk. All benzene cancer risk values exceeded 1×10^{-6}, from 0.57×10^{-6} to 2.35×10^{-5}. The results demonstrated that children were more vulnerable to indoor VOCs than adults. The CR caused by benzene exposure for children in the bedroom was 2.35×10^{-5}, which was approximately 23 times greater than 1×10^{-6}. Thus, indoor benzene contamination was a serious threat to human health, especially for children.

CONCLUSIONS

Indoor air pollution, which poses a significant threat to human health, has become a serious topic because of the increasing variety in decorating materials. We investigated the characteristics of $PM_{2.5}$, formaldehyde, and 8 selected VOCs in 6 newly decorated apartment units during the decorating process in Xi'an, China; our results provide a health risk assessment of formaldehyde and partial VOCs in the bedroom, living room, kitchen, and bathroom 1 year after decorating for both children and adults. Whereas indoor $PM_{2.5}$ mostly originated outdoors, indoor formaldehyde and VOCs originated primarily in the decorating materials. The formaldehyde and VOC concentrations decreased in the order of bedroom > living room > kitchen > bathroom, mainly due to using different decorating materials, and were strongly related, in particular, to wallpaper, wooden flooring, and wooden furniture. This conclusion was further verified by sampling data for formaldehyde and VOC concentrations measured in 200 other rooms decorated within 2 years in Xi'an. The highest HI of the indoor formaldehyde and VOCs in the monitored rooms was obtained in the bedroom, followed by the living room, kitchen, and bathroom. The cancer risk assessment showed that benzene, with a CR of 2.35×10^{-5}, was the most harmful pollutant among the monitored VOCs.

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