Assessment of exposure of children swimmers to trihalomethanes in an indoor swimming pool

Xiaoshuang Wang and Shaoxia Dong

ABSTRACT

This study aimed to understand the exposure levels of trihalomethanes (THMs) in an indoor swimming pool and calculate the risks of exposure to THMs, based on the presence of each THM species, of children swimmers aged 6–17, in Beijing, China. We obtained exposure factors for the children through questionnaires and measured THM concentrations through laboratory tests, and we combined the results with an exposure model to calculate the risks, with consideration of different exposure routes (oral ingestion, inhalation and dermal absorption). In terms of exposure factors for the swimmers aged 6–17, the average body weight, exposure duration, exposure frequency, swimming time, shower time, changing time, warm-up exercise and rest time, skin surface area and ingestion rate of pool water were 40.46 kg, 2.70 years, 96 events/year, 64.03 min/event, 17.04 min/event, 15.31 min/event, 12.71 min/event, 1.37 m^2 and 48.93 ml/event, respectively. The THM concentrations in swimming pool water, shower water, swimming pool air and locker room air were 67.17 μg/L, 12.64 μg/L, 358.66 $\mu g/m^3$ and 40.98 $\mu g/m^3$, respectively. The average cancer risk of THMs was 5.44×10^{-6}, which is an unacceptable risk according to the United State Environmental Protection Agency (USEPA) Guidelines. The average hazard index was 0.007, i.e., less than 1, indicating that the noncancer risk was acceptable. Chloroform (TCM) was the main substance in four species of THMs and inhalation exposure was the main exposure pathway. The risk of cancer and noncancer from inhalation exposure to THMs accounts for 97–99% of the total risk. As a result, the disease control authorities and administrative department should pay attention to the health and safety of swimming facilities and, at the same time, establish standards for THMs in the air through further research.

Key words | children, indoor swimming pool, risk assessment, THMs

Xiaoshuang Wang
Shaoxia Dong (corresponding author)
National Institute of Environmental Health,
Chinese Center for Disease Control and Prevention,
Beijing 100050,
China
E-mail: *dongshaoxia@nieh.chinacdc.cn*

HIGHLIGHTS

- Although many studies have conducted health risk assessments of adult exposure to THMs in China, few studies have reported the health risks of children exposure to THMs in swimming pools. This study is a health risk assessment of young swimmers aged 6–17 years.
- Most studies only considered the exposure of swimmers during swimming but did not consider the exposure to other behavioral patterns. This study not only considers the exposure of swimmers when swimming, but also when changing clothes, showering, doing warm-up exercises and resting.

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- The exposure factors in the health risk assessment model of many studies basically refer to the recommendations of the USEPA. Due to differences in regions, diet and living habits, the exposure factors vary widely among countries. There is a certain bias in the risk assessment of Chinese people based on USEPA exposure factors. This study determined the relevant exposure factors of young swimmers using a questionnaire survey.

INTRODUCTION

Swimming is praised as the best sport in the 21st century. With the development of society, swimming has gradually become a popular recreational fitness sport. Duan (Xiaoli 2013) shows that people prefer swimming in public swimming places, and indoor swimming pools are an important type of public swimming pool. There are many ways to disinfect indoor swimming pools. Chlorination is a common disinfection method for swimming pool water, and it is the most effective and lowest-cost method compared with others (Daizhi *et al.* 2016). However, while chlorine inactivates pathogens in swimming pools, it causes reactions with natural organic matter, bromide, iodide and human inputs (e.g., constituents of sweat and urine, skin particles, hair, microorganisms, cosmetics, and other personal care products), forming disinfection byproducts (DBPs) (Hrudey 2009). Though over 100 different DBPs have been identified thus far, the most commonly detected DBPs in chlorinated pool water are trihalomethanes (THMs), mainly including chloroform (TCM), bromoform (TBM), dibromochloromethane (DBCM) and bromodichloromethane (BDCM). THMs are present not only in the swimming pool water but also in the airspace above the pool water. Due to their volatility, THMs are the most likely to evaporate and persist in the air, especially indoors with no proper ventilation (Pándics *et al.* 2018). The World Health Organization (WHO) points out that indoor swimmers can be exposed to THMs mainly by three ways, including oral ingestion, dermal contact and inhalation pathway. Thus, in this study, THMs can be taken in by child swimmers through direct ingestion of pool water, dermal contact with the water, and inhalation of THMs volatilized into indoor air from chlorinated water.

Studies have showed that exposure to THMs could cause damage to health. Several epidemiologic studies have reported that populations exposed to THMs through ingestion exhibit elevated rates of bladder, colon, and rectal cancers (Hamidin *et al.* 2008; Lee *et al.* 2009; Villanueva *et al.* 2015). Animal experiments demonstrated that tumor formation of liver and kidney is associated with exposure to THMs (Ahmed *et al.* 2019). Romberg *et al.* (2017) found that detrimental effects on respiratory function (such as asthma) are also related to the inhalation of THMs. The International Agency for Research on Cancer (IARC) classified carcinogens into five levels based on the severity of carcinogenicity, which are Groups 1, 2A, 2B, 3, 4, and TCM, BDCM, DBCM, TBM were categorized as Groups 2B, 2B, 3 and 3 carcinogens, respectively. 2B indicates likely carcinogenesis, 3 indicates that carcinogenicity requires more experimental evidence. TCM is also listed as a reproductive toxicant. Therefore, people should pay attention to the health risk assessment of THMs in swimming venues. Health risk assessment is divided into carcinogenic and non-carcinogenic risk assessment. Among them, carcinogenic risk refers to the incidence of cancer that exceeds normal levels caused by exposure to carcinogens in a lifetime. The noncarcinogenic chronic toxicity of chemical pollutants in the swimming pool is generally measured relative to the reference dose (RfD). Exposure levels above the RfD may be dangerous. Exposure levels equal to or lower than the RfD are unlikely to be dangerous. As a susceptible population, children are more vulnerable to swimming-related health risks. Villanueva *et al.* (2015) showed that the longer a child swims, the greater the risk of asthma. Bernard *et al.* (2009) found that the longer the swimming time, the higher the risk of bronchiolitis among 6-year-old children. Pándics *et al.* (2018) reported that the cancer risk level of children aged 7–10 was 1.98×10^{-6} and that of children aged 11–14 was 1.19×10^{-6} in the swimming pool.

Paopuree *et al.* (2010) conducted a health risk assessment of children aged 6–12 years exposed to THMs during swimming, and showed the cancer risk was 1.98×10^{-4}. According to previous studies, the predicted health risks were higher than the USEPA regulatory limit of 10^{-6} in most cases. Thus, the health risks of children's exposure to THMs in the swimming pool should be a critical concern. However, in China, many studies focused on adults to do the health risk assessment of THMs exposure, but few studies reported the health risks of children exposed to THMs in swimming pools. Meanwhile, these adult studies only considered exposure to THMs during swimming, but did not consider exposure while changing clothes, showering, doing warm-up exercises and resting. In addition, in these studies the exposure factors adopted in the health risk assessment model mainly refer to the recommendation of the USEPA. While due to differences in geographic regions, diet and living habits, the exposure factors vary widely among countries. So for Chinese people there is a certain bias in the risk assessment based on USEPA exposure factors. Therefore, this study aims to do some preliminary work on the relevant exposure factors of children swimmers and then make the health risk assessment of THMs exposure. A questionnaire survey was carried out to obtain the exposure factors of children in one indoor swimming pool, and THMs concentrations in swimming pool water and in the surrounding air were collected and analyzed. Then the THMs exposure level of children via different pathways were estimated. Finally, cancer risk and noncarcinogenic risk were evaluated.

MATERIALS AND METHODS

Questionnaire

A questionnaire survey was conducted through face-to-face interviews at an indoor swimming pool in Beijing, China, from July to August 2019. The survey method can make the questionnaire results more accurate, improve the quality of the questionnaire results, and the survey time can be more flexible. In the face-to-face questionnaire survey, it is required to be in a relatively quiet and comfortable environment as far as possible, and to avoid the presence of unrelated personnel, otherwise the research subject may cause relevant interference factors when answering the question. A total of 402 amateur swimmers aged 6–17 years old who were local permanent residents (i.e., lived in the local area for half a year or more) were selected by random sampling to be subjects in this study. All subjects participated voluntarily and signed the informed consent form, in which younger children signed the informed consent form by their guardians.

The exposure factors involved in the questionnaire mainly included physiological factors, behavioral mode factors, and intake rate factors. The physiological factors include height, weight, age, and sex. Behavior mode factors include swimming duration, swimming frequency, swimming exercise time, shower time and changing time, warm up exercise time. Intake rate factors include ingestion rate of pool water.

This study was submitted for ethical review to the Ethical Review Committee, and approval was obtained (approval notice number 2019018). Meanwhile, all of the respondents signed the informed consent form before the start of the survey.

Sampling and analysis

Sampling and questionnaires were conducted simultaneously. The water sample collection includes pool water and shower water. The air sample collection includes the air in the rest area around the pool and the air in the locker rooms. The sampling locations, which were disinfected by sodium hypochlorite, were the same as those where the questionnaire survey was administered. Sampling of THMs in the pool water and air was performed eight times, independently, twice a week from July to August 2019. All of the sampling was conducted in the evening when the number of swimmers was usually the greatest for the day (Xiaolu *et al.* 2015).

The detection of THMs in swimming pool water is carried out in accordance with the *Standard Test Method for Drinking Water (GB5750-2006)*. Samples were collected from deep and shallow areas of the swimming pool, and care was taken to collect samples from the central part of each area to avoid the hydraulically stagnant zone, and then to collect male and female shower water samples.

The vials were treated with 0.2–0.5 g ascorbic acid to quench residual chlorine reactions after sampling. The vials or bottles were filled to the top, tightly sealed with screw caps with Teflon lined septa and sent back to the laboratory at 4 °C within a couple of hours. Water samples were analyzed using an automatic purge and trap system coupled to a gas chromatography–electron capture detector (GC–ECD) (Agilent 7890A, USA).

The detection of THMs in the air was performed in accordance with the *Activated Carbon Adsorption-Carbon Disulfide Desorption/Gas Chromatography (HJ 645-2013)*. Swimming pool air and locker room air were pumped through activated adsorbent tubes at a flow rate of 0.2 L/min for 50 min (total of 10 L). The inlet of the air samplers was placed at a distance of 0.5 m from the edge of the pool and locker room at a height of 1.5 m above the water level (Xiaolu *et al.* 2015). THMs were analyzed using an automatic purge and trap system coupled to a gas chromatography–mass spectrometer (GC–MS) (Agilent 7890A-5975C, USA).

Statistical analysis

The data obtained from the questionnaire were entered into an Epidata 3.1 (The Epidata Association, Odense, Denmark) database using the double entry method and logic checks. Data was cleaned and organized using Excel (Version 2007 Microsoft, Redmond, WA, USA), and statistical analysis was performed using the software package SPSS Statistics for Windows, version 21 (IBM Corp., Armonk, NY, USA). Measurement data are expressed by median (M) and range value (R). Counted data are expressed by number of cases (n) and composition ratio (%). The comparison of different genders and age groups uses the rank sum test, and the correlation analysis between different exposure factors uses the Spearman correlation analysis. Independent t-tests were used to compare the THMs concentration of water and air in male and female shower rooms and locker rooms. $P < 0.05$ was considered significant.

Exposure assessment

Based on the exposure factors and THM data collected in this study, an exposure assessment was conducted to evaluate the potential THM uptake via oral ingestion, inhalation, and dermal absorption. The equations for calculating the chronic daily intakes are shown below.

Oral ingestion pathway

According to the USEPA recommended model (USEPA 2009), the equation for estimating the exposure via direct oral ingestion from swimming pool water is as follows:

$$CDI_{oral} = \frac{CW_{sw} \times IR \times ED \times EF}{AT \times BW} \quad (1)$$

where:

CDI_{oral}: the chronic daily dose through ingestion of swimming pool water (mg/kg/day);
CW_{sw}: THM concentration in swimming pool water (mg/L);
IR: ingestion rate of swimming pool water (L/event);
ED: exposure duration, ED means how many years the swimmer has been swimming and was obtained from the questionnaire in this study (years);
EF: exposure frequency (event/year);
BW: body weight (kg);
AT: averaging lifetime (years), refer to Chinese Population Exposure Factors Handbook (Adult Volume), and the value is 70 years (Zhao & Duan 2014).

Dermal contact pathway

The exposure of swimmers to THMs through dermal contact absorption can be divided into two parts. One is the dermal contact absorption of THMs while swimming. The other is the dermal contact absorption of THMs while taking a shower. Hence, the equation for estimating the exposure via dermal contact absorption is as follows:

$$CDI_{der1} = \frac{CW_{sw} \times KP \times ET_{sw} \times ED \times EF \times SA}{\mathrm{AT} \times \mathrm{BW}} \quad (2)$$

$$CDI_{der2} = \frac{CW_{sh} \times KP \times ET_{sh} \times ED \times EF \times SA}{AT \times BW} \quad (3)$$

$$CDI_{der} = CDI_{der1} + CDI_{der2} \quad (4)$$

where:

CDI_{der1}: chronic daily dose through dermal contact while swimming (mg/kg/day);
CDI_{der2}: chronic daily dose through dermal contact while showering (mg/kg/day);
CDI_{der}: total chronic daily dose through dermal contact (mg/kg/day);
CW_{sh}: THM concentration in shower water (mg/L);
Kp: Penetration coefficient of THMs (cm/h), refers to the risk assessment information system (RAIS); the Kp of TCM, TBM, BDCM, and DBCM are 0.0089, 0.0026, 0.0058, and 0.0039 cm/h, respectively (USEPA 2009);
SA: skin surface area (cm^2), it was calcultated from BW and height;
ET_{sw}: exposure time for a swimmer while swimming (h/event);
ET_{sh}: exposure time for a swimmer while showering (h/event).

Inhalation pathway

The exposure of swimmers to THMs through inhalation can be divided into two parts. One is inhalation of THMs while swimming, warming up and resting. The other is inhalation of THMs while taking a shower and changing clothes. Hence, the equations for estimating the exposure by inhalation of THMs are as follows:

$$CDI_{inh1} = \frac{CW_{asw} \times EF \times ED \times (ET_{sw} + ET_{res})}{AT} \tag{5}$$

$$CDI_{inh2} = \frac{CW_{ch} \times EF \times ED \times (ET_{sh} + ET_{ch})}{AT} \tag{6}$$

$$CDI_{inh} = CDI_{inh1} + CDI_{inh2} \tag{7}$$

where:

CDI_{inh1}: the chronic daily dose through inhalation of THMs while swimming, warming up and resting (mg/m^3);
CDI_{inh2}: the chronic daily dose through inhalation of THMs while showering and changing clothes (mg/m^3);
CDI_{inh}: the total chronic daily dose through inhalation of THMs (mg/m^3);
CW_{asw}: THM concentrations in swimming pool air (mg/m^3);
CW_{ch}: THM concentrations in locker room air (mg/m^3);
ET_{ch}: exposure time for a swimmer while changing clothes (h/event);
ET_{res}: exposure time for a swimmer while warming up and resting (h/event).

Risk assessment

Lifetime cancer risk assessment

Carcinogenic risk refers to the incidence of cancer that exceeds normal levels caused by exposure to carcinogens in a lifetime. The lifetime cancer risk of different THM species is calculated by incorporating the exposure assessment and toxicity values (slope factors). In general, the lifetime cancer risk is calculated as:

$$R_{oral} = CDI_{oral} \times SF_{oral} \tag{8}$$

$$R_{der} = CDI_{der} \times SF_{der} \tag{9}$$

$$R_{inh} = CDI_{nh} \times SF_{inh} \tag{10}$$

where:

R_{oral}: lifetime cancer risk of THMs through direct ingestion;
R_{der}: lifetime cancer risk of THMs through dermal contact;
R_{inh}: lifetime cancer risk of THMs through inhalation;
SF_{oral}: slope factor for THMs through direct ingestion (kg·d)/mg);
SF_{der}: slope factor for THMs through dermal contact (kg·d)/mg);
SF_{inh}: slope factor for THMs through inhalation (m^3/mg). The slope factors for 4 THM species are shown in Table 1. SF refer to Risk Assessment Information System (RAIS) (RAIS 2005) and Integrated Risk Information System (IRIS) (IRIS 2005). IRIS belongs to USEPA and is a database of basic toxicity that chronically

Table 1 | Slope factors for 4 THM species for the risk calculation

THMs	SF_{oral}	SF_{der}	SF_{inh}
TCM	6.10×10^{-3} (IRIS)	3.05×10^{-2} (RAIS)	8.05×10^{-2} (IRIS)
BDCM	6.20×10^{-2} (IRIS)	6.33×10^{-2} (RAIS)	6.20×10^{-2}
DBCM	8.40×10^{-2} (IRIS)	1.40×10^{-1} (RAIS)	8.40×10^{-2}
TBM	7.90×10^{-2} (IRIS)	1.32×10^{-2} (RAIS)	3.85×10^{-3} (IRIS)

affects human health under long-term exposure. RAIS was established by the National Laboratory under the US Department of Energy, and is responsible for collecting and organizing data on the health hazards of chemical pollutants in various data sources.

Noncarcinogenic risk assessment

The noncarcinogenic chronic toxicity of chemical pollutants in the swimming pool is generally measured relative to the reference dose (RfD). Exposure levels above the RfD may be dangerous. Exposure levels equal to or lower than the RfD are unlikely to be dangerous. In general, the noncancer risk is calculated as:

$$HI_{oral} = CDI_{oral}/RfD \quad (11)$$

$$HI_{der} = CDI_{der}/RfD \quad (12)$$

$$HI_{inh} = CDI_{inh}/RfD \quad (13)$$

where:

HI_{oral}: hazard index for THM exposure through direct ingestion;
HI_{der}: hazard index for THM exposure through dermal contact;
HI_{inh}: hazard index for THM exposure through inhalation;
RfD: reference dose (mg/(kg·d)), the RfDs for TCM, TBM, BDCM, and DBCM are 0.01, 0.02, 0.02, 0.02 mg/kg/d, respectively (IRIS 2005).

RESULTS

Exposure factors in the risk assessment

A questionnaire survey was conducted among 402 swimmers aged 6–17 years at an indoor swimming pool in Beijing, China. Through the questionnaire, the exposure factors were determined; they included weight and the swimming exercise time, swimming frequency, swimming duration, shower time, warm-up and resting time, changing time and ingestion rate during swimming. SA was calculated by height and weight using the formula: $SA = 0.0305 \times H^{0.35129} \times BW^{0.5437}$. H means Height. Ingestion rate is greatly biased through questionnaires, especially at young age. Therefore, this article refers to the method of Laura *et al.* (2018) to obtain the parameter of ingestion rate in the questionnaire. The results of median IR value (40.50 mL) are close to those of Schets *et al.* (2011) (31–51 mL) and Evans *et al.* (2006) (37 mL). These exposure factors' average value were used in the exposure assessment in this study to avoid biases from other study data and make the final results more accurate. The results are shown in Table 2.

Concentrations of THMs

THM concentrations in water

Table 3 shows the concentration of THMs in swimming pool water and shower water. The source of the shower water at

Table 2 | Exposure factors used in the exposure assessment

		6–<9 years		9–<12 years		12–<15 years		15–<18 years	
Exposure factors	**Unit**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
BW	kg	26.45	25.91	36.87	33.88	53.38	48.02	70.02	53.65
SA	m^2	0.992	0.976	1.240	1.185	1.590	1.489	1.890	1.587
ET_{sw}	min/event	58.11	53.83	67.27	72.78	63.41	68.76	57.20	52.96
ET_{sh}	min/event	14.75	16.80	13.01	19.19	13.12	25.24	13.65	18.59
ET_{ch}	min/event	13.17	13.84	13.04	15.53	12.97	20.58	14.51	22.05
ET_{res}	min/event	14.24	14.33	11.43	10.50	9.71	13.62	12.64	20.85
ED	year	1.38	1.19	2.29	2.46	3.48	4.20	4.81	3.53
EF	events/year	96	60	96	108	108	60	96	60
IR	mL/event	48.93	49.94	52.76	49.04	48.04	52.11	36.44	43.36

Table 3 | THM concentrations in water samples (μg/L)

Water samples		TCM	BDCM	DBCM	TBM	TTHM
Swimming pool water	Median	65.22	0.42	0.06	1.64	67.17
	Range	9.3–159.68	0.18–0.56	0.034–0.13	0.23–3.85	10.43–161.53
Shower water (female)	Median	10.25	2.34	0.39	0.24	13.03
	Range	2.33–13.64	0.95–3.03	0.20–0.58	0.074–0.41	3.48–17.19
Shower water (male)	Median	11.65	2.55	0.37	0.10	12.25
	Range	2.10–14.76	0.75–3.18	0.27–0.47	0.066–0.11	3.20–17.30
P		0.78	0.42	0.08	0.21	0.39

the swimming pool in this study is tap water, and it is heated by a boiler and delivered to the shower room. The median concentrations of total THMs were 67.17 μg/L (range 10.43–161.53 μg/L), 13.03 μg/L (range 3.48–17.19 μg/L) and 12.25 μg/L (range 3.20–17.30 μg/L) in pool water, female shower water and male shower water, respectively. There was no significant difference in the concentration of THMs in male and female shower water ($P > 0.05$). The concentration difference of the four species of THMs was relatively large, and TCM was the most abundant THM, comprising more than 96% of the THMs in the investigated water. The median concentrations of TCM were 65.22 μg/L (range 9.3–159.68 μg/L), 10.25 μg/L (range 2.33–13.64 μg/L) and 11.65 μg/L (range 2.10–14.76 μg/L) in pool water, female shower water and male shower water, respectively.

THM concentrations in air

Table 4 shows the concentration of THMs in swimming pool air and locker room air. The median concentrations of total THMs were 358.66 μg/m^3 (range 276.56–531.29 μg/m^3), 40.98 μg/m^3 (range 29.92–52.05 μg/m^3) and 40.97 μg/m^3 (range 30.00–51.95 μg/m^3) in pool air, female and male locker room air, respectively. There was no significant difference in the concentration of THMs in male and female locker room air ($P > 0.05$). The concentration of THMs in swimming pool air is approximately 9 times higher than that of locker room air. DBCM and TBM were not detected in the air of male and female locker rooms. TCM was the most abundant THM, comprising more than 97% of the THMs in swimming pool air and more than 93% of the THMs in locker room air. The median concentrations of TCM were 348.06 μg/m^3 (range 269.60–516.22 μg/m^3), 38.32 μg/m^3 (range 27.31–49.34 μg/m^3) and 38.30 μg/m^3 (range 27.40–49.10 μg/m^3) in pool air, female and male locker room air, respectively.

Risk assessment of THMs

Lifetime cancer risk of THMs

Table 5 shows the cancer risk of THMs in different age groups and different exposure pathways. The risk from exposure to TCM through inhalation in children aged

Table 4 | THM concentrations in air samples (μg/m^3)

Air samples		TCM	BDCM	DBCM	TBM	TTHM
Swimming pool air	Median	348.06	6.77	0.58	7.87	358.66
	Range	269.60–516.22	6.06–7.40	0.55–0.61	0.0087–8.76	276.56–531.29
Locker room (female)	Median	38.32	2.66	N.D.	N.D.	40.98
	Range	27.31–49.34	1.61–3.72			29.92–52.05
Locker room (male)	Median	38.30	2.72	N.D.	N.D.	38.30
	Range	27.40–49.10	2.721.60–3.85			27.40–49.10
P		0.64	0.11	–	–	0.27

Table 5 | Lifetime cancer risk of THMs

Age	Exposure pathway	TCM	BDCM	DBCM	TBM	TTHM
6– < 9	Oral	3.15×10^{-9}	2.07×10^{-10}	3.97×10^{-11}	1.03×10^{-9}	4.42×10^{-9}
	Dermal	2.72×10^{-8}	5.74×10^{-10}	1.32×10^{-10}	8.54×10^{-11}	2.80×10^{-8}
	Inhalation	2.19×10^{-6}	3.49×10^{-8}	4.29×10^{-9}	2.33×10^{-9}	2.23×10^{-6}
	Total	2.22×10^{-6}	3.57×10^{-8}	4.46×10^{-9}	3.44×10^{-9}	2.26×10^{-6}
9– < 12	Oral	5.05×10^{-9}	3.32×10^{-10}	6.38×10^{-11}	1.64×10^{-9}	7.09×10^{-9}
	Dermal	6.50×10^{-8}	1.23×10^{-9}	2.81×10^{-10}	2.05×10^{-10}	6.68×10^{-8}
	Inhalation	4.53×10^{-6}	6.87×10^{-8}	8.57×10^{-9}	4.85×10^{-9}	4.61×10^{-6}
	Total	4.60×10^{-6}	7.02×10^{-8}	8.92×10^{-9}	6.70×10^{-9}	4.68×10^{-6}
12– < 15	Oral	5.45×10^{-9}	3.59×10^{-10}	6.89×10^{-11}	1.78×10^{-9}	7.66×10^{-9}
	Dermal	7.78×10^{-8}	1.67×10^{-9}	3.84×10^{-10}	2.44×10^{-10}	8.01×10^{-8}
	Inhalation	6.49×10^{-6}	1.06×10^{-7}	1.31×10^{-8}	6.87×10^{-9}	6.62×10^{-6}
	Total	6.58×10^{-6}	1.08×10^{-7}	1.36×10^{-8}	8.89×10^{-9}	6.71×10^{-6}
15– < 18	Oral	3.24×10^{-9}	2.11×10^{-10}	4.09×10^{-11}	1.06×10^{-9}	4.55×10^{-9}
	Dermal	6.47×10^{-8}	1.40×10^{-9}	3.21×10^{-10}	1.98×10^{-10}	6.66×10^{-8}
	Inhalation	7.88×10^{-6}	1.31×10^{-7}	1.52×10^{-8}	8.25×10^{-9}	8.04×10^{-6}
	Total	7.95×10^{-6}	1.33×10^{-7}	1.55×10^{-8}	9.50×10^{-9}	8.11×10^{-6}

6–<9, 9–<12, 12–<15 and 15–<18 years old was 2.19×10^{-6}, 4.53×10^{-6}, 6.49×10^{-6}, and 7.88×10^{-6}, respectively. They were all greater than 10^{-6}, which is an unacceptable risk according to the USEPA Guidelines. This result indicated that children aged 6–17 years have a certain cancer risk when exposed to TCM in indoor swimming pools. Table 5 also shows that the cancer risk from exposure to BDCM through inhalation for 12–<15 and 15–<18 years old was 1.06×10^{-7} and 1.31×10^{-7}, respectively. Although it is an acceptable risk according to the USEPA Guidelines, the risk was closer to 10^{-6} compare to other exposure pathways, which should be taken seriously. The cancer risks from exposure to DBCM and TBM for different age groups and different exposure pathways were significantly lower than 10^{-6}, which means the risks were acceptable and not obvious.

Among the four species of THMs, the order of contribution to the carcinogenic risk of 6–17 years old swimmers through oral ingestion was TCM (71.5%) > TBM (23.7%) > BDCM (4.6%) > DBCM (0.9%), and through dermal contact and inhalation were in the same order, that was TCM (97.7%) > BDCM (2.0%) > DBCM (0.5%) > TBM (0.3%). Among the three exposure pathways, the order of contribution to carcinogenic risk from exposure to THM was inhalation (98.7%) > dermal contact (1.2%) > oral ingestion (0.1%). The results revealed that the highest risk comes from exposure to THMs via inhalation, which also dominates the risk associated with THM exposure. It is obvious that TCM was the most risk THM, comprising more than 71% of THM exposure via oral ingestion and more than 97% of THM exposure via inhalation and dermal pathways. Among children aged 6–17 years old, the cancer risk of males was slightly higher than that of females ($P < 0.05$). In the different age groups, with increasing age, the cancer risk in children aged 6–17 years gradually increased, especially with inhalation.

Noncarcinogenic risk of THMs

Table 6 shows the HI from different exposure pathways to THMs in children aged 6–17 years old. It is clear from Table 6 that the HI of children swimmers were significantly less than 1. This means that the noncarcinogenic risk was acceptable according to the USEPA Guidelines. The highest risk comes from inhalation exposure to THMs, comprising more than 95% of the total noncarcinogenic risk, which is similar to the cancer risk assessment results. TCM was the most risk THM, comprising more than 97% of THMs in all exposure pathways.

DISCUSSION

From the above results, it can be concluded that the median concentration of total THMs was 348.06 μg/m^3 in the

Table 6 | Hazard index of THMs

Age	Exposure pathway	TCM	BDCM	DBCM	TBM	TTHM
6–<9	Oral	5.16×10^{-5}	1.67×10^{-7}	2.37×10^{-8}	6.50×10^{-7}	5.24×10^{-5}
	Dermal	8.92×10^{-5}	4.54×10^{-7}	4.71×10^{-8}	3.23×10^{-7}	9.00×10^{-5}
	Inhalation	2.72×10^{-3}	2.81×10^{-5}	2.55×10^{-6}	3.02×10^{-5}	2.78×10^{-3}
	Total	2.86×10^{-3}	2.88×10^{-5}	2.62×10^{-6}	3.12×10^{-5}	2.92×10^{-3}
9–<12	Oral	8.28×10^{-5}	2.68×10^{-7}	3.80×10^{-8}	1.04×10^{-6}	8.41×10^{-5}
	Dermal	2.13×10^{-4}	9.72×10^{-7}	1.00×10^{-7}	7.75×10^{-7}	2.15×10^{-4}
	Inhalation	5.62×10^{-3}	5.54×10^{-5}	5.10×10^{-6}	6.30×10^{-5}	5.75×10^{-3}
	Total	5.92×10^{-3}	5.66×10^{-5}	5.24×10^{-6}	6.49×10^{-5}	6.05×10^{-3}
12–<15	Oral	8.94×10^{-5}	2.90×10^{-7}	4.10×10^{-8}	1.13×10^{-6}	9.09×10^{-5}
	Dermal	2.55×10^{-4}	1.32×10^{-6}	1.37×10^{-7}	9.25×10^{-7}	2.58×10^{-4}
	Inhalation	8.07×10^{-3}	1.72×10^{-4}	1.56×10^{-5}	1.78×10^{-4}	8.43×10^{-3}
	Total	8.41×10^{-3}	1.73×10^{-4}	1.58×10^{-5}	1.80×10^{-4}	8.78×10^{-3}
15–<18	Oral	5.31×10^{-5}	1.70×10^{-7}	2.44×10^{-8}	6.70×10^{-7}	5.40×10^{-5}
	Dermal	2.12×10^{-4}	1.10×10^{-6}	1.15×10^{-7}	7.49×10^{-7}	2.14×10^{-4}
	Inhalation	9.79×10^{-3}	1.06×10^{-4}	9.03×10^{-6}	1.07×10^{-4}	1.00×10^{-2}
	Total	1.01×10^{-2}	1.07×10^{-4}	9.17×10^{-6}	1.09×10^{-4}	1.03×10^{-2}

surrounding air of an indoor swimming pool in Beijing, China. A comparison with the relevant data from other swimming pool air samples is carried out and shown in Table 7. The concentration of THMs in swimming pool air in this study is close to that of samples taken in Tianjin (Lu 2017) and Taiwan (Hsu *et al.* 2009). THM concentrations in indoor swimming pool air in this study are significantly higher than those reported from Canada (Silva *et al.* 2012), Portugal (Cristina *et al.* 2010) and Italy (Hang *et al.* 2016), especially TCM. However, the concentrations of other species of THMs in the Canadian study (Silva *et al.* 2012), such as BDCM, DBCM and TBM, were higher than those in this study. This may be because the Canadian study tested THMs in 41 swimming pools, which were disinfected differently and some had poor ventilation.

The median concentration in swimming pool water was 67.17 μg/L. A comparison with the relevant data from other swimming pool samples was carried out, and the results are shown in Table 8. Compared with the historical level reported in the literature for Beijing, the results are relatively close (Xiaolu *et al.* 2015). The concentrations of THMs in swimming pool water from this study are lower than those of samples taken in Tianjin and Nanjing (Hang *et al.* 2016; Lu 2017). THM concentrations in this study are at a medium level, slightly higher than those in Canada (Tardif *et al.* 2016), Germany (Peng *et al.* 2016) and Italy (Righi *et al.* 2014) and significantly lower than those in America (Afifi & Blatchley 2015), Portugal (Maia *et al.* 2014), which may be related to the different health standards in each country (Lu 2017).

Most countries or organizations regulate THMs in swimming pool water: the Federation International de Nation Amateur (FINA) and Germany have the most stringent standards, setting the limit of THMs in swimming pool water to

Table 7 | THM concentrations in swimming pool air in other cities and countries (μg/m³)

City/country	Years	TCM	BDCM	DBCM	TBM	Reference
Beijing, China	2019	269.60–516.22	6.06–7.40	0.55–0.61	0.0087–8.76	This study
Taiwan, China	2009	494–743	–	–	–	Hsu *et al.* (2009)
Italy	2010	21–182	–	–	–	Cristina *et al.* (2010)
Portugal	2012	N.D.-373	–	–	–	Silva *et al.* (2012)
Canada	2016	20–320	1–155	N.D.-205	N.D.-103	Tardif *et al.* (2016)
Tianjin, China	2017	127–775	2.9–8.5	N.D.-1.5	N.D.-0.5	Lu (2017)

Table 8 | THM concentrations in swimming pool water in other cities/countries (μg/L)

City/country	Years	TCM	BDCM	DBCM	TBM	Reference
Beijing, China	2019	9.3–160	0.18–0.56	0.034–0.13	0.23–3.85	This study
Beijing, China	2015	33.8[a]	–	–	–	Xiaolu *et al.* (2015)
Tianjin, China	2017	203–445	2.2–7.8	0.1–0.6	N.D.	Lu (2017)
Nanjing, China	2016	46–467	14–256	N.D.-226	2–133	Hang *et al.* (2016)
Canada	2016	7–126	N.D.-30	N.D.-51	N.D.-46	Tardif *et al.* (2016)
Germany	2016	12–46	0.8–2	<0.5	<0.7	Peng *et al.* (2016)
America	2015	12–282	–	N.D.-10	1.41[a]	Afifi & Blatchley (2015)
Italy	2014	2.5–122	1.4–18	0.2–12	N.D.-4	Righi *et al.* (2014)
Portugal	2014	17–400	–	–	–	Maia *et al.* (2014)

[a]mean value.

20 μg/L (Lu 2017). China sets the limit of THMs in swimming pool water to 200 μg/L (Ministry of Health of the PRC 2019). In this study, the THMs in swimming pool water are no more than the Chinese standards. However, there are currently no standards for the concentration of THMs in the air around swimming pools. Nevertheless, the outcome showed that inhalation exposure to THMs is the main exposure pathway, accounting for 99% of the total cancer risk. This is because THMs is a highly volatile pollutant that volatilizes into the air and causes indoor air pollution in swimming pools. In addition, the swimming pool area in this study is 1,250 square meters, and the passenger flow is large. Meanwhile, the ventilation conditions also need to be improved, resulting in higher THMs concentrations in the air. The administrative department and disease control authorities need to detect and manage the effects of disinfection methods, ventilation conditions, customer activities and other factors on the THMs concentration in the air. It is extremely urgent to establish relevant standards for the concentration of THMs in the air in swimming venues. According to the results of the risk assessment in this study, controlling the concentration of THMs in the air around swimming pools to be below 1 μg/m^3, while EF, ED, ET_{res}, ET_{sh}, ET_{ch}, AT remain 96 event/year, 2.7 years, 12.71 min/event, 17.04 min/event, 15.31 min/event and 70 years (average value) and other factors, like ventilation condition and passenger volume, remain unchanged, can lead to cancer risks through inhalation from exposure to THMs below 10^{-6}. Pándics *et al.* (2018) suggested that when the concentration of THMs in the air around swimming pools is below 5 μg/m^3, the risk is within an acceptable range and is close to the results of this study. However, the average THMs concentration (358.66 μg/m^3) in the air of swimming pools in this study is still far from 1 μg/m^3, and there is currently no support from indoor swimming pool simulation or laboratory simulation results. At the same time, the swimming pool in this study has a large area, high passenger flow, and poor ventilation. The recommended value of THMs concentration in the air estimated by these factors may be too low.

A multiple-pathway assessment methodology was employed in this study. The cancer risk of boys and girls from exposure to THMs was 5.51×10^{-6} and 4.48×10^{-6}, respectively. The results indicated that the cancer risk of boys aged 6–17 years was slightly higher than that of girls ($P < 0.05$), which is similar to the Chen *et al.* study (Chen *et al.* 2011). The difference in risk between boys and girls may be because boys swim longer and swim more frequently than girls. With increasing age, the cancer risk of children aged 6–17 years gradually increased. This is because children's height and weight and swimming duration increase with age. The risks from exposure to TCM through inhalation in children aged 6–17 years were all greater than 10^{-6}, which is an unacceptable risk according to the USEPA Guidelines. This indicated that children aged 6–17 have a certain cancer risk when exposed to TCM through inhalation at indoor swimming pools. Unequivocally, the most important THM in terms of risk of exposure was TCM, and the main exposure pathway for child swimmers was through inhalation during swimming. However, at present, there is still controversy regarding the proportion of risks associated with different exposure pathways. Some studies (Wang *et al.* 2007; Lee *et al.* 2009; Chen *et al.* 2011) found that inhalation was the main exposure pathway for swimmers. Other studies (Chowdhury 2015; Espín-Pérez *et al.* 2018) reported that dermal absorption was the main exposure pathway. Dyck (2011) put forward a new viewpoint: the exposure pathway is related to age, and the main exposure pathway of children is through inhalation. With increasing age, the proportion of dermal absorption will gradually increase.

CONCLUSIONS

In this study, we found that the cancer risk in children swimmers increased with age, caused by an increasing in exposure factors such as body weight, exposure time and skin surface area. Therefore, accurate determination of exposure factors are important for health risk assessment. The research regarding exposure factors in swimming should be expanded upon to supplement the basic data in the exposure factors handbook.

This investigation further showed that the major exposure pathway for child swimmers was inhalation during swimming. It contributes to more than 97% of the total health risk. Hence, the risk of inhalation exposure while changing clothes, showering, doing preparatory activities and resting should also be included to make the risk assessment more comprehensive and complete. Conversely, the contribution through dermal absorption while showering is negligible.

Among the four species of THMs, TCM was the most abundant THM, comprising more than 96, 97 and 93% of THMs in swimming pool water, swimming pool air and locker room air, respectively, and leads to the greatest risk. The risks from exposure to TCM through inhalation in children aged 6–17 years were all greater than 10^{-6}, which is an unacceptable risk according to the USEPA Guidelines. This study showed that a decrease in the concentration of TCM to below 1 μg/m^3 in the swimming pool air can effectively reduce the risk of exposure to TCM through inhalation to within an acceptable level. Better management practices for the air at indoor swimming pools are necessary to reduce the risk to bathers' health. Therefore, the administrative departments and disease control authorities should pay attention to the hygiene and safety of swimming facilities and at the same time, establish standards for THMs in the air through further research.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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