

Cancer risk assessment from exposure to trihalomethanes in tap water and swimming pool water

PANYAKAPO Mallika^{1,*}, SOONTORNCHAI Sarisak², PAOPUREE Pongsri¹

1. Department of Environmental Science, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand. E-mail: mallika@su.ac.th

2. School of Health Science, Sukhothai Thammathirat Open University, Nonthaburi 11120, Thailand

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Abstract

We investigated the concentration of trihalomethanes (THMs) in tap water and swimming pool water in the area of the Nakhon Pathom Municipality during the period April 2005–March 2006. The concentrations of total THMs, chloroform, bromodichloromethane, dibromochloromethane and bromoform in tap water were 12.70–41.74, 6.72–29.19, 1.12–11.75, 0.63–3.55 and 0.08–3.40 $\mu\text{g/L}$, respectively, whereas those in swimming pool water were 26.15–65.09, 9.50–36.97, 8.90–18.01, 5.19–22.78 and ND–6.56 $\mu\text{g/L}$, respectively. It implied that the concentration of THMs in swimming pool water was higher than those in tap water, particularly, brominated-THMs. Both tap water and swimming pool water contained concentrations of total THMs below the standards of the World Health Organization (WHO), European Union (EU) and the United States Environmental Protection Agency (USEPA) phase I, but 1 out of 60 tap water samples and 60 out of 72 swimming pool water samples contained those over the Standard of the USEPA phase II. From the two cases of cancer risk assessment including Case I Non-Swimmer and Case II Swimmer, assessment of cancer risk of non-swimmers from exposure to THMs at the highest and the average concentrations was 4.43×10^{-5} and 2.19×10^{-5} , respectively, which can be classified as acceptable risk according to the Standard of USEPA. Assessment of cancer risk of swimmers from exposure to THMs at the highest and the average concentrations was 1.47×10^{-3} and 7.99×10^{-4} , respectively, which can be classified as unacceptable risk and needs to be improved. Risk of THMs exposure from swimming was 93.9%–94.2% of the total risk. Cancer risk of THMs concluded from various routes in descending order was: skin exposure while swimming, gastro-intestinal exposure from tap water intake, and skin exposure to tap water and gastro-intestinal exposure while swimming. Cancer risk from skin exposure while swimming was 94.18% of the total cancer risk.

Key words: tap water; swimming pool water; chlorination; trihalomethanes; cancer risk assessment

Introduction

Disinfection and occurrence of trihalomethanes

Chlorination is a common disinfection method for tap water and swimming pool water as it is the most effective and low-cost method compared with others. However, chlorination could generate various chlorine by-products which are potential carcinogens, especially halogenated organic by-products such as trihalomethanes (THMs), haloacetic acids (HAAs) and so on.

Halogenated organic by-products are generated from chemical reaction between organic matter in water and added chlorine. Factors affecting the reaction are: organic matter, pH, temperature, duration of exposure, and bromide ions. Bromide ions influence the types of THMs due to the substitution reaction of chlorine atoms by bromine atoms (USEPA, 1999).

The WHO (2000a) reported that the highest concentration of chlorine by-products was THMs followed by HAAs. THMs consist of four compounds: chloro-

form (CHCl_3), bromodichloromethane (CHCl_2Br), dibromochloromethane (CHClBr_2), and bromoform (CHBr_3). USEPA (1999) reported that these four THMs are human carcinogens, of which CHCl_3 , CHCl_2Br and CHBr_3 are carcinogen type B2 (human carcinogen) and CHClBr_2 is carcinogen type C (probable human carcinogen). Apart from that, these compounds could cause various hazards such as abortion or teratogenic babies, and children with asthma from inhaling THMs vapor through the respiratory tract (WHO, 2000a, 2000b).

Tap water contains organic matter only from raw water whereas swimming pool water contains that not only from the water but also from swimmers' bodies such as sweat, urine and compounds applied on the skin. These compounds are various nitrogenous organic compounds such as urea, ammonia and amino acids. Moreover, the water used in some swimming pools is from surface and groundwater. Two factors, organic matter in surface water and bromide ions in ground water, would synergistically generate more brominated-THMs (WHO, 2000b; Kim *et al.*, 2002; Judd and Bullock, 2003).

Nieuwenhuijsen (2002) reported that swimming pool

* Corresponding author. E-mail: mallika@su.ac.th.

water contained higher THMs than tap water. If swimmers were in a swimming pool for 1 h, they would be exposed to THMs at a level of 141 times higher than showering in tap water for 10 min. From a report of the WHO, CHCl_3 concentrations in the water of outdoor swimming pools in the US and Germany were 4–420 and 0.69–112 $\mu\text{g/L}$, respectively, whereas indoor swimming pools had a higher concentration (WHO, 2000b).

Additionally, various organizations have defined Maximum Contaminant Levels (MCLs) of these by-products in tap water, including MCLs of total THMs, to be not higher than 100 $\mu\text{g/L}$ (WHO and EU) and 80 $\mu\text{g/L}$ (USEPA phase I) and the Maximum Contaminant Levels Goal (MCLG) of total THMs to be not more than 40 $\mu\text{g/L}$ (USEPA phase II). However, there is no standard value of THMs for swimming pool water.

Risk assessment

USEPA (1989) has developed a method of risk assessment of hazardous compounds including 5 steps: data collection, toxicity assessment, exposure assessment, risk characterization and risk management. This risk assessment method could be applied for both carcinogens and non-carcinogens by assessing ingestion via the gastrointestinal tract, skin contact and inhalation (LaGrega *et al.*, 2001). This research focused on cancer risk only.

According to USEPA method (USEPA, 1989), THMs exposure to the body was assessed from the equations as shown in Table 1. In addition, USEPA (1989) has recommended various values for substitution in these formulas such as the average body weight of the adult of 70 kg and body surface of 1.69–1.94 m^2 . These constant values are for the US population but this research has applied Thai population data; for instance, average body weight of the adult of 55 kg and body surface of 1.72 m^2 , to these equations (Intranont, 2005).

The cancer risk of a certain compound and one route is calculated as follows:

$$\text{Risk} = \text{Intake} \times \text{Slope factor} \quad (1)$$

Total exposure risk of compounds and routes is calculated as follows:

$$\text{Total exposure risk} = \sum \text{Risk} \quad (2)$$

The critical factor for defining potential of cancer risk is the slope factor. The higher the slope factor, the higher the potential of cancer risk. The slope factor values of CHCl_3 , CHCl_2Br , CHClBr_2 and CHBr_3 are 0.0061, 0.062, 0.084

and 0.0079 (kg-d)/mg, respectively (USEPA, 2007). The slope factors of all brominated-THMs are higher than that of CHCl_3 implying that bromide ion in raw water would generate higher potential of carcinogenic by-products.

The objectives of this research were: (1) to investigate the concentration of four forms of THMs in tap water in the area of the Nakhon Pathom Municipality; (2) to investigate the concentration of four forms of THMs in a chlorinated swimming pool located in the Nakhon Pathom Municipality; and (3) to assess cancer risk from exposure to THMs through tap water intake and swimming.

1 Materials and methods

1.1 Sample collection

Tap water and swimming pool water were collected during the period April 2005– March 2006. The sampling methods followed the Standard Methods for the Examination of Water and Wastewater of APHA, AWWA and WEF (1998).

1.1.1 Tap water

Tap water was collected from the tap water distribution system at the water treatment plant of the Nakhon Pathom Municipality. Water samples were also collected along the pipeline to the municipality border. The sampling points were selected based on the direction of the main pipeline so that the samples could be collected directly from main pipeline, not from the minor one or the storage tank. Before sampling, tap water was discarded for 5 min to make sure that the water samples were collected from the main pipe, not the water remaining in the minor one.

1.1.2 Swimming pool water

Water samples were collected from one public swimming pool in the Nakhon Pathom Municipality where the raw water was a mix of tap water and groundwater in a ratio of 1:3. The water area of the swimming pool was divided into 2 parts at the center of the pool: the shallow side and the deep side. Swimming pool water was collected at the center of each side at the level of 30 cm, below the water surface as the average level of human body exposure. The samplings were done at 5:00 pm both on weekdays with fewer swimmers (about 20 swimmers) and at weekends with more swimmers (about 40 swimmers).

1.2 Data analysis

1.2.1 Analyzed parameters

The analyzed parameters were water pH, temperature,

Table 1 Examples of equations for calculation of body exposure to tap water and swimming pool water through various routes

Gastro-intestinal exposure from intake	$\text{CDI} = \frac{\text{CW} \times \text{IR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}}$
Gastro-intestinal exposure while swimming	$\text{CDI} = \frac{\text{CW} \times \text{CR} \times \text{ET} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}}$
Skin exposure while swimming	$\text{AD} = \frac{\text{CW} \times \text{SA} \times \text{PC} \times \text{EC} \times \text{EF} \times \text{ED} \times \text{CF}}{\text{BW} \times \text{AT}}$

Source: LaGrega *et al.* (2001) and USEPA (1989). AD: absorbed dose (mg/(kg-d)); AT: average time (d); BW: body weight (kg); CDI: chronic daily intake (mg/(kg-d)); CF: volumetric conversion factor for water (1 L/1000 cm^3); CR: contact rate (L/h); CW: chemical concentration in water (d/a, events/a); ED: exposure duration (year); EF: exposure frequency (d/a, events/year); ET: exposure time (h/d, h/event); IR: intake rate (L/d) or inhalation rate (m^3/h); PC: chemical-specific dermal permeability constant (cm/h); SA: skin surface area available for contact (cm^2).

total organic carbon (TOC), dissolved organic carbon (DOC), bromide ion, residual chlorine and THMs (in terms of CHCl_3 , CHCl_2Br , CHClBr_2 , and CHBr_3).

1.2.2 Analytical methods

Analytical methods of various parameters were in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA and WEF, 1998). Water pH and temperature were analyzed by Sartorius Model Professional Meter PP-50 (Sartorius, Goettingen, Germany). Residual chlorine was analyzed by iodometric titration. TOC and DOC were analyzed by TOC Analyzer, Tekmar-Dohrman Phoenix 8000 (Tekmar-Dohrman, Ohio, USA). TOC was analyzed for water samples without filtration, whereas DOC was analyzed after filtration through filter paper GF/C with a pore size of $0.45\ \mu\text{m}$. Bromide ion concentration was analyzed by Ion chromatograph, 761 Compact IC (Metrohm, Herisau, Switzerland). Concentrations of the four forms of THMs were analyzed by Head-space gas chromatograph and ECD detector, Autosystem XL (Perkin Elmer, Massachusetts, USA) with Supelco 241 35-U PTEtm-5 column, N_2 and He as carrier gas with a flow rate of $2\ \text{ml/min}$, injection temperature at 220°C , GC cycle time $10\ \text{min}$, oven temperature of 55°C and detector temperature of 300°C . The detection limits of CHCl_3 , CHCl_2Br , CHClBr_2 , and CHBr_3 were 0.03 , 0.05 , 0.05 and $0.07\ \mu\text{g/L}$, respectively. Recoveries of all four THMs determined in spiked samples at the concentrations 5 , 10 and $20\ \mu\text{g/L}$ were in the range of 96% – 104% .

2 Results and discussion

Analytical results are shown in Table 2.

2.1 Concentration of THMs in tap water

The concentrations of total THMs, CHCl_3 , CHCl_2Br , CHClBr_2 , and CHBr_3 in tap water were 12.70 – 41.74 , 6.72 – 29.19 , 1.12 – 11.75 , 0.63 – 3.55 and 0.08 – $3.40\ \mu\text{g/L}$, respectively (Table 2). The THMs with the highest concentration at all water sampling points and all times of sampling were CHCl_3 followed by CHCl_2Br . The distribution of total THMs concentrations in 60 tap water samples is illustrated in Fig.1. It can be seen that most of the concentrations were in the range of 15 – $20\ \mu\text{g/L}$

(21 samples) followed by 20 – $25\ \mu\text{g/L}$ (18 samples). The concentrations of all forms of THMs gradually increased in accordance with the distance from water treatment plant to the sampling point as shown in Fig.2. This might be due to the longer contact time between chlorine and organic matter in pipeline.

Seasonal variation of organic matter in raw water quality was found. After the raw water was treated, the variation of organic matter in filtrated water (the sampling point No. 2) was still found as shown in Fig.3. When the filtrated water was chlorinated, organic matter then reacted with chlorine and formed THMs. Fig.3 clearly shows that total THMs concentrations in chlorinated water (the sampling point No. 3) depends on TOC, DOC and UV-254.

2.2 Concentration of THMs in swimming pool water

The concentrations of total THMs, CHCl_3 , CHCl_2Br , CHClBr_2 , and CHBr_3 in swimming pool water were 26.15 – 65.09 , 9.50 – 36.97 , 8.90 – 18.01 , 5.19 – 22.78 , and ND – $6.56\ \mu\text{g/L}$, respectively. The distribution of total THMs concentrations in 72 swimming pool water samples

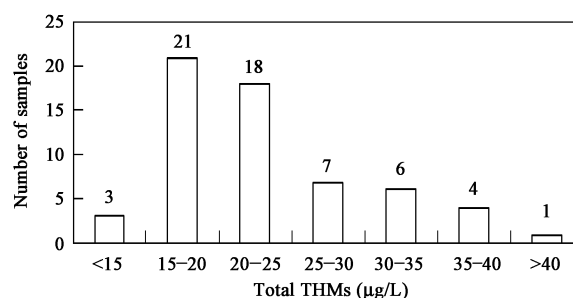


Fig. 1 Distribution of total THMs concentrations in tap water.

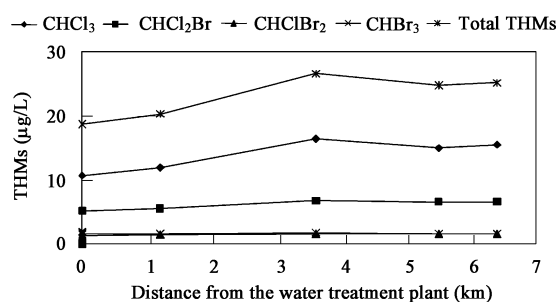


Fig. 2 THMs concentrations in tap water at various distances from water treatment plant.

Table 2 Analytical results of tap water and swimming pool water

Parameter	Tap water			Swimming pool water		
	Range	Average	SD	Range	Average	SD
pH	7.40–8.17	7.84	0.18	6.77–8.95	7.46	0.45
TOC (mg/L)	0.94–2.27	1.46	0.34	0.61–1.50	1.04	0.25
DOC (mg/L)	0.77–2.17	1.33	0.38	0.59–1.47	0.92	0.21
Residual chlorine (mg/L)	ND–0.90	0.40	0.21	ND–8.51	4.32	2.14
Bromide ion (mg/L)	ND–1.68	0.45	0.44	ND–3.90	2.22	1.11
CHCl_3 (μg/L)	6.72–29.19	13.92	4.96	9.50–36.97	20.32	6.67
CHCl_2Br (μg/L)	1.12–11.75	6.12	2.39	8.90–18.01	13.21	2.95
CHClBr_2 (μg/L)	0.63–3.55	1.48	0.71	5.19–22.78	10.22	5.01
CHBr_3 (μg/L)	0.08–3.40	1.64	0.95	ND–6.56	2.98	1.78
Total THMs* (μg/L)	12.70–41.74	23.13	6.63	26.15–65.09	46.72	8.16

* Total THMs calculated from the combination of CHCl_3 , CHCl_2Br , CHClBr_2 , and CHBr_3 concentrations.

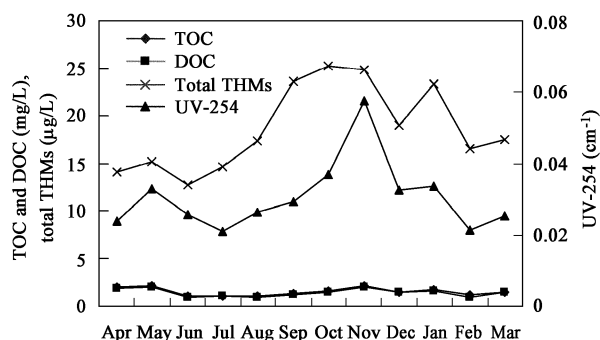


Fig. 3 Seasonal variation of organic matter (TOC, DOC and UV-254) in filtered water (the sampling point No. 2) and total THMs in chlorinated water (the sampling point No. 3).

is illustrated in Fig.4. It can be seen that most of the concentrations are in the range of 45–50 µg/L (36 samples) followed by 40–45 µg/L (12 samples). There was no difference between quality of the water samples collected at the shallow side and the deep side, and also between the water samples collected when there were fewer swimmers or more swimmers.

The concentrations of all THMs in swimming pool water were higher than those in tap water, particularly, brominated-THMs. The THMs with the highest concentration at all water sampling points and all times of water sampling were CHCl_3 followed by CHCl_2Br , which was similar to the results in tap water, except for a great concentration of CHClBr_2 as well.

Organic matter in swimming pool water was from various sources including raw water, swimmers' bodies and various compounds applied on the skin. However, it was found that the concentrations of TOC and DOC in swimming pool water were lower than those in tap water, as shown in Table 2. The swimming pool water was from a mix of tap water and groundwater in a ratio of 1:3. Generally, groundwater contains a lower concentration of organic matter than tap water. By mixing tap water with groundwater, the concentration of organic matter in the water from the swimming pool was thus lower than that in the tap water, although, the organic matter came from the swimmers as well.

The average concentration of bromide ions in the tap water and the swimming pool water was 0.45 and 2.22 mg/L, respectively. It was clearly found that the swimming pool water contained higher bromide ions than tap water owing to the mixing of tap water with groundwater. Groundwater contains high concentrations of bromide ion

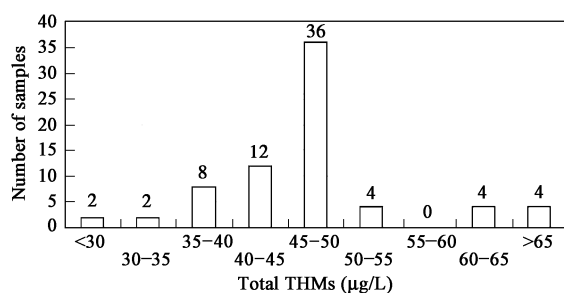


Fig. 4 Distribution of total THMs concentrations in swimming pool water.

which leads to the substitution of chlorine atoms in THMs by bromine atoms. This reaction generates a serious hazard as all brominated-THMs have a higher cancer risk than CHCl_3 , as detailed in Section 2.4.

Overflow water from the swimming pool was filtered through a fabric filter and then reused in the pool. Only suspended matter could be removed by filtration, whereas the dissolved ones such as DOC, bromide ions and residual chlorine remained in the water. Therefore, organic matter, bromide ions and chlorine could react with one another completely; consequently, the concentrations of THMs in the water were relatively high. Moreover, THMs were not removed by filtration, so they accumulated in the swimming pool water.

2.3 Comparison of total THMs concentration in water with the standard values

2.3.1 Tap water

The concentration of total THMs in tap water was in the range of 12.70–41.74 µg/L which is lower than MCLs of the WHO and EU Standards (100 µg/L) and the USEPA Standard phase I (80 µg/L). It implies that tap water containing THMs of the Nakhon Pathom Municipality was safe for intake. However, one water sample in October 2005 contained THMs higher than the MCLG of USEPA phase II (40 µg/L).

From reviewed literature, the concentration of total THMs in the tap water of Turkey, Malaysia, Hong Kong, Canada and Finland was 33–100, 18.59–89.83, 49.3–87.2, 5.1–141 and 11–129 µg/L, respectively (Uyak, 2006; Abdullah *et al.*, 2003; Rodriguez *et al.*, 2004; Nissinen *et al.*, 2002). It was found that total THMs concentration in the tap water of the Nakhon Pathom Municipality was in the same range or lower than that of the above-mentioned countries. Moreover, the concentration of total THMs in the tap water of some countries and in some seasons was higher than the standard values of the WHO, EU and USEPA.

2.3.2 Swimming pool water

As there is no swimming pool water standard for THMs, so the tap water standard was used instead. The concentration of total THMs in swimming pool water was in the range of 26.15–65.09 µg/L which is lower than the MCLs of the WHO, EU Standards and USEPA Standard phase I. It was interesting that 60 out of 72 water samples contained total THMs higher than the MCLG of USEPA Standard phase II. However, the concentrations of total THMs in this pool were lower than those of outdoor swimming pools in the US and Germany, which were 4–420 and 0.69–112 µg/L, respectively (WHO, 2000b).

2.4 Assessment of cancer risk from exposure to THMs in tap water and swimming pool water

This research focused on the assessment of the risk of cancer from exposure to THMs through four routes: (1) gastro-intestinal exposure from intake; (2) skin exposure while bathing/showering; (3) gastro-intestinal exposure while swimming; and (4) skin exposure while swimming.

Inhalation exposure while bathing/showering, as well as while swimming, is excluded as most buildings in Thailand have good ventilation. Consequently, THMs vapor indoor is dispersed so the THMs concentration in the air is expected to be low. This is much different from the western countries where most buildings are confined with the vapor of THMs, so the THMs concentration in the air might be higher. In this research, the swimming pool is an outdoor type, therefore, dispersion of the THMs vapor is high.

Risk assessment was calculated for two cases: Case I– non-swimmer and Case II– swimmer. The assessment was done for the highest concentration of each compound to estimate the highest risk and the average concentration, the risk in general conditions. Data of Thai population (Intranont, 2005) and USEPA Guidance (USEPA, 1989) were used to calculate chronic daily intake (CDI), absorbed dose (AD), total chronic daily intake (CDI_T) and cancer risk as shown in Section 1.2.

Case I: non-swimmer

Non-swimmers are exposed to THMs in tap water through two routes: the gastro-intestinal tract from intake and skin exposure while bathing/showering. Results of the risk assessment are shown in Table 3. It was found that cancer risks, calculated from the highest and the average concentrations of THMs, were 9.40×10^{-5} and 4.65×10^{-5} , respectively. According to USEPA Guidance (USEPA, 1989), if cancer risk is in the range of 10^{-4} – 10^{-6} , it is an

acceptable risk. Thus, this is a case of acceptable risk.

From reviewed literature, cancer risks of THMs intake from tap water in Turkey, Taiwan and Hong Kong were 1.18×10^{-4} , 1.80×10^{-4} and 1.99×10^{-5} , respectively (Uyak 2006; Hsu *et al.*, 2001; Lee *et al.*, 2004). Calculated from the average concentration as shown in Fig.5a, the percentage contributions to total cancer risk of $CHCl_2Br$, $CHClBr_2$, $CHCl_3$ and $CHBr_3$ were 62.87%, 21.27%, 13.61% and 2.25%, respectively. The compound with the highest concentration in tap water at all water sampling points and all times of water sampling was $CHCl_3$. The compound with the highest cancer risk was $CHCl_2Br$, followed by $CHClBr_2$ with slope factors of 0.062 and 0.084, respectively, whereas the slope factor of $CHCl_3$ was only 0.0061. It shows that bromide ions in raw water substitute chlorine atoms in $CHCl_3$ to become brominated-THMs, which are likely to cause more carcinogenesis.

From assessment of the exposure routes, the risk of cancer from exposure to THMs through gastro-intestinal exposure was high, up to 99.73%, whereas skin exposure was only 0.27%. This might be due to the shorter exposure duration of tap water to skin while bathing/showering.

Case II: swimmer

Swimmers are exposed to THMs in tap water from both intake and swimming. The results of risk assessment only from swimming are shown in Table 4. Cancer risk from swimming only was calculated from the highest and the

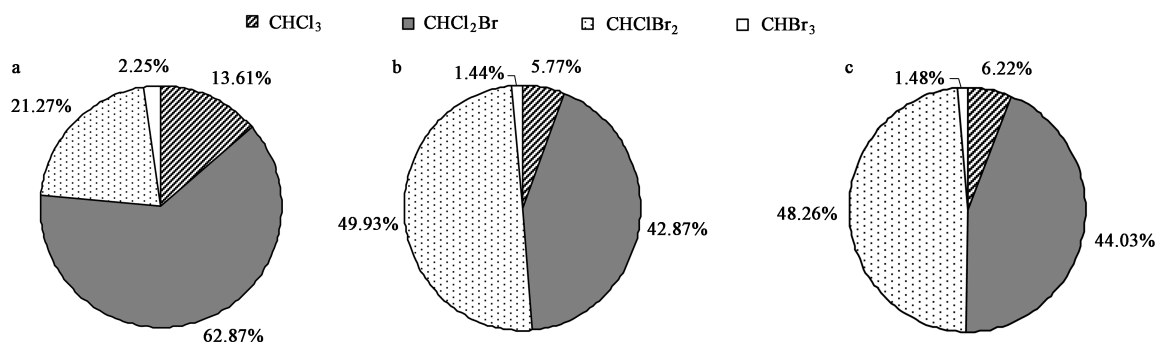


Fig. 5 Percentage contributions of cancer risk of THMs calculated from the average concentration in (a) tap water (b) swimming pool water and (c) tap water and swimming pool water.

Table 3 Cancer risk assessment of THMs in tap water

THMs	Concentration (µg/L)	CDI** (mg/(kg body weight-d))	AD** (mg/(kg body weight-d))	$CDI_T = CDI + AD$ (mg/(kg body weight-d))	Slope factor ((kg-d)/mg)	Cancer risk**
Assessment from the highest concentration						
$CHCl_3$	29.19	1.59×10^{-3}	5.84×10^{-4}	2.18×10^{-3}	0.0061	1.33×10^{-5}
$CHCl_2Br$	11.75	6.41×10^{-4}	2.65×10^{-4}	9.05×10^{-4}	0.062	5.61×10^{-5}
$CHClBr_2$	3.35	1.83×10^{-4}	8.38×10^{-5}	2.67×10^{-4}	0.084	2.24×10^{-5}
$CHBr_3$	3.40	1.85×10^{-4}	8.93×10^{-5}	2.75×10^{-4}	0.0079	2.17×10^{-6}
				Total risk		9.40×10^{-5}
Assessment from the average concentration*						
$CHCl_3$	13.92	7.59×10^{-4}	2.79×10^{-4}	1.04×10^{-3}	0.0061	6.33×10^{-6}
$CHCl_2Br$	6.12	3.34×10^{-4}	1.38×10^{-4}	4.72×10^{-4}	0.062	2.92×10^{-5}
$CHClBr_2$	1.48	8.07×10^{-5}	3.70×10^{-5}	1.18×10^{-4}	0.084	9.89×10^{-6}
$CHBr_3$	1.64	8.95×10^{-5}	4.31×10^{-5}	1.33×10^{-4}	0.0079	1.05×10^{-6}
				Total risk		4.65×10^{-5}

Data of Thailand different from USEPA are as follows: average population age = 64 years, average body weight = 55 kg, body surface area = 1.72 m^2 (Intranont, 2005) and amount of water intake = 3 L/(person-d) (Stuart *et al.*, 2001). * Average concentration from all water sampling points and all months; ** calculation by USEPA method.

Table 4 Cancer risk assessment of THMs in swimming pool water

THMs	Concentration (µg/L)	CDI** (mg/(kg body weight-d))	AD** (mg/(kg body weight-d))	CDI _T = CDI + AD (mg/(kg body weight-d))	Slope factor ((kg-d)/mg)	Cancer risk**
Assessment from the highest concentration						
CHCl ₃	36.97	6.45×10 ⁻⁷	1.29×10 ⁻²	1.29×10 ⁻²	0.0061	7.90×10 ⁻⁵
CHCl ₂ Br	18.01	3.14×10 ⁻⁷	7.10×10 ⁻³	7.10×10 ⁻³	0.062	4.40×10 ⁻⁴
CHClBr ₂	22.78	3.97×10 ⁻⁷	9.97×10 ⁻³	9.97×10 ⁻³	0.084	8.38×10 ⁻⁴
CHBr ₃	6.56	1.14×10 ⁻⁷	3.02×10 ⁻³	3.02×10 ⁻³	0.0079	2.38×10 ⁻⁵
				Total risk		1.38×10 ⁻³
Assessment from the average concentration*						
CHCl ₃	20.32	3.54×10 ⁻⁷	7.12×10 ⁻³	7.12×10 ⁻³	0.0061	4.34×10 ⁻⁵
CHCl ₂ Br	13.21	2.30×10 ⁻⁷	5.21×10 ⁻³	5.21×10 ⁻³	0.062	3.23×10 ⁻⁴
CHClBr ₂	10.22	1.78×10 ⁻⁷	4.47×10 ⁻³	4.47×10 ⁻³	0.084	3.76×10 ⁻⁴
CHBr ₃	2.98	5.20×10 ⁻⁸	1.37×10 ⁻³	1.37×10 ⁻³	0.0079	1.08×10 ⁻⁵
				Total risk		7.53×10 ⁻⁴

Data of Thailand different from USEPA are as follows: average population age = 64 years, average body weight = 55 kg, body surface area = 1.72 m² (Intranont, 2005) and amount of water intake = 3 L/(person-d) (Stuart *et al.*, 2001). * Average concentration from all water sampling points and all months; ** calculation by USEPA method.

Table 5 Total cancer risk of THMs from tap water intake and swimming*

	Tap water	Swimming pool	Total risk
Assessment from the highest concentration			
CHCl ₃	1.33×10 ⁻⁵	7.90×10 ⁻⁵	9.23×10 ⁻⁵
CHCl ₂ Br	5.61×10 ⁻⁵	4.40×10 ⁻⁴	4.96×10 ⁻⁴
CHClBr ₂	2.24×10 ⁻⁵	8.38×10 ⁻⁴	8.60×10 ⁻⁴
CHBr ₃	2.17×10 ⁻⁶	2.38×10 ⁻⁵	2.60×10 ⁻⁵
Total risk	9.40×10 ⁻⁵	1.38×10 ⁻³	1.47×10 ⁻³
Assessment from the average concentration			
CHCl ₃	6.33×10 ⁻⁶	4.34×10 ⁻⁵	4.97×10 ⁻⁵
CHCl ₂ Br	2.92×10 ⁻⁵	3.23×10 ⁻⁴	3.52×10 ⁻⁴
CHClBr ₂	9.89×10 ⁻⁶	3.76×10 ⁻⁴	3.86×10 ⁻⁴
CHBr ₃	1.05×10 ⁻⁶	1.08×10 ⁻⁵	1.19×10 ⁻⁵
Total risk	4.65×10 ⁻⁵	7.53×10 ⁻⁴	7.99×10 ⁻⁴

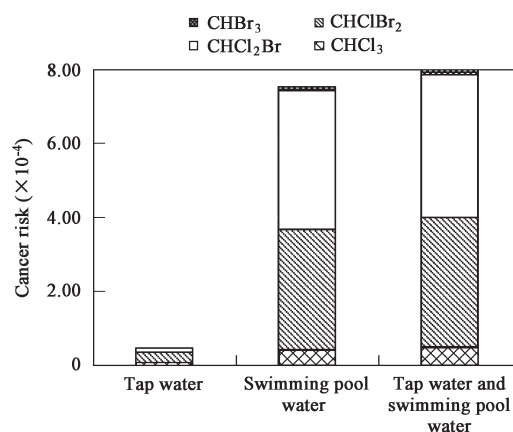
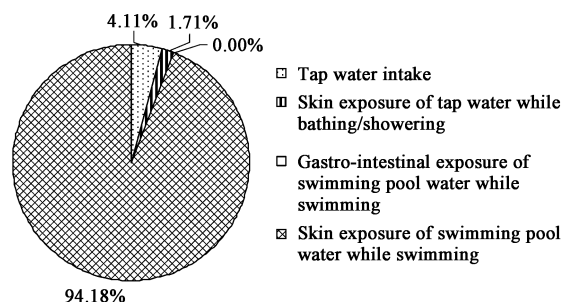
* Inhalation of THMs is excluded.

average concentrations of THMs, which were 1.38×10⁻³ and 7.53×10⁻⁴, respectively. The latter is an unacceptable risk as the USEPA Guidance (USEPA, 1989); therefore, this condition needs to be improved.

Additionally, total cancer risk from exposure to THMs from tap water intake and swimming is shown in Table 5 and Fig.6. Cancer risks, calculated from the highest and the average concentrations of THMs, were 1.47×10⁻³ and 7.99×10⁻⁴, respectively. It was found that the risk of cancer through THMs exposure from swimming was 93.9%–94.2% of the total risk, which was rather high. This might be due to the high concentrations of brominated-THMs generated from organic matter in tap water and bromide ions in groundwater. All brominated-THMs are highly potent carcinogens compared with chloroform.

From Fig.5b, percentage contributions of cancer risk from swimming pool concentrations of CHClBr₂, CHCl₂Br, CHCl₃ and CHBr₃ were 49.93%, 42.87%, 5.77% and 1.44%, respectively. The order of cancer risk of THMs in swimming pool water was different from that in tap water due to the bromide ion effect in groundwater, as mentioned above. Fig.5c shows percentages of total risk from both tap water and swimming pool water. It can be seen that the order of total cancer risk shown in Fig.5c is similar to that of swimming pool water in Fig.5b.

From the assessment of the exposure routes, as shown

**Fig. 6** Cancer risk of tap water and swimming water calculated from the average concentration.**Fig. 7** Percentage contributions of cancer risk of THMs from various routes.

in Fig.7, it was found that percentage contributions of cancer risk from the various routes of skin exposure while swimming, gastro-intestinal exposure from tap water intake, skin exposure while bathing/showering, and gastro-intestinal exposure while swimming were 94.18%, 4.11%, 1.71% and 0.0%, respectively. It implies that the main route is skin exposure while swimming.

2.5 Risk management

From the assessment, cancer risk from tap water intake was acceptable but cancer risk through contact with THMs from swimming pool water was unacceptable and the issue

needs to be addressed. One possible solution could avoid the mixing of tap water with groundwater since organic matter in tap water and bromide ion in ground water have a synergistic reaction, which generates brominated-THMs. Raw water for the swimming pool should be supplied from either tap water or groundwater.

Swimmers should clean their body properly and not apply skin compound before getting into the pool as organic matter from swimmers' bodies and skin compounds are also THMs precursors.

2.6 Uncertainty of risk assessment results

According to USEPA Guidance (USEPA, 1989) and this case study, the uncertainty of risk assessment was summarized as following:

The cancer risk assessment is lifetime cancer risk, therefore, it is possible that individually, exposure characteristics of THMs may change. For instance, sometimes swimmers are not exposed to tap water from the Nakhon Pathom Municipality but from other sources where the concentration of THMs is varied or they swim in other swimming pools which use different raw water leading to a different concentration of THMs.

USEPA (1989) recommends that risk assessment should be performed for the worst case. Therefore, this research assessed cancer risk from the highest concentration of contaminants, which was the worst situation, and additionally assessed from the average concentration as the general situation.

This method assessed risk from the toxicity of each compound and then combined all risks. Actually, the compounds might have either synergistic or antagonistic effects on one another.

Cancer risk assessment in this research was summarized from THMs only. But in the real situation, tap water and swimming pool water consist of many carcinogens, especially other chlorination by-products causing cancer such as haloacetic acids, haloketones and chlorophenols. Therefore, the total cancer risk should be higher than the values estimated in this paper due to the exposure to other carcinogens.

If there is not good ventilation in the buildings or swimming pool, it will cause more carcinogenesis from inhalation exposure to THMs.

3 Conclusions

This research was performed by collecting water samples and then analyzing the concentration of THMs in the tap water and swimming pool water of the Nakhon Pathom Municipality during the period April 2005–March 2006.

From the results of cancer risk assessment, it is necessary to reduce the risk in the swimming pool. The recommendations for risk management of the swimming pool include avoidance of mixing tap water with groundwater and a campaign for swimmers to clean their bodies and not apply skin compounds before entering the pool.

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