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Development of a multi-pathway probabilistic health risk assessment model for swimmers exposed to chloroform in indoor swimming pools

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ABSTRACT

For swimmers, exposure to chloroform, a probable carcinogen, in indoor swimming pools can be through different pathways such as ingestion, dermal absorption, inhalation during swimming, and inhalation during resting. In order to evaluate health risk results from excessive exposure to chloroform, concentrations of chloroform in pool water were first collected and analyzed. Then, a two-layer model is used, which is capable of estimating the concentrations of chloroform in the boundary layer adjacent to the water surface and the concentrations of chloroform in indoor swimming pool air. The use of stratification model is important for estimating the risks for swimmers since they are exposed to these kinds of situations while performing swimming and resting in indoor swimming pools environment. The incremental lifetime cancer risk (ILCR) was then estimated using the multi-pathway exposure model. The results showed that the 95th percentile of ILCRs calculated for male and female swimmers were 2.80×10^{-4} and 2.47×10^{-4}, respectively. The major exposure routes were found to be inhalation during swimming which contributes to more than 99% of the total health risk. Our study suggested that to protect swimmers from excessive exposure to chloroform, alternative methods or processes of disinfection should be considered for swimming pool managers.

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1. Introduction

Due to its relatively low cost and effectiveness against bulk water microorganisms, chlorination is a commonly used disinfection method for tap water and swimming pool water. During the chlorination processes, the formation of the disinfection byproducts (DBPs) can occur in water as a result of reactions between the disinfectant and the organic contaminants present in water [1]. The World Health Organization (WHO) reported that the most abundant components of DBPs were trihalomethans (THMs) followed by haloacetic acids (HAAs) [2]. Chloroform ($CHCl_3$) is the most abundant THM chemical that is present in treated waters [3,4].

Epidemiological studies have found that exposure to THMs could be associated with increased risks of bladder, colon/rectum and brain cancers [5–7]. Chloroform was classified as a class 2B carcinogen by the International Agency for Research on Cancer (IARC) based on evidences obtained from experimental animals. There was, however, insufficient epidemiological evidence to support the role of chloroform to threaten public health [8]. Other studies showed that exposure to THMs can cause reproductive health effects, including intrauterine growth retardation, low birth weight, preterm birth, congenital malformations, and stillbirth [9–11].

For swimmers, exposure to chloroform in indoor swimming pools can be through inhalation of chloroform volatilized into indoor air from chlorinated water, direct ingestion of pool water, and dermal contact with the water. Hence, concentrations of chloroform in pool water and in air of the swimming pool environment are two of the important variables determining the levels of chloroform exposure for swimmers. Previous studies suggested that concentrations of THMs in pool water were highly associated with the number of swimmers in pools, the chlorine dose, the bromide content, the extent of outgassing of volatile THMs, and the use of THMs-containing water for pool water supply [12–14]. The emission of chloroform from pool water into air in indoor swimming pools highly depends upon the environmental conditions (indoor airflow velocity, chloroform concentration in pool water, pool water temperature, indoor air temperature, and indoor airflow pattern) and the number of both swimmers and nonswimming visitors [3,14,15].

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Based on the real sceneries of indoor swimming pool environment, we have developed a mathematical model that considers the concentrations of chloroform in pool water, the relevant variables of environmental conditions, and the occupant activities to predict the chloroform concentrations in various air regions in indoor swimming pools [15]. In comparison with the field measurements and literature-derived data, the model generated a reliable prediction for the chloroform concentrations in indoor swimming pool air. This simulation model suggested that chloroform concentrations are significantly different in two kinds of indoor swimming pool airs. The first kind of air with very high concentration of chloroform is located in the boundary layer just overlaying the swimming pool water with a depth of several tens of centimeters. The second one with relatively low concentration of chloroform belongs to most of the indoor swimming pool air, outside the boundary layer over the water surface. Similar results were obtained from other studies which measured air concentrations of chloroform within the corresponding height above the swimming pool water surface [13]. Notably, while swimming, swimmers are inhaling the first kind of air with very high concentration of chloroform because the respiratory zone of the swimmers is consistent with the boundary layer. Conversely, while resting, swimmers are inhaling the second kind of air with relatively low concentration of chloroform. This implied that estimating the risk for a swimmer exposed to chloroform through inhalation should be divided into two parts, the one while the swimmer is swimming and the one while the swimmer is resting because the swimmer is exposing to completely different chloroform levels in the two situations. In this study, the risks for a swimmer exposed to chloroform through inhalation while swimming and resting are individually estimated, and the different concentrations of chloroform in the boundary layer and outside the boundary layer will be estimated using the method developed as described by Hsu et al. [15].

In the past, public sanitation or health risk assessment regarding the human exposed to THMs has been focused on the drinking water. Discussion and investigation of exposure of swimmers to the THMs and the related risk are limited. Additionally, the different risks of chloroform through inhalation while swimming and resting are not individually considered. Therefore, the purpose of this study is to use the simulation model that is capable of estimating the concentration of chloroform in the mentioned boundary layer and the average concentration in an indoor swimming air to undertake probabilistic risk assessment for swimmers exposure to chloroform. Since many studies have shown that concentration of chloroform in swimming pool water is the most abundant THM chemical species in pool water [3,4]. Therefore, this study used chloroform as an example to elucidate the risks for swimmers exposure to stratification of THMs layers in indoor swimming pool environment.

The chloroform concentrations in swimming pool water were first collected and analyzed. Concentrations of chloroform in the boundary layer and in indoor swimming pool air were simulated. Exposure to chloroform in indoor swimming pool for different pathways (ingestion, dermal absorption, inhalation during swimming, and inhalation during resting) were estimated. Finally, incremental lifetime cancer risk (ILCR) was then estimated. Monte Carlo simulation was applied to determine the propagation of uncertainty through the risk characterization process.

2. Methodology

2.1. Field sampling and laboratory analysis of chloroform in water

Swimming pool water samples were collected in a public indoor swimming pool in Kaohsiung, Taiwan. Sampling and analysis of chloroform in the pool water were performed eight times independently from November, 2007 to April, 2008. The sampling processes followed the drinking water sampling criteria for volatile organic compounds regulated by Taiwan Environmental Protection Agency. For each sampling, triplicate pool water samples were collected in volatile organic analysis vials from 20 cm below the water surface and sealed immediately with silicone-faced septa. The vials were treated with 25 mg ascorbic acid to quench residual chlorine reactions before sampling. Water samples were analyzed using an automatic purge and trap system (SOLATek72) coupled to a gas chromatography–mass spectrometry (GC–MS) (Agilent 6890N/Agilent 5973 Network). In addition to the field samples, quality control samples were collected and analyzed during laboratory analysis. The relative deviation of the quality control samples was within 20% and the recovery of laboratory control standards were between 90 and 110%.

During sampling, number of nonswimming visitors (N_w) and swimmers (N_s) in the swimming pool were counted. In addition, indoor airflow velocity, and temperature of air and of swimming pool water were measured and recorded.

2.2. Mathematical model for simulation of chloroform in indoor swimming pool air and in the respiratory zone of swimmers

The rate of chloroform volatilization from indoor swimming pool water to indoor air can be significantly influenced by environmental conditions, such as indoor airflow velocity, chloroform concentration in pool water, pool water temperature, indoor air temperature and indoor airflow patterns, as well as the level of occupant activities, such as the number of swimmers and nonswimming visitors [13,16]. For insight into the mechanisms of chloroform emission across the air–water interface and the complex interactions of mass-transfer processes among the above mentioned variables, a mathematical model of indoor swimming pools for chloroform release from pool water to air was developed in our previous work [15]. Moreover, considering of exposure in different breathing zones of swimmers and nonswimming visitors, the concept of stratification of chloroform layers in the presented model was, therefore, taken into account for use in exposure assessment in which the swimming pool indoor air was divided into two air compartments, i.e. the boundary layer concentration for swimmers and the vertical concentration of chloroform above the boundary layer for nonswimming visitors. Mass transfer of chloroform across the air–water interface was based upon the two-film theory in which the overall mass-transfer coefficient is the sum of two individual phase resistances, i.e. gas phase and liquid phase [17]. The gas-phase mass-transfer coefficient was calculated by coupling the concept of laminar boundary layer theory [18], while the liquid-phase mass-transfer coefficient was estimated using the eddy cell model for the mixing effects of swimmers [19] and the penetration theory associated with the dynamic effect of pool water surface wave enhanced turbulence in the mass transfer across the liquid–gas interface for pool water circulation [20]. Furthermore, a novel approach was first proposed to quantitatively describe the impact of occupant activities on air chloroform mixing levels in terms of the specific energy dissipation rates [15]. The intensity of occupant physical activities basically depends on the number of swimmers and nonswimming visitors.

A schematic of a typical indoor swimming pool is shown in Fig. 1. In summary, the resulting formulas of concentration boundary layer thickness (BLT), δ, gas-side boundary layer concentration (BLC) of chloroform, C_{BL}, and vertical concentration of chloroform above the boundary layer, C_{ave}, were developed by our previous

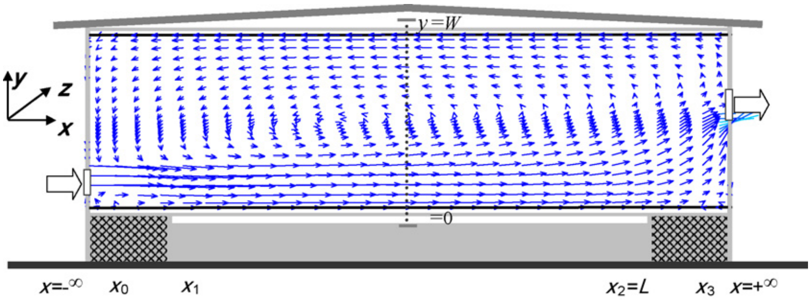

Fig. 1. Schematic diagram of a typical indoor swimming pool and the vector plot of indoor airflow pattern at x–y plane. The spatial domain of $x = \pm\infty$ means the outdoor area of indoor swimming pool. The regions from x_0 to x_1 and x_2 to x_3 represent the indoor swimming pool deck areas. The distance from x_1 to x_2, i.e. L, is the length of swimming pool. W is the room height above the pool water surface and $y = 0$ is set to be at the water/air interface.

work as follows [15]:

$$C_{\mathrm{BL}} = HC_w\left(1 - \frac{3}{2}\left(\frac{y}{\delta}\right) + \frac{1}{2}\left(\frac{y}{\delta}\right)^3\right) \quad (1)$$

$$\delta = 4.64(N_{Re,x})^{-1/2}(\mathrm{Sc})^{-1/3}(x) \quad (2)$$

$$C_{\mathrm{ave}} = J\left(\frac{1}{\mathrm{Pe}^2}\left(1 - e^{Pe\frac{x-L}{W}}\right) + \frac{1}{\mathrm{Pe}}\frac{x}{W}\right) + \left(\frac{R}{R+1}\right)C_{\mathrm{ave}}|_{x=x_3}, \quad (3)$$

where H is the Henry's constant of chloroform, C_w is the chloroform concentration in pool water, y is the vertical distance from the pool water surface, $N_{\mathrm{Re},x}$ is Reynolds number at a given position of the x-direction, Sc is Schmidt number, x represents a given position in the horizontal direction along the length of swimming pool, J is the mass flux of chloroform emitted from the pool water surface, Pe is the Péclet number, L and W are the length and width of indoor swimming pool, and R represents the indoor airflow recycle ratio reflected the indoor air-flow pattern. Thus, it is clear that the level of chloroform concentration in indoor swimming pool air can be eventually estimated using the three terms J_q, Pe, and R that cover all mentioned environmental conditions and occupant activities. By using Eqs. (1) and (3), one is able to estimate the concentrations of chloroform in the boundary layer ($0 < y < \delta$) as well as average concentrations of chloroform in the indoor swimming pool air.

The model agrees well with our own environmental measurements [15] and literature-derived data [13,21]. In this study, the presented model was, therefore, used to provide creditable supporting data of the air concentrations of chloroform (both in the boundary layer and outside the boundary layer) under the influence of environmental conditions and occupant activities for a further investigation in health-related risk assessment of people when attending indoor swimming pools.

2.3. Multi-pathway exposure assessment for swimmers

Based on the Guidelines for Safe Recreational Water Environments—Volume 2 [4], the exposure of swimmers to THMs in an indoor swimming pool environment is assumed to include three exposure pathways: direct ingestion of the water; inhalation of volatile or aerosolized solutes, as well as dermal contact and absorption through skin. We used Eqs. (4)–(7) to estimate the dose of stressor from the specific exposure route.

2.3.1. Direct ingestion of swimming pool water (CDI_{oral})

The equation for estimating the dose through direct ingestion of the swimming pool water is as follows:

$$CDI_{\mathrm{oral}} = \frac{C_w IR_{\mathrm{ing}} \alpha ET EF CF_1 ED}{BW AT}, \quad (4)$$

where CDI_{oral} is the chronic daily dose through ingestion of swimming pool water (mg/kg/day), C_w is chloroform concentration in water (μg/L), IR_{ing} is the ingestion rate of swimming pool water (L/h), α is defined as the time fraction of total exposure time for the swimmer to perform swimming (unitless), ET is the total exposure time for a swimmer in a considered indoor swimming pool (h/event), EF is the exposure frequency (event/month), ED is the exposure duration (years), BW is the body weight (kg) and AT is the averaging lifetime (days) and CF_1 is the unit conversion factor (1.2×10^{-2} mg-month/μg-year).

2.3.2. Inhalation of chloroform during swimming (CDI_{inhs})

Exposure of swimmers to chloroform through inhalation can be divided into two parts. One is inhalation of chloroform while performing swimming exercise. In this case, swimmers are exposed to very high concentrations of chloroform in the boundary layer above the swimming pool water surface. Hence, the equation for estimating the dose by inhalation of chloroform in the boundary layer is as follows:

$$CDI_{\mathrm{inhs}} = \frac{C_{\mathrm{BL}} IR_{\mathrm{inhs}} \alpha ET EF CF_1 ED}{BW AT}, \quad (5)$$

where CDI_{inhs} is the chronic daily dose through inhalation of chloroform in boundary layer (mg/kg/day), C_{BL} is the concentration of chloroform in the boundary layer (μg/m^3) and IR_{inhs} is the inhalation rate during swimming (m^3/h).

2.3.3. Inhalation of chloroform during resting (CDI_{inhr}) at the pool edge

The second type of inhalation exposure of chloroform is that people inhale ambient air from indoor swimming pool environment rather than boundary layer when taking a rest at the pool edge. In this case, we used the average concentrations of chloroform in the air of indoor swimming pool environment for estimation of the exposure levels. The equation for estimating the dose in this situation is as follows:

$$CDI_{\mathrm{inhr}} = \frac{C_{\mathrm{ave}} IR_{\mathrm{inhr}} (1-\alpha) ET EF CF_1 ED}{BW AT}, \quad (6)$$

where CDI_{inhr} is the chronic daily dose through inhalation of chloroform in ambient air of the indoor swimming pool (mg/kg/day), C_{ave} is the average concentration of chloroform in indoor swimming pool air (μg/m^3), IR_{inhr} is the inhalation rate during resting (m^3/h) and $1 - \alpha$ is the time fraction of total exposure time other than swimming in indoor swimming pools (unitless).

2.3.4. Dermal contact absorption (CDI_{dermal})

The equation for estimating the dose through dermal contact absorption of the swimming pool water is as follows:

$$CDI_{\mathrm{dermal}} = \frac{C_w SA K_p \alpha ET EF CF_2 ED}{BW AT}, \quad (7)$$

where CDI_{dermal} is the chronic daily dose through dermal contact of swimming pool water (mg/kg/day), SA is the skin surface area (m^2),

Table 1
Slope factors of chloroform for multi-pathway risk assessment.

Exposure route	Slope factor $(\text{mg/kg/day})^{-1}$
Oral (RAIS)	6.10×10^{-3}
Inhalation (RAIS)	8.05×10^{-2}
Dermal[a]	6.10×10^{-3}

RAIS: Risk Assessment Information System (USDOE) [22].
[a] To be assumed same as the value of oral exposure route.

K_p is the penetration coefficient of chloroform (m/h) and CF_2 is unit conversion factor (12 mg-L-month/μg-m^3-year). In this model, the absorption fraction of skin exposed to chloroform was assumed to be 100%.

2.4. Risk assessment for swimmers exposed to chloroform in indoor swimming pools

Based on the multi-exposure routes discussed above, the total incremental lifetime carcinogenic risk assessment was estimated using the following equation:

$$Risk_{\text{total}} = CDI_{\text{oral}}SF_{\text{oral}} + (CDI_{\text{inhs}}+CDI_{\text{inhr}})SF_{\text{inh}}+CDI_{\text{dermal}}SF_{\text{dermal}}, \tag{8}$$

where $Risk_{\text{total}}$ is the total incremental lifetime cancer risk (unitless), SF_{oral}, SF_{inh} and SF_{dermal} $((\text{mg/kg/day})^{-1})$ are the slope factors from the specific exposure route via oral, inhalation and dermal, respectively.

The slope factor of a specific route was taken from the Risk Assessment Information System (RAIS) sponsored by the U.S. Department of Energy (DOE), Office of Environmental Management [22]. We summarized the values in Table 1. Since the SF_{dermal} value of chloroform is not available in RAIS, the slope factor was estimated from SF_{oral} as suggested by Lee et al. [23].

2.5. Monte Carlo simulation

The variability and sensitivity analysis of the predictions of the risk assessment model was carried out by using the Monte Carlo simulation technique. Due to inherited natural variability, equation variables can be defined in terms of a probability density function derived from a limited number of observations. The software program Crystal Ball® (Version 7.3, Decisioneering, Inc., Denver, CO, USA) was used to analyze data and to estimate distribution parameters. The distribution type was selected based on statistical criteria. To explicitly account for this uncertainty/variability and its impact on the estimation of cancer risk and hazard index, a Monte Carlo simulation was adopted. To test the convergence and the stability of the numerical output, we performed independent runs at 1, 4, 5, and 10 thousand iterations with each parameter sampled independently from the appropriate distribution at the start of each replicate. The result shows that 5000 iterations are sufficient to ensure the stability of results. The result of Monte Carlo simulation provides a confidence interval (5th and 95th quartiles) of health risk for swimmers exposed to chloroform in indoor swimming pools.

Table 2 shows the selected types of probability distribution for random variables. These include the chloroform concentrations in water body, inhalation risk parameters including inhalation rate during swimming and resting, dermal risk parameters including dermal surface area as well as risk assessment model parameters such as body weight, exposure time and exposure frequency. Since the concentrations of chloroform in the boundary layer above the swimming pool surface and in indoor swimming pool air were derived from the input concentration of chloroform in swimming pool water, distributions of the concentrations of chloroform in these two areas were determined by the input of chloroform concentrations in pool water.

3. Results and discussions

3.1. Concentrations of chloroform in an indoor swimming pool environment

Fig. 2 shows the range of chloroform concentrations collected from eight different times of independent sampling in a public indoor swimming pool at Kaohsiung, Taiwan. The concentrations of chloroform in this swimming pool water ranged from 7.96 to

Table 2
Risk parameters considered as random variables for uncertainty analysis in this study.

Input parameters	Unit	Values	Distribution	Reference
Chloroform concentrations				
In swimming pool water (C_w)	μg/L	7.96–12.44 (9.81 ± 1.36)	Lognormal	This study
In the boundary layer (C_{BL})	μg/m^3	494–743 (609 ± 85)		This study
In indoor swimming pool ambient air (C_{ave})	μg/m^3	11.34–17.04(13.97 ± 1.94)		This study
Exposure factors				
Intake rate of swimming pool water while swimming (IR_{ing})	L/h	0.025		[24]
Inhalation rate during swimming for male ($IR_{\text{inhs-male}}$)	m^3/h	0.75		[25]
Inhalation rate during resting for male ($\text{IR}_{\text{inhr-male}}$)	m^3/h	0.40		[25]
Inhalation rate during swimming for female ($\text{IR}_{\text{inhs-female}}$)	m^3/h	0.51		[25]
Inhalation rate during resting for female ($IR_{\text{inhr-female}}$)	m^3/h	0.31		[25]
Exposure time (ET)	h/event	1.92 ± 1.73	Lognormal	[26]
Time fraction of total exposure time for the swimmer to perform swimming (α)	Unitless	0.5–0.95	Uniform	This study
Exposure frequency (EF)	event/month	7.36 ± 11.04	Lognormal	[26]
Exposure duration (ED)	yrs	30		
Body weight for male (BW_{male})	kg	69.5 ± 24.8	Lognormal	[25]
Body weight for female (BW_{female})	kg	57.9 ± 32.8	Lognormal	[25]
Skin surface area for male (SA_{male})	m^2	1.76 ± 0.26	Lognormal	[25]
Skin surface area for female (SA_{female})	m^2	1.54 ± 0.34	Lognormal	[25]
Average lifetime for male (AT)	days	73.5 × 365 = 26827.5		[25]
Average lifetime for female (AT)	days	79.7 × 365 = 29090.5		[25]
Other parameters				
Penetration coefficient of chloroform (K_{p})	m/h	8.92×10^{-5}		[22]
Number of nonswimming visitors (N_w)		17.2 ± 16.19	Normal	This study
Number of swimmers (N_s)		27.0 ± 16.69	Normal	This study
Temperature of air (T_A)	°C	30.75 ± 1.1	Normal	This study
Temperature of swimming pool water (T_W)	°C	27.6 ± 1.43	Normal	This study
Indoor swimming pool airflow recycle ratio (R)	Unitless	0.5		[15]
Indoor airflow velocity (ν_x)	m/s	0.20 ± 0.06	Normal	This study

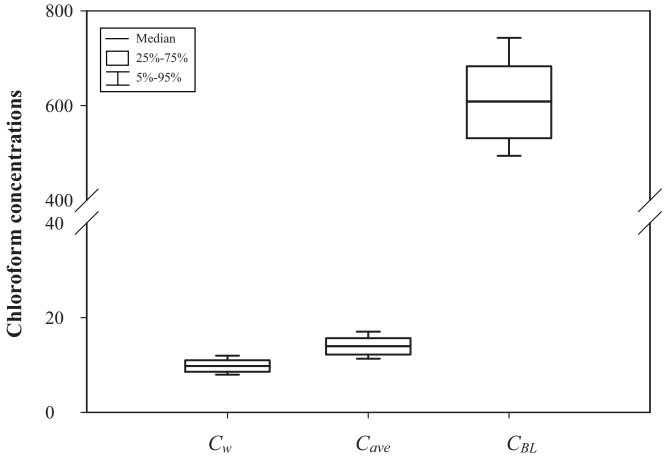

Fig. 2. Analytical results showing the concentrations of chloroform in swimming pool water (C_W, μg/L) and simulation results showing the concentrations of chloroform in boundary layer (C_{BL}, μg/m^3) and the average concentration of chloroform in indoor swimming pool air (C_{ave}, μg/m^3).

12.44 μg/L. The median value of chloroform in swimming pool water was 10.23 μg/L.

In Fig. 2, we also presented the predicted chloroform concentrations in the boundary layer above swimming pool water surface and the average of chloroform concentrations in indoor swimming pool air using the model that we have developed previously [15]. By using the average values for all the parameters listed in Table 2 and inputting the analyzed chloroform concentration in pool water, we obtained the concentrations of chloroform that ranged from 494 to 743 μg/m^3 in the boundary layer and from 11.34 to 17.04 μg/m^3 in indoor swimming pool air. These results showed that the concentrations of chloroform in the boundary layer were much higher than those of outside boundary layer by a factor of approximately 40. The simulation clearly showed that compared with nonswimming visitors or while resting in indoor swimming pool, swimmers in the pool were exposed to higher concentrations of chloroform due to higher concentrations of chloroform immediately adjacent to their breathing zone.

A comparison with the relevant data from other swimming pool samples was carried out and shown in Table 3. The concentrations of chloroform in swimming pool water in this study were lower than that of samples taken in Modena, Italy [3,28]. However, the concentrations were within the range of reported values compared with other studies conducted in other areas of the world [27,29,30]. Since the source of water in this indoor swimming pool was from tap water, we compared our data with results previously obtained by Hsu et al. [31] in which water samples were collected from three water treatment plants located in three different areas in Taiwan. The previous analysis showed that the chloroform concentrations in chlorinated water ranged from 4.2–27.6 μg/L. The concentrations of chloroform detected in the present study are therefore consistent with results obtained from the previous study. However, because pool water is recycled, the concentrations are cumulative from the beginning of disinfection process [29,32]. These studies suggested that concentrations of chloroform in swimming pool water are generally much higher than those in drinking water.

Table 3
Comparison of concentration of chloroform in swimming pool water with other studies.

Chloroform concentration in water (μg/L)	City/country	Reference
7.96–12.44 (swimming pool)	Kaohsiung/Taiwan	This study
3.04–27.8 (swimming pool)	Modena/Italy	[27]
25–43 (swimming pool)	Modena/Italy	[3]
16.97–47.08 (swimming pool)	Modena/Italy	[28]
7.1–24.8 (swimming pool)	Heidelberg/Germany	[29]
9.50–36.97 (swimming pool)	Nakhon Pathom/Thailand	[30]
4.2–27.6 (tap water)	Taiwan	[31]

3.2. Assessment of health risk for swimmers exposed to chloroform in indoor swimming pools

The probabilistic distributions of carcinogenic risk for swimmers exposed to chloroform can be through direct oral ingestion, inhalation (swimming and resting), and dermal contact absorption. The variations that can influence the risks include chloroform concentrations in water, exposure frequency, exposure time, body weight, body surface area, number of swimmers, number of nonswimming visitors, temperature of air, temperature of swimming pool water, and indoor airflow velocity were evaluated with Monte Carlo Simulation.

Fig. 3A1–D1 shows the predicted probability density functions of ILCR for two different sex groups of swimmers through four different exposure routes (oral, inhalation-swimming, inhalation-resting, and dermal contact absorption). Fig. 3A2–D2 shows the box and whisker plots of predicted ILCR. The box represents the 25th and 75th percentiles and whiskers are the 5th and 95th percentiles. The cross line in the box represents the median value of the predicted ILCR. The results of simulation indicated that ILCRs for swimmers through oral exposure route ranged from 10^{-10} to 10^{-8}, through inhalation during swimming ranged from 10^{-6} to 10^{-4}, through inhalation during resting ranged from 10^{-8} to 10^{-6}, and through dermal contact absorption ranged from 10^{-9} to 10^{-7}. These results clearly demonstrated that inhalation during swimming exhibited the highest predicted value of ILCR, suggesting that the most important exposure route in contributing to the overall health risk for a swimmer in an indoor swimming pool is through inhalation of chloroform during swimming.

The probabilistic distribution function of total carcinogenic risks from exposure to chloroform in indoor swimming pools in this study is shown in Fig. 4A1. The box and whisker plots of total ILCR are shown in Fig. 4A2. The median and the 95th percentile of total ILCR for male swimmers are 3.41×10^{-5} and 2.80×10^{-4}, respectively. For female swimmers, the median and the 95th percentile of total ILCRs are 2.90×10^{-5} and 2.47×10^{-4}, respectively. The results predicted that swimming in indoor swimming pools may pose high potential carcinogenic risk for swimmers due to high exposure to chloroform. The lifetime cancer risks for swimmers were higher than the USEPA acceptable risk (10^{-6}).

3.3. Contribution from different exposure pathways

Based on the recommendation of WHO [2], multiple-pathway assessment methodology was employed in this study. The exposure routes considered include ingestion, inhalation-swimming, inhalation-resting, and dermal contact absorption. The relative importance of exposure pathways was evaluated in terms of their contribution to the total carcinogenic risk.

In this part of simulation, we used the average values for all the parameters shown in Table 2 (N_w, N_s, T_w, T_a, v_x, C_w, ET, EF, BW_{male}, BW_{female}, SA_{male}, SA_{female}) to perform the estimation. The contributions to the total carcinogenic risk from different pathways are illustrated in Table 4. For male swimmers, the order of carcinogenic risk contribution is inhalation-swimming (99.35%) > inhalation-resting (0.61%) > dermal contact (0.04%) > oral ingestion (0.01%). Similarly, for female swimmers, the risk contribution percentage is in the same order of inhalation-swimming (99.25%) > inhalation-resting (0.69%) > dermal contact (0.05%) > oral ingestion (0.01%).

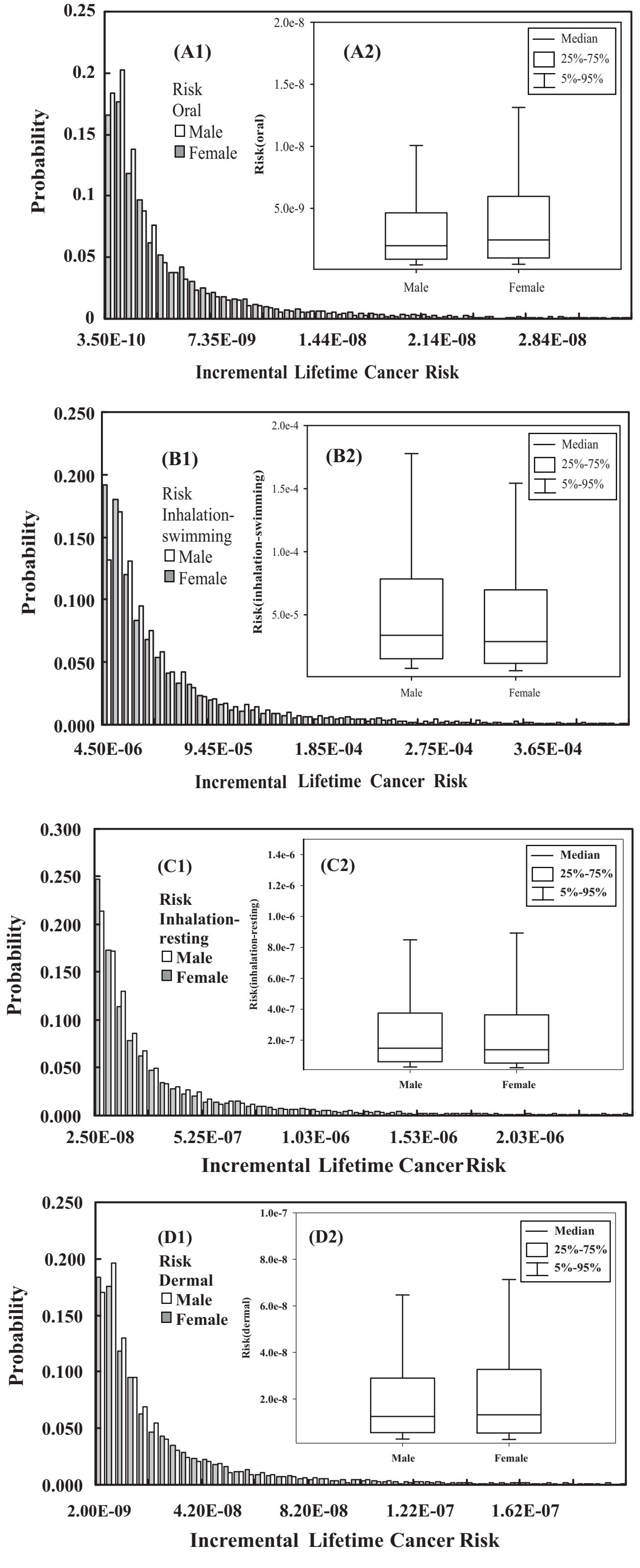

Fig. 3. Predicted probability density functions of incremental lifetime cancer risk for different exposure routes (A1–D1) and box and whisker plots (A2–D2) of cancer risk for male and female swimmers who are exposed to chloroform in indoor swimming pools.

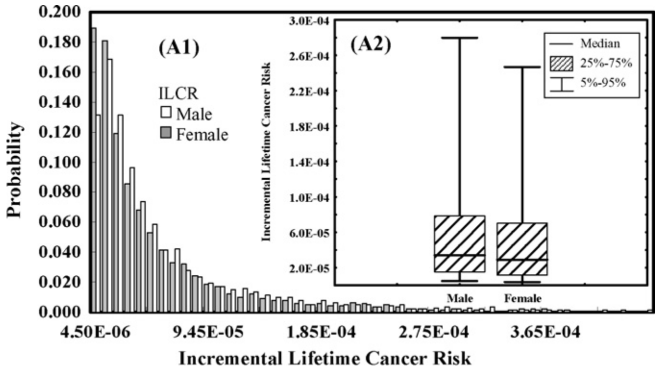

Fig. 4. Predicted probability function of total incremental lifetime cancer risk (A1) for swimmers who are exposed to chloroform in indoor swimming pools, and box and whisker plots of ILCR (A2) for males and females.

Table 4
The percentage contribution of total ILCR risk for different exposure pathways in indoor swimming pool.

Exposure route	Total ILCR (%)	
	Male	Female
Oral ingestion	4.08×10^{-9} (0.01%)	4.77×10^{-9} (0.01%)
Inhalation-swimming	6.83×10^{-5} (99.35%)	5.42×10^{-5} (99.25%)
Inhalation-resting	4.16×10^{-7} (0.61%)	3.77×10^{-7} (0.69%)
Dermal contact	2.56×10^{-8} (0.04%)	2.62×10^{-8} (0.05%)
Total ILCR	6.87×10^{-5} (100%)	5.46×10^{-5} (100%)

The results indicated that the major exposure pathway of chloroform for swimmers is through inhalation during swimming.

Erdinger et al. [29] conducted an experiment to quantify the body burden resulting from exposure to chloroform in water and in air for the swimmers. The chloroform concentrations in blood samples for subjects with scuba tank swimmers, without scuba tank swimmers, and nonswimming visitors walking around the pool were 0.32 ± 0.26 μg/L, 0.99 ± 0.47 μg/L, and 0.31 ± 0.25 μg/L, respectively. The levels of chloroform in the blood of subjects with scuba tank swimmers and nonswimming visitors walking around the pool were comparable, while the levels of chloroform in the blood of subjects without scuba tank swimmers were approximately three times higher than those in the other two groups. The results suggest that breathing plays an important role for the uptake of chloroform for swimmers.

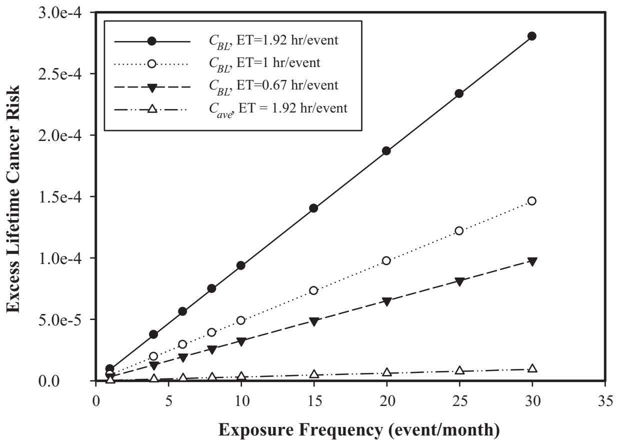

Fig. 5. Comparison of the ILCRs for swimmers who are exposed to chloroform in indoor swimming pools using concentrations in boundary layer (C_{BL}) versus using average air concentration (C_{ave}) under different exposure frequencies and exposure lengths of time.

Table 5
Key parameters for reducing the health risk for swimmers.

Run	C_w (μg/L)	C_{BL} (μg/m^3)	C_{ave}[a] (μg/m^3)	T_w (°C)	N_w	*EF* (event/month)	*ET* (h/event)	95% ILCR[b]
1	5.0	316.38	0.76	28	0	30	1.0	160
2	5.0	274.04	0.68	25	0	30	1.0	138
3	5.0	274.04	7.06	25	20	30	1.0	138
4	2.0	126.55	0.30	28	0	15	1.0	31.5
5	2.0	109.62	0.27	25	0	15	1.0	27.3
6	2.0	85.69	0.24	20	0	15	1.0	22.0
7	2.0	109.62	2.83	25	20	10	0.67	12.5
8	1.0	54.81	0.14	25	20	10	0.67	6.18
9	0.5	27.40	0.07	25	20	10	0.67	3.00
10	0.15	8.22	0.02	25	20	10	0.67	0.91

[a] Median value.
[b] $\times 10^{-6}$.

The results of our simulation further demonstrated the importance of inhalation in risk estimation for swimmers. It showed that the inhalation pathway contributes to more than 99% of total health risk indicating that the major exposure pathway of chloroform for swimmers is through inhalation, especially inhalation during swimming.

3.4. Comparison of the ILCR for frequent swimmers with general swimmers

Based on the assumption that a daily indoor swimming pool swimmer who has frequent exposure to chloroform should have a higher ILCR compared to a casual swimmer, we compared the difference of ILCR for different swimmers with different swimming frequency and exposure time.

Fig. 5 shows the ILCRs for swimmers who are exposed to chloroform in indoor swimming pools under different exposure frequencies and exposure lengths of time using either concentrations of chloroform in boundary layer or in indoor air as the simulation conditions. The simulation was performed at constant air temperature (30.75 °C), water temperature (27.6 °C), indoor airflow velocity (0.20 m/s), time fraction of total exposure time for swimmer to perform swimming (0.7), body weight (69.5 kg), skin surface area (1.76 m^2), chloroform concentration in water (9.81 μg/L), chloroform concentration in the boundary layer (591.91 μg/m^3), and average chloroform concentration in the indoor-swimming pool air (15.79 μg/m^3). The results showed that an increase in exposure frequency was associated with increased ILCR. Similarly, an increase in exposure time was associated with increased ILCR. In addition, using boundary layer concentration of chloroform to estimate the ILCR for swimmers, the range was from 9.33×10^{-6} (EF = 1 event/month) to 2.80×10^{-4} (EF = 30 event/month), whereas using the average air concentration of chloroform to estimate the ILCR, the values ranged from 3.08×10^{-7} (EF = 1 event/month) to 9.24×10^{-6} (EF = 30 event/month). Obviously, using the average indoor air concentration of chloroform to estimate ILCR may result in underestimation of health risk for swimmers. Therefore, our results suggest that it is more appropriate to use the chloroform concentrations in the boundary air above pool water to evaluate the risk associated with chloroform exposure for swimmers performing swimming exercise in indoor swimming pools.

3.5. Guideline for swimming pool managers and swimmers to protect swimmers' health

In the previous sections, we have identified the most influential pathway to the health risk evaluation for chloroform exposure to swimmers in an indoor swimming pool is chloroform inhalation during swimming. This is because the source of chloroform in indoor swimming pool air is from pool water and it is mainly accumulated in the boundary layer above the pool surface due to the low dispersion ability in the boundary layer [15]. In order to protect the health of swimmers, reducing the concentrations of chloroform while maintaining its effect on disinfection in swimming pool water should be evaluated. As shown in Fig. 4, exposure frequency and exposure time have a positive association with the ILCR. Reducing these factors is another method to reduce the health risks associated with chloroform exposure for swimmers. Other factors that can potentially reduce the concentrations of chloroform in indoor air include reducing the pool water temperature, as well as decreasing the levels of water-contained chloroform volatilization to decrease the concentrations of chloroform in air [15]. Therefore, in order to better understand the proper control guideline for reducing the health risk due to exposure to chloroform in indoor swimming pools, we conducted a series of simulations by altering variables including concentrations of chloroform in pool water, exposure frequencies, exposure times, pool water temperatures, and numbers of nonswimming visitors to determine to what extent that swimmers can be protected from ILCR. To present the assessment results in a more conservative fashion, the risk values at 95 percentile were used for the comparison and the ILCR was set at the acceptable levels defined by USEPA. The results are shown in Table 5.

The outcome showed that reducing the concentration of chloroform in poor water, exposure frequency, and exposure time can effectively, linearly reduce the ILCR. However, even the chloroform concentrations were reduced to 0.5 μg/L in pool water, the exposure frequency was reduced to 10 event/month, and the exposure time was reduced to 0.67 h/event, the 95 percentile of estimated ILCR still exceeded the acceptable levels by a factor of 3 as Run 9. Run 10 in Table 5 is the only condition that the estimated ILCR was lower than the acceptable levels. The results suggest that to ensure that the health risk associated with chloroform exposure is within the acceptable range for a swimmer that goes to indoor swimming pool 10 event/month and 0.67 h/event, the concentrations of chloroform in swimming pool water should be controlled at less than 0.15 μg/L when the swimming pool water temperature is at 25 °C. Alternatively, other methods or processes of disinfection should be considered for indoor swimming pool water management.

4. Conclusions

In this study, we have found that exposure to chloroform for swimmers in indoor swimming pool water could lead to high carcinogenic risks. However, the noncarcinogenic risk for swimmers exposure to chloroform is insignificant. The 95th percentile of ILCRs calculated for swimmers in this study for male and female swimmers were 2.80×10^{-4} and 2.47×10^{-4}, respectively. These values exceeded the acceptable risk level (10^{-6}) suggested by USEPA.

In this investigation, the major exposure routes for swimmers were found to be inhalation during swimming. It contributes to more than 99% of total health risk. Conversely, the contribution through inhalation while resting is negligible. Generally, swimmers have high breathing rates during swimming. In addition, the breathing zones of swimmers have high concentrations of chloroform. The calculated concentration of chloroform in boundary layer was approximately 40 times higher than its concentration in indoor air. Therefore, our study showed that inhalation during swimming dramatically increased the uptake of chloroform for swimmers. Our results suggest that it is important to use the chloroform concentrations in the boundary above the water surface to provide reasonable evaluation of the risks associated with chloroform exposure for swimmers in the indoor swimming pools, or the risks will be significantly underestimated by up to 40 times.

Our results further showed that exposure frequencies and the lengths of exposure time have profound influence on the carcinogenic risk caused by the exposure to chloroform in pool water. Consequently, professional or athlete swimmers are expected to have a significantly higher risk than do general public swimmers. Specifically, our results showed that, in average, a swimmer who goes to an indoor swimming pool daily exhibits one order of magnitude higher levels of ILCR than a swimmer who goes to an indoor swimming pool once a week.

Finally, our simulation showed that the decrease in the concentration of chloroform in the pool water can effectively and linearly reduce the risk of chloroform exposure for a swimmer. However, even the chloroform concentration was reduced to 0.5 μg/L in pool water, the exposure frequency was down to 10 event/month, and the exposure time was reduced to 0.67 h/event, the 95 percentile of estimated ILCR still exceeded the acceptable levels by a factor of 3. Hence, to protect swimmers from the health risks associated with excessive chloroform exposure in indoor swimming pools, alternative methods or processes of disinfection need to be considered for swimming pool managers. This can be partially achieved by employing appropriate disinfection techniques through the removal of precursors prior to disinfection by introducing improved pretreatments [33].

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