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Assessing microbial and chemical exposure risks of *Giardia* in indoor swimming pool water disinfected by chlorine

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ABSTRACT

Swimming pools adopt chlorination to ensure microbial safety. *Giardia* has attracted attention in swimming pool water because of its occurrence, pathogenicity, and chlorine resistance. To control *Giardia* concentrations in pool water and reduce the microbial risk, higher chlorine doses are required during disinfection. Unfortunately, this process produces carcinogenic disinfection byproducts that increase the risk of chemical exposure. Therefore, quantitatively evaluating the comparative microbial vs. chemical exposure risks that stem from chlorination inactivation of *Giardia* in swimming pool water is an issue that demands attention. We simulated an indoor swimming pool disinfection scenario that followed common real-world disinfection practices. A quantitative microbial risk assessment coupled with a chemical exposure risk assessment was employed to compare the *Giardia* microbial exposure risk (MER) and the trihalomethane chemical exposure risk (CER) to humans. The results demonstrated a 22% decrease in MER- and CER-induced health exposure risk, from 8.45E-5 at 8:00 to 6.60E-5 at 19:00. Both the MER and CER decreased gradually, dropping to 3.26E-5 and 3.35E-5 at 19:00, respectively. However, the CER exceeded the MER after 18:30 and became the dominant factor affecting the total exposure risk. Past the 18 hr mark, the contribution of trihalomethane CER far exceeded the risk aversion from microbial inactivation, leading to a net increase in total exposure risk despite the declining MER. Swimmers may consider swimming after 19:00, when the total exposure risk is the lowest. Lowering water temperature and/or pH were identified as the most sensitive factors to minimize the overall health exposure risk.

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Introduction

Swimming is a whole-body healthy exercise that has been gaining popularity. In fact, it is among the top five most popular exercises in countries such as China and the United States (US CB, 2020). However, modern-day swimming pools pose a major concern because microbes that persist in the water could engender health adverse events in swimmers who may become exposed via a multitude of pathways. Consequently, it is imperative to quantify and ensure the safety of swimming pool water. Among the many microorganisms in swimming pool water, *Giardia* has become one of the chief health pathogens of concern and has attracted much attention due to its occurrence, pathogenicity, and resistance to chlorine (Jarroll et al., 1981; Porter et al., 1988; Schets et al., 2004; Shields et al., 2008). *Giardia* is a unicellular protozoa, which mainly parasitizes in the host's intestines and gallbladder (Hartman et al., 1942; Wolfe et al., 1975). Prior epidemiological studies suggest that the main route of infection exposure for *Giardia* is through water (An et al., 2012). Typical symptoms involve abdominal pain, vomiting, and diarrhea (Halliez et al., 2015). In severe cases, *Giardia* can lead to death (Ning et al., 2018). Every year, 200 million people worldwide are affected by waterborne *Giardia*, a ubiquitous chlorine-resistant and pathogenic organism (Li et al., 2017). In response, many countries' standards require the inactivation of *Giardia* in municipal water supplies (Ministry of Health of the People's Republic of China and National Standardization Administration of China, 2006; US EPA, 1998). Unfortunately, violations may occur, resulting in detectable concentrations of *Giardia* in swimming pool water (Oliveri et al., 2006; Schets et al., 2004).

Most swimming pools worldwide use chlorination to keep pathogens at bay (Kim et al., 2002; Lee et al., 2010). Unfortunately, *Giardia* cysts are resistant to chlorine and larger dosages of chlorine is required to reliably limit dangerous concentrations of *Giardia* in pool water (Jarrol et al., 1981). Paradoxically, when chlorination inactivates *Giardia* to reduce the microbial exposure risk (MER), harmful, and potentially carcinogenic, disinfection byproducts (DBPs) can result, increasing the risk of chemical exposure in swimming pool water (Hang et al., 2016; Plewa et al., 2011). Prior studies indicate a directly correlative relationship between the quantity of DBPs and higher disinfectant dosages (Crittenden et al., 2012). Trihalomethanes are usually the most abundant DBPs in swimming pool water resulting from chlorination (Erdinger et al., 2004; Sun et al., 2019) and are mainly composed of four compounds: chloroform ($CHCl_3$), monobromodichloromethane ($CHCl_2Br$), dibromomonochloromethane ($CHClBr_2$), and bromoform ($CHBr_3$) (Wang et al., 2020). These compounds are all carcinogenic, of which $CHCl_3$, $CHCl_2Br$ and $CHBr_3$ are type B2 carcinogens (probable human carcinogens), and $CHClBr_2$ is a type C carcinogen (possible human carcinogen) (US EPA, 1999). The increased chemical exposure risks (CERs) therefore contradict the very purpose of microbial inactivation–the protection of human health. Subsequently, a quantitative evaluation of the comparative MERs and CERs that stem from chlorination inactivation of *Giardia* in swimming pool water is crucial but remains undone.

In this work, we simulated an indoor swimming pool design scenario to emulate common disinfection practices in real-world scenarios. A quantitative microbial risk assessment coupled with a chemical exposure risk assessment was employed to systematically quantify and compare the *Giardia* microbial exposure risk (MER) and the trihalomethane chemical exposure risk (CER) to humans. Recommendations to lower the exposure risks for swimmers were additionally provided. The results presented here provide a quantitative roadmap to facilitate better pool management and can inform individual decisions to minimize the overall human MER and CER in indoor swimming pools.

1. Materials and methods

1.1. Scenario construction

Based on the available literature on typical disinfection practice in swimming pools, we constructed an indoor swimming pool scenario described as follows. The source water for the swimming pool was municipal tap water, and sodium hypochlorite was applied as a disinfectant on top of the existing residual chlorine in tap water (Hao et al., 2014; Hu et al., 2020). Disinfection of fresh pool water started at 7:00 and business hours were from 8:00 to 20:00 (Editorial Office of "Journal of Environment and Health", 2007). The input parameters were determined based on literature and design handbook data. The concentration of *Giardia* was set at 0.185/L (the average concentration of *Giardia* in tap water), and the instantaneous concentration of residual chlorine was assumed to be 1 mg/L according to the national standard assuming a water temperature between 23°C and 30°C (Hao et al., 2014; State Administration for Market Regulation and China National Standardization Administration, 2019). The TOC of water was 10 mg/L (Anchal et al., 2020) and the Br^- was 0.5 mg/L (Chowdhury et al., 2016). As most pools adopt a water recycling system that runs once per day with purification technologies, assessing the performance of treatment technologies prove difficult. Our study assumed that pool water was changed once per day to reflect typical daily purification techniques (Hu et al., 2020). Additionally, swimmers usually swim at a fixed time, and swimming durations vary between sexes. Male swimmers swim for 0.727 hr on average while female swimmers swim for 0.729 hr (Lu, 2017; Ministry of Environmental Protection, 2013). Detailed pool disinfection-relevant parameters are provided in Table 1. It was assumed that the MER exposure caused by *Giardia* in swimming pools and the trihalomethane CER exposure to swimmers were identical from the inception to the end of the swim. Parameters for the indoor swimming pool scenario were systematically collected from different studies. While as many variables as possible were incorporated to better reflect real world cases, data unavailability and assumptions for models were inevitable. Consequently, an estimation error in real-world dynamics is probable.

Table 1 – Environment of swimming pool and parameter settings of disinfection technology.

Parameter	Range	Value	Ref.
Initial concentration of *Giardia* (pieces/L)	0.14~0.23	0.185	a
Water temperature (°C)	23~30	25	b
pH	7.0~7.8	7	b
Initial chlorine concentration (mg/L)	0.3~1	1	b
TOC (mg/L)	4.3~34.21	10	c
UV_{254} (cm^{-1})	0.178~0.789	0.5	c
Br^- (mg/L)	0.28~1.09	0.5	d

a: Hao et al. (2014); b: Ministry of Health of the People's Republic of China and National Standardization Administration of China (2006); c: Anchal et al. (2020); d: Chowdhury et al. (2016).

2. QMRA

2.1. Hazard identification

Giardia is a pathogen that the National Water Standard regulates as part of an effort to contextualize water quality (Ministry of Health of the People's Republic of China and National Standardization Administration of China, 2006). Compared to other pathogenic microorganisms, *Giardia* is less susceptible to chlorination disinfection of the swimming pool due to high chlorine resistance, which may result in an increased prevalence of infections among swimmers (Jarrol et al., 1981). Subsequently, we identified *Giardia* as a chief pathogen of concern.

2.2. Exposure assessment

Giardia is known to cause infection after ingestion; the pivotal problem of exposure assessment is determined by the instantaneous concentration of *Giardia* at time of entering the swimming pool under the design scenario. The calculation of exposure dose is provided in Haas et al. (2014) by the equation below:

$$\mathrm{Dose} = N \times IR \times ET \tag{1}$$

where Dose is the exposure dose of *Giardia* in mg/time, N is the instantaneous concentration of *Giardia* in cyst/L, IR (0.028 L/hr) is the human body's oral water intake per hour in the swimming pool (according to "Chinese Population Exposure Parameters Manual (Adult Volume)" (Ministry of Environmental Protection, 2013)), and ET is the swimming duration in 0.727 hr per instance (Lu, 2017).

To determine the instantaneous concentration N of *Giardia* in the exposure assessment model, it is imperative to assess the disinfection kinetics of *Giardia* inactivation by residual chlorine, which is expressed by the Chick–Watson law (Chick, 1908).

$$N = N_0 \exp\left(-k_b \int_0^t C dt\right) \tag{2}$$

It is therefore necessary to investigate the time series variation of residual chlorine C. In the current design scenario, the walls of the swimming pool are cleaned once per day. The reduction in residual chlorine on the walls is negligible and can be ignored when compared to the chlorine decay in water (Hua et al., 1999). Accounting for the effect of water temperature on chlorine decay, Eq. (2) can be expressed as:

$$N = N_0 \exp\left\{-0.243 \times \exp\left(-\frac{0.52527}{RT}\right) \int_0^t C_0 \exp\left[-\exp\left(-\frac{9.91}{T} + 30.99\right)t\right] dt\right\} \tag{3}$$

where N is the instantaneous concentration of *Giardia* in cysts/L, N_0 is the initial concentration of *Giardia* in cysts/L, C_0 is the instantaneous concentration of residual chlorine (mg/L as Cl_2), t is the contact time in hr, T is the water temperature in K, and R is the ideal gas constant. A detailed derivation of Eq. (3) is provided in Appendix A.

2.3. Dose response assessment

The global Rendtorff *Giardia* infection model (Rendtorff et al., 1954) that used human volunteers as hosts was used:

$$P_{\mathrm{response}} = 1 - \exp(-k \times \mathrm{Dose}) \tag{4}$$

where P_{response} is the MER of swimmers (dimensionless), dose is the exposure dose of *Giardia* per exposure in mg/time, and k is the infection constant of *Giardia* in time/mg with a value of 1.99E-02 (Rendtorff et al., 1954).

3. CRA of trihalomethane exposure

3.1. Hazard identification

Trihalomethane is a group of disinfection byproducts widely present in swimming pools disinfected by sodium hypochlorite (Lee et al., 2009), and some of sodium hypochlorite trihalomethane derivatives are known carcinogens (US EPA, 1999). The exposure risks of four common trihalomethanes (chloroform, bromodichloromethane, dibromochloromethane, bromoform) were studied in this paper. These compounds were selected due to recommendations by the US Environmental Protection Agency to monitor these compounds in water (UNEP and IPCS, 2000). The CER of trihalomethane includes both the carcinogenic and non-carcinogenic risk. The assessment was conducted based on the CER assessment model recommended by the US EPA (US EPA, 2009). It should be noted that the non-carcinogenic risk of trihalomethane is relatively small (Basu et al., 2011;

Panyakapo et al., 2008; Tokmak et al., 2004; Wang et al., 2007), so this study assumed the CER of trihalomethane to be approximately equal to the carcinogenic risk of trihalomethane.

3.2. Exposure assessment

Three routes of exposure exist for trihalomethanes in swimming pools: inhalation (the four trihalomethanes are volatile, swimmers may inhale these trihalomethanes when they breathe above the water surface), ingestion (accidental ingestion of pool water), and dermal absorption. Before quantifying the exposure dose via different exposure routes, however, it is imperative to determine the concentration of trihalomethanes.

Generation models were employed to obtain the concentration of trihalomethanes in the swimming pool under certain initial conditions (Watson, 1993). The generation model for each trihalomethane is given as follows:

$$CHCl_3 = 0.064(TOC)^{0.329}(UV_{254})^{0.874}(Br^- + 0.01)^{0.404}(pH)^{1.161}(C_0)^{0.269}(T)^{1.018} \quad (5)$$

$$CHCl_2Br = 0.0098(Br^-)^{0.181}(pH)^{2.55}(C_0)^{0.497}(t)^{0.256}(T)^{0.519} \quad (6)$$

$$CHClBr_2 = 14.998(TOC)^{-1.665}(Br^-)^{1.241}(C_0)^{0.729}(t)^{0.261}(T)^{0.989} \quad (7)$$

$$CHBr_3 = 6.533(TOC)^{-2.031}(Br^-)^{1.388}(pH)^{1.603}(C_0)^{1.057}(t)^{0.136} \quad (8)$$

where $CHCl_3$ is chloroform in µg/L, $CHCl_2Br$ is bromodichloromethane in µg/L, $CHClBr_2$ is dibromochloromethane in µg/L, $CHBr_3$ is bromoform in µg/L, TOC is total organic carbon in mg/L, UV_{254} is the ultraviolet absorption of water at 254 nm wavelength (cm^{-1}), Br^- is the bromide ion concentration in mg/L, C_0 is the initial chlorine concentration in mg/L, T is the water temperature in °C, and t is the disinfection contact time in hr. However, the predicted concentration for the $CHCl_3$ model was not time-dependent, and the time series change of $CHCl_3$ concentration after chlorination was excluded. Therefore, we modified the model by adding a time variable (the amount of chlorine consumed per hr is used to replace the initial chlorine concentration C_0 to calculate the production of chloroform) to reflect the time series characteristics of the $CHCl_3$ concentration after chlorination. Eq. (5) could then be expressed as:

$$CHCl_3 = 0.064(TOC)^{0.329}(UV_{254})^{0.874}(Br^- + 0.01)^{0.404}(pH)^{1.161}\{C_0[1 - \exp(-k_a t)]\}^{0.269}(T)^{1.018} \quad (9)$$

where k_a is the chlorine decay coefficient.

The three exposure routes were characterized according to exposure models developed by US EPA (2009) shown below:

$$LAEC = C_a \times ET \times EF \times ED/AT \quad (10)$$

$$CDI = C_W \times IR \times EF \times ED/(BW \times AT) \quad (11)$$

$$DAD = DA_{eventT} \times EV \times ED \times EF \times SA/(BW \times AT) \quad (12)$$

where LAEC is the average daily exposure of trihalomethane via inhalation in mg/m^3, CDI is the average daily exposure of trihalomethane via gastrointestinal intake in mg/(kg•day) DAD is the average daily exposure of trihalomethane via skin absorption in mg/(kg•day). C_a is the concentration of trihalomethane in the air calculated by multiplying the concentration of trihalomethane in the water (derived from the trihalomethane generation model) by the volatilization ratio in mg/m^3 (Appendix A Table S3). This paper does not consider the continuous accumulation of THMs in the air, which may have led to lower estimations of volatile THMs than those in practice. C_w, in mg/L, is the concentration of trihalomethane in the water calculated by subtracting the trihalomethane in the air from the trihalomethane as output by the trihalomethane generation model. IR is the oral intake dose in L/hr, ET is the swimming duration in hr/day, EF is the swimming frequency in day/year, EV is the single-day swimming frequency in time/day, ED is the swimming cycle in years, SA is the skin surface area in m^2, BW is the average weight of the population in kg, and AT is the life expectancy of the population in years. The calculation of the average single-event absorption amount DA_{event} is shown as below (US EPA, 2009):

$$DA_{event} = \begin{cases} 2K_pC_W\sqrt{\frac{6\tau ET}{\pi}}ET \leq 2.4\tau \\ K_pC_W(ET + 2\tau)ET > 2.4\tau \end{cases} \quad (13)$$

where DA_{event} is the average single-event absorption in $mg/(cm^2$•time), K_p is the skin permeability coefficient of the pollutant in cm/hr, C_w is the pollutant's concentration in water in mg/L, and τ is the lag in absorbed chemical exposure in hr/swim.

The remaining parameters, such as the pollutant skin permeability coefficient K_p of trihalomethane and the lag time τ of a single exposure event, are recommended by the US EPA as shown in Appendix A Table S4. The swimming time ET, swimming frequency EF, single-day swimming frequency EV, and swimming cycle ED in the behavior pattern of swimmers are determined by literature (Lu, 2017; Ministry of Environmental Protection, 2013). The physiological parameters of swimmers in the indoor swimming pool scene, such as weight BW, life expectancy AT, skin surface area SA and other parameters related to gender, are described in Appendix A Table S5. Season has a varying effect on exposure dose. Swimming times (ET) tend to be longer during the summer whereas swimming frequency (EF) tends to be higher in the winter. While swimming durations during the summer are the longest with a seasonal average of 0.755 hr/day, swimming frequencies during the summer is also the lowest with days swam of 2.28 days/year. This contradictory relationship between swimming duration and swimming frequency results in seasonally varying exposure to THMs. Therefore, factoring in all variations and sources in exposure accounts for differences in sex and season and calculates the exposure dose of THMs accordingly.

3.3. Dose response assessment

We used the CER models for trihalomethanes recommended by the US EPA for different exposure pathways to assess the CER of trihalomethanes in swimming pools (US EPA, 2009). The result was expressed probabilistically by the equations below:

$$Risk_{inhale} = LAEC \times IUR \quad (14)$$

$$Risk_{oral} = CDI \times SF_{oral} \quad (15)$$

$$Risk_{dermal} = DAD \times SF_{dermal} \quad (16)$$

$$Risk_{chemical} = Risk_{inhale} + Risk_{oral} + Risk_{dermal} \quad (17)$$

where $Risk_{chemical}$ is the CER of each trihalomethane, expressed in probability, $LAEC_{sw}$ is the average daily exposure of trihalomethane via inhalation in mg/m^3, IUR is the unit respiratory risk of trihalomethane in m^3/mg, CDI is the daily average exposure of trihalomethane via ingestion in mg/(kg•day), SF_{oral} is the carcinogenic slope factor of trihalomethane via ingestion, DAD is the average daily dermal exposure of trihalomethane in mg/(kg•day), and SF_{dermal} is the carcinogenic slope factor of trihalomethane via dermal exposure. Select summary data are provided in Appendix A Table S5.

We characterized acceptable CER levels per the standard outlined by the US EPA. The CER is acceptable when the risk value is between 1.0E-06 and 1.0E-04, negligible when the risk value is less than 1.0E-06, and hazardous when the risk value is greater than 1.0E-04.

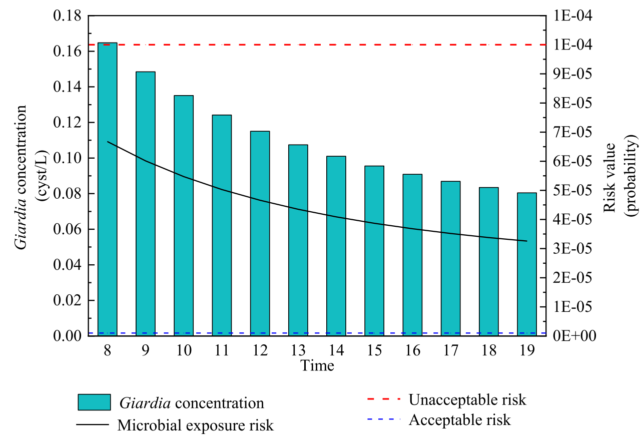

Fig. 1 – Time series of MER vs *Giardia*. The MER decreased continuously over time, with the maximum value being 6.67E-5 at 8:00, the time of opening. All risk values were within acceptable range of 1E-6 (red) to 1E-4 (blue). The rate of decrease of MER reduced gradually with time. Risk values lower than 1E-6 are categorically acceptable with negligible risk; values between 1E-6 and 1E-4 are simply acceptable; and values greater than 1E-4 constitutes an excess risk and needs to be the dealt with in time (US EPA, 2009).

4. Coupling of MER and CER

Swimmers were assumed to be exposed to *Giardia* and trihalomethanes in the pool simultaneously. Since the exposure risks caused by *Giardia* and trihalomethanes were expressed probabilistically, coupling the MER and the CER is reasonable. We calculated the overall exposure risk as follows:

$$Risk_{all} = P_{response} + Risk_{chemical} \quad (18)$$

where $Risk_{all}$ is the total exposure risk, $P_{response}$ is the MER, and $Risk_{sw}$ is the CER. It is important to note that *Giardia* causes acute toxicity, while trihalomethanes cause chronic toxicity. Although the risks that stemmed from *Giardia* and THMs were summed in this work as they were expressed in probability values, the rationality of additive toxicity risks between these outcome parameters still requires further investigation.

5. Sensitivity analysis

Sensitivity analysis was performed by adjusting the value of each input variable by 10% individually from its median. The corresponding change in the output metric characterized the relative importance of each input variable. The derived sensitivity coefficients allow for ranking orders of environmental and disinfection process parameters that may affect the exposure risk, providing a much-needed basis for better managing behaviors to exposures to swimming pool water. There are seven input variable that affected total exposure risk, which are initial chlorine concentration, Br^-, TOC, pH, disinfectant contact time, initial *Giardia* concentration, and water temperature. The initial chlorine concentration is an important factor in determining the inactivation rate of residual chlorine on *Giardia*, the production of trihalomethanes, the risk of microbial exposure to *Giardia* (MER), the risk of chemical exposure to trihalomethanes (CER), and a combination of the two risk categories. The total exposure risk has an impact. Br^-, TOC, and pH are one of the precursors of trihalomethanes, and their size affects the generation of trihalomethanes, which in turn affects the chemical exposure risk of trihalomethanes. The duration of disinfection will affect the concentration of *Giardia* and the concentration of trihalomethanes produced. The initial *Giardia* concentration directly affects the microbial exposure risk of *Giardia*, the chemical exposure risk of trihalomethanes, and the combined total exposure risk of the two. Water temperature can alter the chlorine decay coefficient and inactivation kinetic constant, summarily modifying the trihalomethane generation.

6. Results and discussion

6.1. Giardia MER

The MER decreased continuously over time, with the maximum value being 6.67E-5 at 8:00, the time of opening. At 19:00, the MER was the lowest at 3.26E-5. All measurements fell within the recommended range of 1E-6 to 1E-4. However, the rate of decrease of MER reduced gradually from 0.66E-5 per hour at 8:00 to 0.12E-5 per hour at 19:00 (Fig. 1).

In cases where the swimming pools extended their business hours to 22:00 at night (for instance, during holidays and summer), the MERs would further drop to 3.06E-5, which was 0.19E-5 lower than the CER at 19:00 (discussed in depth below

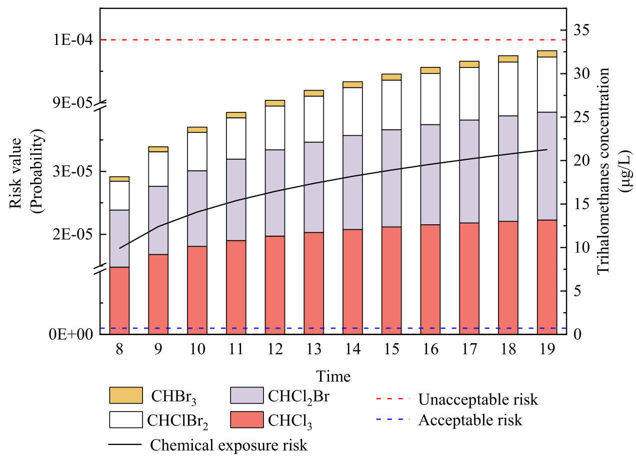

Fig. 2 – Time series of trihalomethane CER. The trihalomethane CER to swimmers in swimming pools gradually increased over time, from 1.78E-5 at 8:00 to 3.35E-5 at 19:00. The rate of increase of CER reduced gradually with time.

in Section 6.3). At this time, the rate of risk further decreased to 0.09E-5 per hr.

We identified seven factors that affected the MER, including initial chlorine concentration, Br^-, TOC, pH, disinfectant contact time, initial *Giardia* concentration, and water temperature. These variables influence disinfection kinetics of *Giardia* inactivation by residual chlorine and in turn, the generation model for each trihalomethane (Fig. 7b). The most impactful parameter that affected the MER was the initial concentration of *Giardia* on the MER; unfortunately, pool managers have little influence over this variable. The second most sensitive parameter was the disinfection contact time which is more manageable, for instance by delaying the addition of disinfectants when disinfectant levels are below detection. The Br^-, TOC, and pH did not affect the MER because they do not alter disinfection kinetics of *Giardia* inactivation by residual chlorine significantly. Warmer water temperature accelerates chlorine decay which is critical in keeping *Giardia* concentrations at bay; a 10% increase in the *Giardia* concentration results in a MER increase by 3.8%. Pool managers should therefore control and maintain the water temperature within specified limits. Based on simulation results, swimmers are advised to swim after 19:00, at which the MER was found to be 51.2% lower than that of swimmers at 8:00.

6.2. Trihalomethane CER

The trihalomethane CER of swimmers in swimming pools increased gradually with time, from 1.78E-5 at 8:00 to 3.35E-5 at 19:00, a 1.9-fold increase (Fig. 2). When considering only the CER, swimmers should start swimming at 8:00 given that at this time, the CER was the lowest at 1.78E-5. When the swimming pool was disinfected an hour in advance at 6:00 instead of 7:00 and swimmers entered the swimming pool at 8:00, the CER increased by 29.1% to 2.12E-5. Therefore, if swimming pool managers aim to inactivate microorganisms such as *Giardia* with chlorine, it is prudent to analyze the increased risk of trihalomethane chemical exposure.

Six factors were identified to have affected the risk of chemical exposure substantially: disinfectant contact time, bromine concentrations, TOC, pH, initial chlorine concentration, and water temperature (Fig. 7c). pH had the greatest impact on the CER, followed by water temperature. Naturally, the CER can be modulated by adjusting pH and/or water temperature.

6.3. Total exposure risk

The total exposure risk decreased gradually with time, from 8.45E-5 at 8:00 when the swimming pool opened to 6.60E-5 at 19:00, representing a 22% decrease (Fig. 6). Between 8:00 and 18:30, the MER was the dominant factor affecting the total exposure risk, but the MER decreased gradually with time due to more complete inactivation of *Giardia*, representing a decline from 79% contribution at 8:00 to 49% at 19:00. After 18:30, the CER replaced MER as the dominant factor, affecting the total exposure risk (Fig. 6). When business hours were extended from 19:00 to 22:00 such as during holidays, the CER was 1.14 times the microbiological exposure risk at closing, accounting for 53% of the total risk.

Alarmingly, after 18 hr of chlorination, the total exposure risk began to increase due to the CER over time. The growth rate of the trihalomethane CER was 0.05E-5 per hour, surpassing the rate of reduction of 0.049E-5 per hour for the MER to *Giardia*, leading to a gradual increase in the total exposure risk. Therefore, from the perspective of total exposure risk, swimmers are recommended to start swimming at 19:00. During holidays and extended business hours, the total exposure risk may increase due to the accumulation of DBPs. This raises concerns over the health risks of DBPs because pool water, in many cases, may not be filtered but rather used repetitively without any purification treatments for extended times (Dallolio et al., 2013; Kim et al., 2002.). In such cases, the DBP CER may rise to hazardous levels as there are no interventions regarding DBP precursor removal or DBP removal.

Among the total exposure risks of different exposure routes, the rank order was ingestion > dermal absorption > inhalation (Fig. 3). Ingestion accounted for the highest proportion of chemical exposure, at 99.78%. The proportion of skin absorption paled in comparison at a paltry 0.18%. The inhalation-induced CER of trihalomethanes was the lowest at only 0.04%. These results are inconsistent with other swimming pool research (Chen et al., 2011; Dyck et al., 2011; Erdinger et al., 2004; Lee et al., 2009; Lu, 2017). The reason behind these discrepancies is most likely due to prior research being conducted in settings with poor building air circulation, which may lead to higher air trihalomethane concentrations than those predicted by the model in this work. Therefore, if swimmers accidentally swallow pool water, it is advised to spit out any remaining pool water and rinse afterwards to minimize pool water ingestion. We also attributed total exposure risks to different types of trihalomethanes (Fig. 4). The rank order was $CHCl_2Br$ > $CHClBr_2$ > $CHCl_3$ > $CHBr_3$, of which the total exposure risk caused by $CHCl_2Br$ accounted for the highest proportion at 18.1%; the total exposure risk caused by $CHClBr_2$ was the second highest, at 12.4%. No significant difference

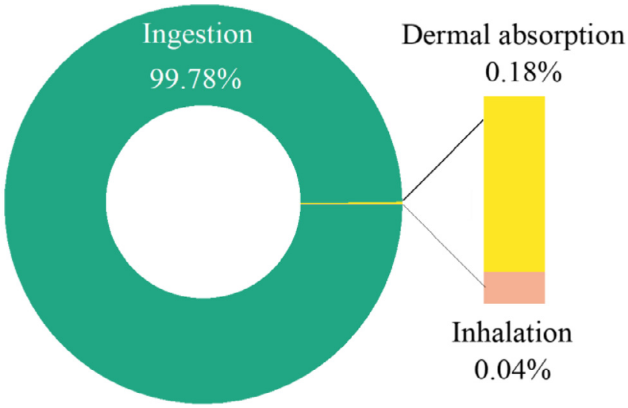

Fig. 3 – Proportion of total exposure risk through different exposure routes. Among the total exposure risks of different exposure routes, the rank order was ingestion > dermal absorption > inhalation. The ingestion route accounted for the highest proportion of chemical exposure, reaching 99.78%.

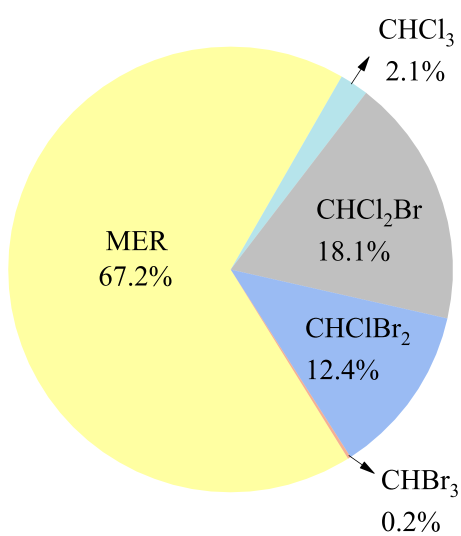

Fig. 4 – Proportion of total exposure risk of different trihalomethanes. The CER rank order was: $CHCl_2Br$ > $CHClBr_2$ > $CHCl_3$ > $CHBr_3$, of which the total exposure risk caused by $CHCl_2Br$ accounted for the highest percentage at 18.1%.

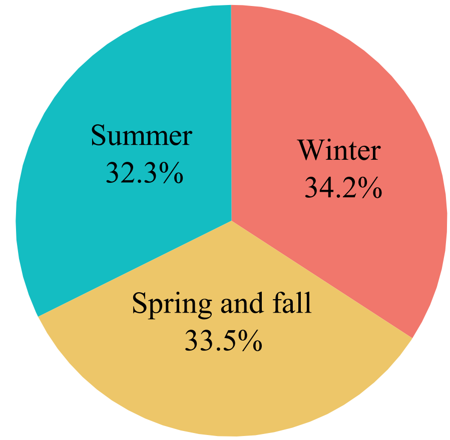

Fig. 5 – Proportion of total exposure risk by different seasons, the total exposure risk in winter was the highest, accounting for 34.2% of the total MER and CER of the year.

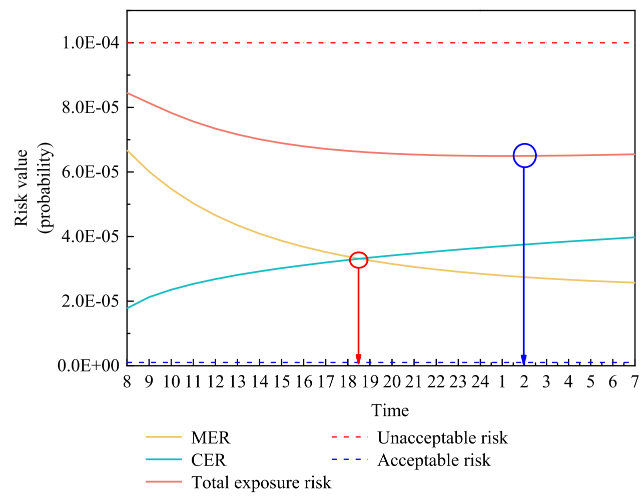

Fig. 6 – Time distribution of exposure risks from 8:00 to 7:00 the next day. Time after 20:00 represent special cases (such as extended business hours on holidays). After 18:30 (circled in red), the chemical exposure risk exceeded the MER and became the dominant factor affecting the total exposure risk. After 18 hr of chlorination (circled in blue), the total exposure risk began to increase with time.

was observed in total exposure risk between different seasons (Fig. 5). The total exposure risk in winter was the highest, accounting for 34.2% of the year, followed by spring and autumn combined, accounting for 33.5%. Summer was the lowest, accounting for 32.3%. These observations are consistent with literature (Lu, 2017). For winter, the swimming frequency is typically higher than in other seasons due to cold weather when people tend to go swimming indoors where the water temperature is kept warm, despite shorter swim times compared to other seasons.

Seven factors were identified to have affected the total exposure risk: treatment time, Bromine concentrations, TOC, pH, initial chlorine concentration, initial *Giardia* concentration, and water temperature (Fig. 7a). The initial concentration of *Giardia* once again had the greatest impact on the total exposure risk, followed closely by pH and water temperature. If the *Giardia* concentration of tap water (source water for pools) is kept below 1 cyst/10 L, the total exposure risk can be reduced by 28%. The disinfection contact time and pool water temperature can be modulated accordingly to minimize the overall exposure risk. If the pool water was disinfected two hours in advance of any swimmers entering the pool, this would reduce the total exposure risk at 8:00 by 4%. Water temperature and total exposure risk are directly correlated. In this study's simulation, the total exposure risk was initially 7.26E-5 at 25°C and increased to 7.61E-5 at 27.5°C, a 1.05-fold increase. Similarly, the total exposure risk dropped to 6.96E-5 when the tem-

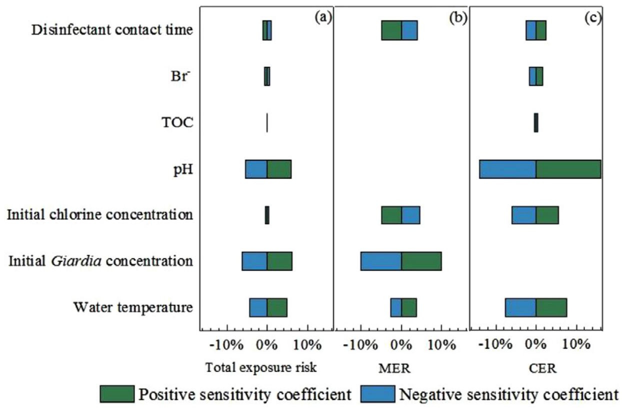

Fig. 7 – Sensitivity coefficients (Y-axis) for the seven most sensitive input parameters with respect to exposure risk (X-axis), performed by adjusting each input value by 10% individually from its median. Exposure risk is sub-categorized by total exposure risk (a), MER (b), and CER (c).

perature decreased to 22.5°C, suggesting a causal relationship. Keeping pool water temperatures artificially low may serve as a safeguard against microbial growth. We recommend pool temperatures at or below 23°C as the risk of total exposure is reduced by 3.4% in comparison to 25°C.

7. Conclusions and recommendations

It is important to note that while we gathered data to emulate real-world dynamics, deviations are unavoidable due to a lack of information to account for numerous other DBPs in swimming pools. This work functions as a foundation for future studies. The total exposure risk of swimming pool water continued decreasing until up to 18 hr of disinfection by chlorination after which the contribution of trihalomethane CER far exceeded the risk aversion from microbial inactivation, resulting in a net increase in the total exposure risk despite the declining MER. At 18:30, the CER exceeded the MER and became the dominant factor contributing to the total exposure risk. Pool water pH and water temperature were identified as the most influential operational parameters that pool managers can control to reduce the total exposure risk. Swimming pools managers are advised to maintain a pH of around 7.0 and a water temperature of around 23°C, potentially reducing the total exposure risk by 3.4%. It is also recommended to add sodium hypochlorite in advance to disinfect the swimming pool. Evidence suggests that disinfecting the pool water two hours before swimmers enter the pool can reduce the total exposure risk by 4%. Ingesting pool water is the most common exposure route and is summarily discouraged. Swimmers should strongly consider swimming after 19:00, assuming a minimal effect on water quality pollution by the human body during the exposure simulation period, and when the total exposure risk is only 78% of swimming at 8:00. Multiple disinfection methods should be applied in tandem to inactivate the chlorine-resistant *Giardia*, thereby reducing the total exposure risk. If only a single mode of disinfection (chlorination) is applied due to external reasons, swimmers are recommended to swim after 19:00. Future studies are encouraged to incorporate more biological and chemical indicators to account for their potential impact on the overall risk assessment.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.05.006.

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