Probabilistic approach for health hazard assessment of trihalomethanes through successive showering events

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Received: 26 July 2021 / Accepted: 13 October 2021 / Published online: 27 October 2021
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Abstract

Trihalomethanes (THMs) are common disinfection by-products in chlorinated tap waters. They can cause various cancers and non-cancer health hazards. Ingestion, dermal contact, and inhalation are the three exposure routes considered in the THM hazard or risk assessments. Among these, inhalation hazard is generally calculated by assuming the initial concentration as zero. This assumption fails to address the case of continuous or successive showers that can happen in shared showering facilities such as student hostels or gymnasiums. In the present study, the leftover THM concentration from the previous bath was considered to assess the chronic daily intakes (CDI) and hazard index (HI) for successive showers. For this, tap water of a university campus was analyzed to understand the extent of THM exposure at consumer points and the result obtained was used for the hazard assessment. Total THM concentrations varied from 0.51 to 68.9 µg L⁻¹. To address the variability of the model input parameters, 50,000 iterations of Monte Carlo simulation were carried out. Maximum HI values of 7.94E⁻² ± 3.63E⁻², and 6.69E⁻² ± 3.08E⁻² were observed for the 1st shower for females and males, respectively. This value increased exponentially up to the 5th shower and thereafter, the value was constant. The methodology followed in the present study successfully determines the risk and hazard of THMs through successive showers.

Keywords Hazard quotient · Hazard index · Chronic daily intake · Monte Carlo simulation · Disinfection by-products · Non-cancer risk

Introduction

Trihalomethanes (THMs) are a class of disinfection by-products (DBPs) that commonly form in chlorinated water and wastewater. One of the main routes of exposure to trihalomethanes (THMs) for humans is the ingestion of tap water. Total THMs (TTHMs) include trichloromethane (TCM), bromodichloromethane (BDCM), dibromochloromethane (DBCM), and tribromomethane (TBM). These compounds are either probable or possible carcinogens and belong to Group B2 or Group C USEPA risk categories with hepatic, urinary, or gastrointestinal systems as their target tumor sites (IRIS 2021; Evelampidou et al. 2020; Cotruvo and Amato 2019; Font-Ribera et al. 2018). The non-cancer health issues related to THMs include the following: TCM can cause fatty cyst formation in the liver (hepatic system), BDCM poses hazards to the urinary system, DBCM and TBM can adversely affect the hepatic system, and all THMs together can cause reproductive disorders (IRIS 2021; Zeng et al. 2016).

Risk assessments are performed to understand the potential health effects of exposure to a physical, chemical, or biological agent or a combination of two or more compounds such as the THMs in this study. Health risk calculations can be done for cancer risk and non-cancer risk (Ahmed et al. 2019; Amjad et al. 2013; Kujlu et al. 2020; Mosaferi et al. 2021). Cancer risks due to THMs have been widely discussed in the literature but non-cancer risks have not received the attention they deserve. Showering is known to be a major contributor to cancer and non-cancer health risks due to THMs in tap water. However, the risks associated
with the cumulative intake of THMs by inhalation in shower stalls after successive uses were not found in the literature. Therefore, the objective of the current study was to determine the non-cancer health hazards associated with THMs in tap water and exposure by inhalation of these volatile compounds during successive showers.

Several studies reported health risks or hazards due to THMs in tap water. Water samples from Iran had TTHM concentrations of $133.2 \pm 179.5 \, \mu g \, L^{-1}$ resulting in a hazard index (HI) of 0.2 through drinking water and HI of 0.02 through dermal contact with the water (Mosaferi et al. 2021). Similarly, water samples from 5 treatment plants of eastern India which had TTHM concentrations in the range of 231–484 μg L$^{-1}$ had a HI of 0.49 through drinking water and HI $= 1.39 \times 10^{-5}$ through dermal contact with water (Kumari and Gupta 2018).

The risk assessment of THMs is generally performed using the US Environmental Protection Agency (USEPA) guidelines which predict the chronic daily intakes (CDI) through various exposure routes (USEPA 1980). Computational human exposure models for TTHM risk assessment are modifications to the USEPA method based on the population exposed. A deterministic approach to such models fails to address the variability in these input parameters. Instead, a probabilistic method considering the variability in input parameters is recommended and recent THM risk assessments are based on probabilistic methods (Chowdhury 2013; USEPA 2019; Mosaferi et al. 2021). The three exposure pathways for THM risk assessment are ingestion through drinking water, dermal absorption, and inhalation.

While the first route stays relatively unchanged for different populations, the other two that can happen while showering, washing, or cleaning with water are prone to variability depending on the living conditions and daily routines of the population. For instance, mechanical dishwashing eliminates dermal absorption that can occur during the hand washing of utensils. A common assumption in the inhalation CDI assessment is that the shower room air is considered free of THMs before any showering events (initial THM concentration $= 0$) (Chowdhury 2013; Kujlu et al. 2020). This assumption is correct only for the household shower rooms where members use separate bathrooms or there is enough time between successive showering events so that the THM concentration left by the previous user have subsided. However, this assumption fails in the case of shared showering facilities such as student hostels and dormitories, gymnasiums, swimming pools, backpackers’ lodges, sports complexes, and small bed and breakfast establishments with common bathrooms where multiple showering events can occur successively and therefore, from the second shower onwards, the TTHMs in the shower air cannot be assumed to be zero. Often in these facilities, there is little time between two successive shower events to diminish the TTHMs left by the previous user, i.e., there is a buildup of TTHMs in the shower stalls. Hence, this amount needs to be accounted for while calculating the inhalation CDI and subsequent risks.

In the present study, tap water samples were analyzed for the extent of TTHM concentration at consumer point and the impact of successive showering events on daily intake and non-cancer health hazards due to TTHMs for a campus community. A probabilistic method was adopted to incorporate the variability in input parameters and to reduce the uncertainty associated with them in the modified exposure models.

**Methodology**

**Hazard quotient and hazard index**

The two health hazard indices used in the present study are hazard quotient (HQ) and hazard index (HI). These two indices are typically used in the risk characterization of chemical substances to describe the non-cancer health hazards and were first defined by the USEPA – National-Scale Air Toxics Assessment (NATA) as HQ as “the ratio of the potential exposure to a substance and the level at which no adverse effects are expected” and HI as “the sum of hazard quotients for toxics that affects the same target organ or organ system” (USEPA 2015; Alimohammadi et al. 2018). Thus, for a mixture of certain chemical compounds such as THMs, HI is the sum of HQs of individual THMs. The terms target hazard quotient (THQ) and total target hazard quotient (TTHQ) have also been used in previous literature to represent non-cancer HQ and HI, respectively (Alimohammadi et al. 2018). An HQ or HI of 1 or lower indicates adverse non-cancer health hazards are unlikely over a lifetime of exposure and can be considered to cause negligible hazards. As such, HQ or HI greater than 1 means an increased potential for adverse effects although the end effect will be dependent on several factors.

**THM analysis and study population**

Triplicate tap water samples were collected for THM analysis from 20 halls of residence in the Indian Institute of Technology Kharagpur (IITKgp) campus in December 2019. For this, 100-mL brown glass vials with Teflon septa were prepared by acid washing followed by oven drying, and they were conditioned with ammonium thiosulfate to quench the residual chlorine present in samples. Collected samples were immediately transferred to the laboratory and kept at 4°C. The samples were analyzed for THM concentrations within 24 h using a gas chromatograph (GC) equipped with an electron capture detector (ECD) (Trace 1300, Thermo Fisher Scientific Ltd., Austria). For preconcentration of samples, a purge and trap
(P&T) unit (Lumin, Teledyne Tekmar, USA) with nitrogen as the purging gas was used. Standard preparation, quality check, sampling, and instrumental conditions were as per the USEPA Method 501.1 with few modifications (USEPA 1979). The oven temperature program of GC and purging program of P&T are given in Table 1.

The student community of the IITKgp was selected as the study population. The shower rooms in the halls of residence are shared by the inmates. Thus, in each shower room, successive showering events can happen in the shower rooms, which are back showering events happen in the shower rooms, which are shared by the inmates. Thus, in each shower room, successive showering events happen in the shower rooms, which are not considered for this population.

**Modeling and simulation**

Chronic daily intake (CDI) through inhalation of THMs in the shower room is predicted for the THM concentration in the shower air \(C_{air}\). The calculation of \(C_{air}\) generally follows Little’s theory which assesses individual through inhalation is shown below (USEPA 1980):

\[
\text{CDI}_{inh,i} = \frac{C_{air,i} \times Er \times t \times R \times F \times EF \times ED \times CF}{BW \times AT}
\]

where \(t\) is the showering duration (min),

\[
b = \frac{1}{V_s} \times \left\{ \left( \frac{Q_w}{H} \right) (1 - e^{-N}) + Q_g \right\},
\]

and

\[
a = \frac{1}{V_s} \times \left\{ Q_w \times C_{w,i} \times (1 - e^{-N}) \right\}
\]

where \(V_s\) is the volume of the bathroom (L), \(Q_w\) is the water flow rate in the bathroom (L min\(^{-1}\)), \(H\) is Henry’s constant at 40°C for each THM (unitless), \(Q_g\) is the airflow rate in the shower (L min\(^{-1}\)), \(C_{w,i}\) is the concentration of \(i\)th THM in the shower water (μg L\(^{-1}\)), and \(N\) is the non-dimensional overall mass transfer coefficient. \(N\) can be calculated as:

\[
N = \frac{\text{KoLA}}{Q_w}
\]

where KoLA is the overall mass coefficient of each THM (L min\(^{-1}\)) (Table 2).

The equation used for calculating CDI of THMs by an individual through inhalation is shown below (USEPA 1980):

\[
\text{CDI}_{inh,i} = \frac{C_{air,i} \times Er \times t \times R \times F \times EF \times ED \times CF}{BW \times AT}
\]

where \(C_{air,i}\) is the chronic daily intake of \(i\)th THM by inhalation (mg kg\(^{-1}\) day\(^{-1}\)), \(Er\) is the absorption efficiency of THMs through the respiratory system, \(R\) is the breathing rate (m\(^3\) min\(^{-1}\)), \(F\) is the showering frequency (events day\(^{-1}\)), \(EF\) is the exposure frequency (day year\(^{-1}\)), \(ED\) is the exposure duration (years), \(CF\) is the conversion from μg to mg (0.001), \(BW\) is the body weight of the individual (kg), and \(AT\) is the averaging time (days).

Similarly, the CDI through oral as well as dermal pathways were determined using the following equations (Chowdhury 2013; Téllez Tovar and Rodríguez Susa 2020):

\[
\text{CDI}_{oral,i} = \frac{C_{air,i} \times IR \times EF \times ED \times CF}{BW \times AT}
\]

\[
\text{CDI}_{der,i} = \frac{C_{air,i} \times SA \times Pd \times t \times F \times EF \times ED}{BW \times AT}
\]

**Table 1** Operating conditions of the gas chromatograph and preconcentration unit

| Gas chromatograph          | Carrier gas: nitrogen at 1.2 mL/min, analytical column: TG5 MS—30 m×0.25 mm×0.25 μm, injector: split/splitless, 250 °C, detector: ECD, 300 °C, Oven program: 31 °C for 1 min, 31 to 40 °C at 1 °C/min, 40 °C to 200 at 80 °C/min, 200 °C for 2 min |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Purge and trap unit        | Purge gas: nitrogen at 10 mL/min, trap: VOCARB 3000, injection volume:5 mL, Purging program: purge: 11 min, dry purge: 1 min, desorb: 2 min, bake: 2 min                                                                 |
where CDI\textsubscript{ing,i} and CDI\textsubscript{der,i} are respectively the chronic daily intake of \textit{i}th THM through oral and dermal routes, IR is the drinking water ingestion rate (L day\textsuperscript{-1}), SA is the skin surface area (m\textsuperscript{2}), Pd is the permeability of THMs through human skin (m min\textsuperscript{-1}), \( t \) is showering duration (min), and \( F \) is showering frequency (events day\textsuperscript{-1}). The CDI was found by summing up respective individual CDIs, i.e.:

\[
\text{Total CDI} = \sum_{i=1}^{4} \sum_{j=1}^{3} \text{CDI}_{ij}
\]

(10)

where \textit{i} represents 4 THM species (TCM-TBM) and \textit{j} represents 3 exposure routes (oral, dermal, and inhalation). Hazard quotient (HQ) and hazard index (HI) were assessed using the following equations (Mosaferi et al. 2021).

\[
\text{HQ}_i = \frac{\text{CDI}_i}{\text{RfD}}
\]

(11)

\[
\text{HI}_j = \sum_{i=1}^{4} \text{HQ}_{ij}
\]

(12)

depicted similarly, the overall hazard index (HI\textsubscript{T}) was calculated as follows:

\[
\text{HI}_T = \sum_{i=1}^{4} \sum_{j=1}^{3} \text{HQ}_{ij}
\]

(13)
In the case of successive showers, total CDI and HI were calculated for both females and males using the respective inhalation CDI and the final result was correlated against the health criterion as hazard index of unity.

**Adjustment for water temperature**

Generally, warm water of 35–45 °C is preferred for showers and baths, and for that cold (room temperature) and hot waters are mixed (Chowdhury et al. 2020). The term $C_{w_i}$ in Eqs. 5, 8, and 9 is the THM concentration in cold tap water, which needs to be modified for inhalation and dermal HI to include the result of mixing with heated water. Ingestion HI can be left as it is since generally cold or room temperature water is preferred over hot water for consumption. This modification was admitted as the THM formation continues in the tap water since water purification systems leave residual free chlorine in the supply water to protect from future contamination, and natural organic matter is not removed completely by conventional treatment units. THM formation follows complex mechanisms, and it varies depending on water chemistry, residual chlorine, water temperature, and several other parameters (Padhi et al. 2019b). However, it is difficult to incorporate all the reaction parameters. The effect of water temperature was considered in this study where the rate of increase in THM concentrations in both hot and cold water were determinable. To do that, the $C_{w_i}$ in the current study was altered using a model suggested by Chowdhury et al. (2020). Using the rate of increase in THM concentration in hot water ($k_h$) and cold water ($k_w$), THMs in the mixed water can be predicted as:

$$C_{w_i} = C_{w_i} \times e^{(k_h-k_w)T}$$

(14)

where $C_{w_i}$ is the THM concentration in mixed water ($\mu g L^{-1}$) and $C_{w_i}$ is the THM concentration in cold tap water; $k_h$ and $k_w$ ($s^{-1}$) were determined using the following equation.

$$k = 0.0011e^{0.0407T}$$

(15)

where $T$ is the water temperature (°C), which was taken as 10 to 20°C with a median of 15°C for cold tap water since the sampling was carried out in the winter season. The parameters in all of the above equations, their values, and units are given in Table 2. Since these parameters are prone to uncertainty, triangular distribution was assumed for all of them which is explained below.

**Addressing the uncertainty and variability in the models**

Mathematical models used to forecast exposures are computational representations of complex real-life scenarios that involve many assumptions along with available data. Therefore, the accuracy and reliability of such models need to be assessed. One way to do that is by addressing the variability associated with the inputs and parameters involved in the models. These parameters can be the duration of the activity, gender, population, and exposure-related parameters which can vary within and between individuals. Instead of a deterministic approach, the USEPA guidelines for human health exposure assessment recommend opting for probabilistic methods such as Monte Carlo simulations for model calculations (USEPA 2019). Accordingly, in the current study, the same was adopted with 50,000 iterations using Companion by MINITAB™ software. The overall variability in the model input parameters was incorporated through statistical distributions. The THM concentration data of the samples were analyzed with the distribution identification tool of MINITAB™ software to identify the statistical distributions. The distribution with the least Anderson–Darling (AD) value (with $p$-value > 0.05) and with the highest correlation coefficient was selected in the goodness-of-fit test (Chowdhury et al. 2020). Besides that, a visual examination of the distribution ID plots was also done to finalize the most appropriate statistical distribution. For the other input parameters, triangular distributions with the most likely values of minimum, maximum and mean were adopted. Triangular distributions were selected as they minimize the biases associated with possible outliers and incorporate the variability into the model (Table 2).

**Results and discussion**

**THM concentration at consumer points**

The water distribution network of the study area is served mainly by a conventional water treatment plant (WTP) which is situated within a few kilometers of the sampling locations. Raw water to the WTP is river water and groundwater from a few deep wells within the campus. The treated water was stored in various overhead tanks before distribution to most of the sampling locations. Few deep wells within the university campus were either feeding those overhead tanks with chlorination as the only treatment process, or they were bypassing the WTP or they were used entirely for a hall of residence after passing through an in-house treatment unit of pressure filtration followed by chlorination. THMs were observed at 18 out of 20 sampling locations at concentrations less than the maximum contamination levels ($MCL = 80 \mu g L^{-1}$) recommended by the USEPA for drinking water (Table 3). As shown in Table 3, the statistical distribution of each THM was identified by considering each one of the triplicate samples to meet the criteria for the number of samples needed for distribution identification. The two
sampling locations which were devoid of any THMs were found to have zero free and total residual chlorine, indicating that these two halls were served by in-house deep wells and the water was not disinfected before supply. Total THM (TTHM) at the 18 locations with disinfection varied between 0.51 and 68.91 µg L\(^{-1}\) with a mean of 17.65 ± 11.43 µg L\(^{-1}\). This amount is comparatively less than what was observed in other parts of India. In another study conducted in the same state where the current study was carried out, the TTHMs at a WTP were as high as 594 µg L\(^{-1}\) (Mishra et al. 2014). It should be noted that previous studies from India considered either THM formation potential (THMFP) after laboratory chlorination of source water, or the THM concentrations reported were for chlorinated samples at the outlets of WTPs (Basu et al. 2011; Padhi et al. 2019a; Tak and Kumar 2017). THMFP represents the maximum THMs that can be formed in water samples under laboratory conditions. THM concentration tend to varies both within the group (with increasing reaction time a shift towards the formation of brominated THMs may happen) or between groups (with longer distribution lines, a reduction in THMs, and increase in haloacetic acids is likely) depending on reaction time, residual chlorine availability, and precursor properties (Hua and Reckhow 2012; Yu et al. 2019). Therefore, in real life, the previously reported THMFP or WTP THM concentrations may not represent the same exposure magnitude at the consumer points.

To understand the actual case of THMs at consumer points, samples from taps of households need to be collected and analyzed as in the present study. Although such studies are available from different parts of the world, only one study was found that reported THM concentrations at consumer points in India (Cotruvo and Amato 2019; Wang et al. 2019). A DBP survey conducted in Rajasthan analyzed distribution system samples from storage tank taps for 24 DBP classes (Furst et al. 2018). TTHM concentrations in the range of 35–99 µg L\(^{-1}\) were observed in this study.

### THM production in heated water

The THM growth rate\((k)\) determined using Eq. 15 was found to increase exponentially with increasing temperature (Fig. 1). There was a slight increase in THM formation in the mixed water for all 4 compounds. A total of 50,000 random realizations were generated for THM concentrations in the heated water \((C_{hw})\) (Table 3) using the statistical parameters for THM concentrations in normal tap water \((C_w)\) in Eqs. 14 and 15, and the results were used in the CDI and HI assessments. The distribution identification test of \(C_{hw}\) data showed the best-fit statistical distributions of each THMs. The AD values for each of the best-fit distributions were 0.329 \((p > 0.5)\), 0.324 \((p = 0.525)\), 0.729 \((p = 0.057)\), and 0.558 \((p = 0.149)\) respectively for TCM, BDCM, DBCM, and TBM.

![](image.png)

**Fig. 1** The effect of water temperature on THM formation in mixed shower water

| THM compound          | Average concentration (µg L\(^{-1}\)) and distribution                  |
|-----------------------|------------------------------------------------------------------------|
|                       | Normal tap water                                                      |
|                       | After mixing with heated water                                        |
| Trichloromethane      | 3 – Parameter Weibull, Shape: 1.438, scale: 5.595, threshold: 0.3189   |
|                       | 3 – Parameter Weibull, Shape: 1.440, scale: 5.832, threshold: 0.3318 |
| Bromodichloromethane  | Normal, Mean: 8.415, SD: 5.332                                        |
|                       | Normal, Mean: 8.710, SD: 5.527                                        |
| Dibromochloromethane  | Normal, Mean: 10.76, SD: 6.106                                         |
|                       | Normal, Mean: 11.20, SD: 6.308                                         |
| Tribromomethane       | Normal, Mean: 3.243, SD: 1.662                                         |
|                       | Normal, Mean: 3.365, SD: 1.725                                         |

\(^a\)Standard deviation
CDI and HQs through ingestion and dermal routes

The Monte Carlo simulations for CDI assessment resulted in 50,000 realizations of the daily intakes of THMs for females and males. The minimum–maximum range of CDI for ingestion of drinking water by females was 1.85E-06 – 3.36E-03 mg kg\(^{-1}\) day\(^{-1}\) with a median of 1.48E-04 mg kg\(^{-1}\) day\(^{-1}\) and that of males was 2.16E-06 – 2.71E-03 mg kg\(^{-1}\) day\(^{-1}\) with a median of 7.69E-04 mg kg\(^{-1}\) day\(^{-1}\). In the case of dermal absorption, females had a CDI of 2.05E-07 – 5.63E-04 mg kg\(^{-1}\) day\(^{-1}\) with a median of 1.58E-04 mg kg\(^{-1}\) day\(^{-1}\) and males had a CDI of 5.06E-07 – 5.03E-04 mg kg\(^{-1}\) day\(^{-1}\) with a median of 1.48E-04 mg kg\(^{-1}\) day\(^{-1}\). For both exposure routes, DBCM had the highest contribution to CDI as it had the highest concentration among all four THMs. The results of HQ assessment for individual THMs through each of the exposure routes are summarized in Table 4. As shown in the table, females had a higher hazard rate than males through all routes. This can be attributed to the lower body weight (BW) and higher exposure duration (ED) (life expectancy) compared to that of males.

CDI and HI through inhalation during successive showers

The CDI and the HI for 10 successive showering events for both females and males are displayed in Figs. 2 and 3, respectively. In the case of females, the CDIs of TCM, BDCM, DBCM, and TBM for the first shower were 3.03E-08 ± 2.83E-08, 4.78E-08 ± 3.90E-08, 5.23E-08 ± 3.90E-08, and 1.40E-08 ± 9.85E-09, respectively, which increased by 1.9 times for the 5th and 10th showers by 2 times for the 10th shower (Fig. 2a). The same increase was observed for the CDIs of males which were 2.58E-08 ± 2.40E-08 for TCM, 4.09E-08 ± 3.33E-08 for BDCM, 4.41E-08 ± 3.30E-08 for DBCM, and 1.19E-08 ± 8.31E-09 for TBM for the first shower (Fig. 3a). For all showering events, the CDIs were in the order of DBCM > BDCM > TCM > TBM for both genders. Interestingly, the DBCM-CDIs for the 5th and 10th showers were 7.2 and 7.4 times higher than the TBM-CDI, 3.3 and 3.4 times higher than the TCM-CDI, and 2.0 and 2.1 times higher than the BDCM-CDI of the first shower. This tendency was observed for both genders. Overall, there was a significant increase in CDI up to the 5th showering event (Figs. 2a and 3a), thereafter the rate of increase was slow.

In the case of HI, CDI followed the same trend where the rate of increase was exponential till the 5th shower and slowed down subsequently. The HQs of individual THMs for 1st, 5th, and 10th showers are listed in Table 4 For the first shower, the mean TCM-HI was 3.03E-06 ± 2.83E-06 and 2.58E-06 ± 2.40E-06, BDCM-HI was 2.39E-06 ± 1.95E-06 and 2.05E-06 ± 1.67E-06, DBCM-HI was 2.61E-06 ± 1.95E-06 and 2.21E-06 ± 1.65E-06, and TBM-HI was 7.01E-07 ± 4.92E-07 and 5.93E-07 ± 4.16E-07, for females (Fig. 2b) and males (Fig. 3b), respectively. The rate of increase in HI was also similar to that of CDI, i.e., the 5th and 10th showers had respectively 1.94- and 2-times higher HI than that of the first shower for all THMs. However, the order of HIs for all showering events was TCM > DBCM > BDCM > TBM.

| Compound | Ingestion | Dermal | Inhalation 1st shower | Inhalation 5th shower | Inhalation 10th shower |
|----------|-----------|--------|-----------------------|-----------------------|-----------------------|
| Female   | TCM       | 1.74E-02 | 1.45E-02 | 3.03E-06 | 5.88E-06 | 6.06E-06 |
|          | BDCM      | 1.52E-02 | 2.55E-03 | 2.39E-06 | 4.63E-06 | 4.78E-06 |
|          | DBCM      | 1.96E-02 | 3.26E-03 | 2.61E-06 | 5.06E-06 | 5.22E-06 |
|          | TBM       | 5.88E-03 | 9.86E-04 | 7.01E-07 | 1.36E-06 | 1.40E-06 |
| Male     | TCM       | 1.40E-02 | 1.36E-02 | 2.58E-06 | 4.99E-06 | 5.15E-06 |
|          | BDCM      | 1.24E-02 | 2.38E-03 | 2.05E-06 | 3.96E-06 | 4.09E-06 |
|          | DBCM      | 1.58E-02 | 3.05E-03 | 2.21E-06 | 4.28E-06 | 4.41E-06 |
|          | TBM       | 4.79E-03 | 9.19E-04 | 5.93E-07 | 1.15E-06 | 1.18E-06 |

Total hazard index through successive showers

The total HI was calculated for both genders by summing the HIs of each exposure route (Fig. 4a, b). For both genders, the order of significance of exposure route HIs to total HI was ingestion > dermal > inhalation. The inhalation HI was significantly less than that of both ingestion and dermal HIs. The HI through ingestion route...
for females \((5.80\times10^{-2} \pm 2.39\times10^{-2})\) and that of males \((4.70\times10^{-2} \pm 1.92\times10^{-2})\) were respectively 6642 and 6334 times higher than the inhalation HI for the first shower, which decreased to 3324 and 3170 times by the time of the 10th shower. Similarly, the HI through the dermal route was 2.7 and 2.3 times less than the ingestion HI for females and males, respectively.

A summary of previous studies that assessed the health hazards of THMs is shown in Table 5. The HI observed in the present study are consistent with past estimates. The high HI of samples collected from Indian WTPs and the HIs observed in the current study show that the HI of tap water varies at different stages of distribution indicating the need for THM occurrence surveys at the consumer points (Kumari and Gupta 2018). In general, cancer risk is given higher priority in THM risk assessments while non-cancer risks are often ignored (Ahmed et al. 2019). Further, in the HI assessments, inhalation HI is not estimated either because the inhalation CDI is several times less than the ingestion and dermal CDIs or because of the lack of RfD values for inhalation exposure (Kujlu et al. 2020; Kumari and Gupta 2018; Mosaferi et al. 2021). However, it cannot be neglected as special living conditions such as common showering facilities have an incremental effect on total HI through inhalation.

As shown in Fig. 4, total HI was less than unity and hence the water supply in this study was unlikely to cause any non-cancer health hazard to the study population. It needs to be noted that, the main health concern regarding THMs is that they are carcinogenic to humans. Thus, a cancer risk assessment study using the same CDIs as calculated in the present study and cancer slope factors of
Fig. 3 Incremental increase in inhalation a chronic daily intake and b hazard index for males through successive showers

Table 5 THM concentration and associated health hazard index for tap waters at different locations

| Location          | THM concentration (µg L⁻¹) | Hazard indexᵃ | Reference                |
|-------------------|----------------------------|----------------|---------------------------|
| Canada and Saudi  | C: 3.7–20.0                | C: 0.026       | (Chowdhury 2013)          |
| Arabia            | S: 1.7–9.4                 | S: 0.0154      |                           |
| Indiaᵇ           | 324–594                    | NAᵈ            | (Mishra et al. 2014)      |
| Indiaᵇ           | 231–484                    | 0.49101        | (Kumari and Gupta 2018)   |
| China            | 18.8–39                    | 0.030          | (Wang et al. 2019)        |
| Bangladesh       | 20.2 ±8.40–439.2±24.12     | NA             | (Ahmed et al. 2019)       |
| Iran             | 98.1–101.8                 | 0.0356         | (Kujlu et al. 2020)       |
| Iran             | 18–39                      | 0.0265         | (Mohammadi et al. 2020)   |
| Iran             | 0–683                      | 0.22           | (Mosaferi et al. 2021)    |
| India            | 0.51–69                    | 0.07           | This study                |

ᵃSum of oral and dermal hazard index
ᵇCanada
ᶜSaudi Arabia
ᵈNot assessed
eWater samples were collected from treatment plant
each THM can reveal the cancer risk for the same water. The findings of the present study are similar to those of Chowdhury et al. (2020). This is the only study that used the same approach for successive showering events, but with a different model. They observed similar patterns in the incremental increases of CDIs as well as HIs and cancer risk for up to 9 showering events, exponential increase in the beginning, and slower rate of increase towards the 9th event.

**Conclusions**

THMs were measured at the consumer points in Halls of Residence in IIT Kharagpur campus and revealed the true exposure concentrations unlike the THMFP or THM concentrations at WTPs that were reported previously in the literature. This makes the present study the first one to address the THM concentration at consumer points of an Indian water supply. Inhalation of THMs is one of the three major exposure routes for multi-pathway risk assessment which can occur mostly while showering, or through swimming pools, dealing with chlorinated disinfectants, by washing clothes or dishes. However, THM inhalation risk through showering has been studied with the assumption that the initial THM concentration is zero, which is not the case in common shower stalls where successive showering events take place. The computational human exposure model developed in the current study considers the THMs in the air left behind by the previous user of the shower stall and, therefore, it can be used to evaluate the effect of successive shower events for daily intakes and risk assessment. The inhalation CDI and HI of THMs was found to increase exponentially up to the 5th showering event and thereafter at a slower rate for both females and males. When compared to ingestion and dermal routes, inhalation route posed comparatively less risk to the total. However, with successive showering, this was found to increase up to 2 times by the 7th event. Out of all four THMs, DBCM contributed the highest to CDI and TCM to the total HI for both genders. Further, due to differences in physical parameters such as body weight and exposure duration (life expectancy), non-cancer risk to females was 16% higher than for males. Thus, the results of this study indicate that non-cancer risk increases with successive showering events even though the total HI in this study remained < 1.

**Author contribution** NP was involved in the conceptualization, design of study, THM analysis, modeling, Monte Carlo simulation, and writing – original draft; SG was involved in the design of study, supervising, and writing – review, editing, and correspondence; SC was involved in supervising and writing – review and editing. All authors read and approved the final manuscript.

**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval and consent to participate** No animals or human beings, human data or human tissue were used in this study.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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