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Modelling the concentration of chloroform in the air of a Norwegian swimming pool facility-A repeated measures study

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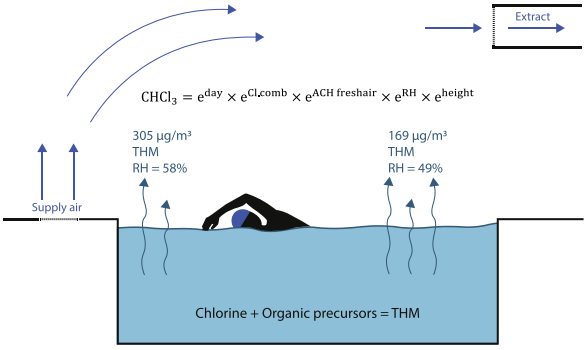
HIGHLIGHTS

- The efficiency of the traditional ventilation strategy in a Norwegian swimming facility was examined
- The covariance between air-and water quality parameters were evaluated
- Determinants for chloroform in the air were examined using a linear mixed effect model
- Predictor variables for chloroform in the air were height above water, fresh air supply, day of the week, combined chlorine and relative humidity

GRAPHICAL ABSTRACT



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ABSTRACT

Certain volatile disinfection by-products (DBPs) off-gassing from pool water can cause eye and skin irritations, respiratory problems, and even cancer. No guidelines or recommendations concerning DBPs in the air exist in Norway. Traditionally, ventilation strategies in indoor swimming pools are based on reducing condensation on the windows rather than ensuring proper air quality in the users' breathing zone.

A total of 93 air samples of airborne concentrations of trihalomethanes (THMs) were collected via stationary sampling. We investigated the distribution of total THM (tTHM) 0.05 m and 0.60 m above the water surface at six different locations in the poolroom and the covariation between the water and air quality parameters. Based on a linear mixed effects model, the most important determinants in terms of predicting the air concentration of $CHCl_3$ were height above water surface, air changes of fresh air per hour, concentration of combined chlorine in the water, relative humidity (RH) and day of the week. Approximately 36% of the total variability could be attributed to these variables; hence, to reduce the average exposure in the poolroom, hazard control should focus on these variables. Based on the identified predictor variables, the supplied air should be controlled based on water quality in addition to the traditional control censors for RH and air temperature used in the ventilation system of Norwegian swimming facilities.

1. Introduction

Chlorine is the most used water disinfectant worldwide. In Norwegian pool facilities, chlorine is often used in combination with UV

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treatment. Proper water disinfection is necessary in order to prevent the growth of hazardous microorganisms (World Health Organization, 2006), but disinfection of water with oxidizing biocides also leads to the formation of unwanted disinfection by-products (DBPs). >600 DBPs have currently been identified in disinfected water (The European Chemicals Agency, 2017). Even though a small amount of water is ingested during swimming, dermal penetration and inhalation are considered the most important routes for exposure (Chowdhury, 2015; Erdinger et al., 2004). Although there is disagreement (Löfstedt et al., 2016), exposure to volatile chloramines is considered to be the main reason for the increased prevalence of respiratory conditions, such as voice loss, sore throat, phlegm and asthma, observed in pool workers and swimmers (Chu et al., 2013; Guglielmina Fantuzzi et al., 2012; Jacobs et al., 2007). As a result, the World Health Organization (WHO) has suggested a provisional guideline value for chlorine species, expressed as NCl_3, in the ambient air of swimming facilities being limited to 0.5 mg/m^3 (World Health Organization, 2006).

Quantitatively, one of the most important group of DBPs are trihalomethanes (THM), with chloroform ($CHCl_3$), bromodichloromethane ($CHCl_2Br$), dibromochloromethane ($CHClBr_2$), and bromoform (CHBr3) being most common (The European Chemicals Agency, 2017). The two THMs $CHCl_3$ and $CHCl_2Br$ are, according to the International Agency for Research on Cancer (IARC), classified as group 2B, i.e., they are possibly carcinogenic to humans (World Health Organization, 2017). The high volatility and dermal penetration potential of the four THMs suggest that both dermal penetration and inhalation are important pathways for exposure (Erdinger et al., 2004).

1.1. Control of water and air quality in Norwegian indoor swimming pool facilities

In Norway, a declaration that the legal requirements of free and combined chlorine in swimming pool water are met must be made (Norwegian Ministry of Health, 1996). However, unlike many other countries, no upper acceptable limits for the four THMs in pool water exist. A typical indoor swimming pool ventilation system in Norway consists of supply diffusors at floor level along the window facade and return grills in the ceiling or on one wall. The ratio between fresh air and recirculated air is controlled using set points for air temperature and air relative humidity (RH). Traditionally, this ventilation strategy was chosen to prevent condensation on windows due to the cold climate in Norway and the subsequent large difference in temperature and enthalpy between indoor and outdoor air. However, stricter energy requirements now mandate the use of better- insulated windows, and condensation along the window facade is no longer considered to be of great importance. No legal requirements concerning air volume and air circulation in Norwegian swimming pool facilities exist. However, the Norwegian Industrial Technological Research Centre (SINTEF) has proposed some guidelines, one of which is to change the air volume 4–7 times per hour (ACH) in pool facilities, in general, and 8–10 ACH in rooms with hot water pools. The suggested fresh air supply is 2.8 l/s per m^2 of water surface (SINTEF Byggforsk, 2003), which is well below the suggested 10 l/s per m^2 of water surface proposed by the WHO (World Health Organization, 2006). To reduce the evaporation rate from humid skin and the water surface, it is suggested that the air temperature be kept between 1 °C and 3 °C above the water temperature, with a maximum air temperature of 31 °C. Accordingly, the air velocity above the water's surface should be <0.15 m/s (SINTEF Byggforsk, 2003).

In recent years, research has shown that poor air quality in indoor swimming pool facilities, caused by volatile DBPs off-gassing from pool water, results in an increased prevalence of irritative symptoms and asthma among workers, swimmers, and users who visit swimming pools on a regular basis (Bernard et al., 2003; Bernard et al., 2009; Varraso et al., 2002). Still, recommendations concerning ventilation focus on how to reduce water evaporation and energy consumption rather than on how to ensure proper air quality in the swimmers' breathing zone. The modelling of DBPs has been a focus in many different articles, and one of the most frequent technique used in their analyses has been multivariate regression (Al-Omari et al., 2005; Bessonneau et al., 2011; Westerlund et al., 2016).

The aims of the present study are to

1. Document the distribution of the four THMs 0.05 m and 0.60 m above the water surface in various locations in the poolroom in the morning and afternoon, and
2. By the use of a linear mixed effects model, identify the most important determinants of exposure.

2. Method

2.1. Study objective

Repeated measures design was chosen to study one pool facility located outside the city of Trondheim, Norway. This facility consists of seven swimming pools: one sports pool (25 m) with a diving springboard and platforms, three therapy pools, one baby pool, one wave pool, one Jacuzzi, and two fountains. Samples were collected during morning and afternoon, once or twice per week between the 2nd of October and 6th of November 2017. The number of visitors to this facility per year is approximately 120,000. On sampling days, the pool facility was used mainly for school children's swimming lessons (in the sports pool) and for water aerobics (in one therapy pool) for elderly people. The swimming pool water was disinfected using electrolysis of NaCl in combination with ultraviolet (UV) treatment during sampling. The water supply was from the municipal water works. The total ventilation rate, i.e., the sum of recirculated air and fresh air, was adjusted to deliver between 29,000 m^3/h (night mode ventilation) and 44,000 m^3/h (afternoon mode ventilation) of air. The total air volume in the pool facility is approximately 12,000 m^3.

2.2. Sampling plan

Air samples were collected on six days using a test stand with two heights: 0.05 m and 0.6 m above the water surface. In the morning, samples were collected from location 1 (n = 24), 2 (n = 12), 3 (n = 12) and 4 (n = 12), and, in the afternoon, samples were collected from location 1 (n = 12), 2 (n = 12), 5 (n = 6), and 6 (n = 6), see Table 1. In total, 16 samples were collected each day over time and space to represent the air quality. The samples collected from locations 1–4 were collected simultaneously from 0.05 m and 0.6 m above the water surface and by the two long sides of their respective pools, where locations 2 and 3 were on each long side of the sports pool, and locations 1 and 4 were on each long side of the therapy pool. The samples collected from locations 5 and 6 were collected only 0.6 m above the floor and 1.5 m from the pool edges bordering each side of the centre of the pool facility. The results are based on 93 out of 96 collected air samples. Three samples were rejected due to tube leakage during analysis. Information on air temperature and RH was obtained using one EasyLog USB. This logger was attached to the test stand 0.4 m above the floor or water surface and logged information about absolute air temperature and RH at intervals of 120 s. Information about free and combined chlorine, pH, and water temperature was received from the supervisory control and data acquisition (SCADA) system located in the pool facility. This online logging system collects information on water quality every second minute during the day. Information on fresh air supply, recirculated air, extracted air, and total air supply was collected from the air handling unit (AHU) that provides information on the different damper positions and how much air is being extracted and supplied to the pool facility every minute during the day.

Table 1
Measured air and water quality parameters by sampling location.

Location	Time	Height	n	RH (%)	T_{air} (°C)	$CHCl_3$ (μg/m^3)	$CHCl_2Br$ (μg/m^3)[a]
1	Morning	0.05 m	11	57.6 ± 3.5	29.4 ± 0.7	207.5 ± 56.3	3.4 ± 1.3
		0.60 m	12			176.2 ± 52.2	2.6 ± 0.7
	Afternoon	0.05 m	6	56.3 ± 2.3	29.4 ± 0.6	166.9 ± 44.6	3.2 ± 2.1
		0.60 m	6			131.4 ± 33.8	1.7 ± 0.9
2	Morning	0.05 m	5	57.5 ± 1.9	29.1 ± 0.2	272.5 ± 77.2	6.7 ± 0.8
		0.60 m	5			174.2 ± 41.9	2.8 ± 2.1
	Afternoon	0.05 m	6	58.6 ± 1.7	29.1 ± 0.6	272.3 ± 93.1	6.3 ± 2.7
		0.60 m	6			198.2 ± 67.4	3.6 ± 2.2
3	Morning	0.05 m	6	53.7 ± 3.8	29.0 ± 0.5	146.5 ± 29.6	1.2 ± 1.7
		0.60 m	6			127.9 ± 33.1	0.8 ± 1.1
4	Morning	0.05 m	6	59.5 ± 2.4	30.2 ± 0.2	216.7 ± 104.2	3.5 ± 1.0
		0.60 m	6			197.1 ± 129.6	1.3 ± 1.1
5	Afternoon	0.60 m	6	56.9 ± 5.0	27.5 ± 0.9	180.4 ± 91.8	2.3 ± 1.6
6	Afternoon	0.60 m	6	60.3 ± 2.8	28.8 ± 0.4	212.9 ± 48.3	3.0 ± 0.7

Abbreviations: n = number of samples; RH = relative humidity in the air; T_{air} = air temperature.
[a] The average of the quantified samples. Samples below the limit of quantification or below the detected limit are not included in the calculated average mean for $CHCl_2Br$.

2.3. Method of sampling, laboratory analysis, and quality assurance

Sampling, analysis, and quality assurance are in accordance with the published US EPA Method TO-17 (Compendium of methods for the determination of toxic organic compounds in ambient air, 1999). The method used for active air sampling was to collect ambient air onto automatic thermal desorption tubes (ATD) of stainless steel containing 0.20 g of Tenax TA 35/60 (Markes Int.). At 20 °C, $CHCl_3$ and $CHCl_2Br$ have reported breakthrough volumes of 3.8 l and 3.4 l per 200 mg/Tenax TA, respectively (Baroja et al., 2005). The breakthrough volume reduces by a factor of 2 for each 10 °C rise in temperature and is also effected by the pump flow (International Organization for Standardization, 2000). To find the safe sampling volume for the THM in the air, different pump flows were tested (7 ml/min, 20 ml/min, 40 ml/min, 50 ml/min and 100 ml/min) for 20 min at 0.05 m above the water surface. During these tests, the test tubes were coupled in series with an identical back-up tube to analyse if >5% of the THMs could be identified on the back-up tube. In the EPA's TO-17, it is recommended that the pump flow be above 10 ml/min in order to minimize errors due to ingress of volatile organic compounds (VOCs) via diffusion (United States Environmental Protection Agency, 1999). In the present study, two ACTI-VOC low-flow pumps (Markes Int.), adjusted to deliver a flowrate of 40 ml/min for 20 min. This pump flow rate provided a satisfactory result and was chosen to keep the uncertainty related to the flow calibration as low as possible. The pumps were calibrated in situ before and after each sample.

Determination of THMs in the air was performed with a Unity thermal desorber (Markes International) coupled an with Agilent Technologies 5975T LMT-GC/MSD. Thermal desorption was carried out for 10 min at 284 °C with a flow rate of 30 ml/min, and the collected THMs were sent to a cold trap packed with Tenax TA. Secondary desorption was then carried out with a carrier gas flow rate of 20 ml/min from the trap. The separation was performed on a capillary column (DB-1; ID 0.25 mm and 0.25 μm film thickness). The oven temperature was adjusted with a temperature program to go from 35 °C to 90 °C using 5 °C/min steps and maintain a post-run temperature of 230 °C. A selection ion monitoring (SIM) mode was used for identification and quantification of the collected THMs.

2.4. Method validation and quality assurance

Both external and internal calibration methods were utilized. For the internal calibration, the sorbent tubes were spiked with 250 ng 8260 Internal Standard Mix 2 (Supelco) containing chlorobenzene-d_5, 1.4-dichlorobenzene-d4 and fluorobenzene in methanol. For external calibration, a five-point calibration curve, ranging from 0.5 ng to 500 ng, was created for each of the four THMs. A THM calibration mix (Supelco) in methanol (n = 25) was used for this purpose. All duplicate measures and volume pairs of tubes were within a precision of 5%. Once per week, one test tube, 0.05 m above water surface, was coupled in series with an identical back-up tube to verify no breakthrough (United States Environmental Protection Agency 1999).

Identification and quantification of THMs were performed in selection ion monitoring (SIM) mode in the laboratory of the division of Health, Safety and Environment at the Norwegian University of Science and Technology (NTNU). The water activity, air and water temperature, number of users, RH, pH, free and combined chlorine, supplied and extracted air volume, and amount of fresh air and recirculated air were recorded during sampling. Statistical analyses were performed using the Statistical Package for Social Sciences (SPSS) 25.00.

2.5. Statistical analysis

One-way analysis of variance (ANOVA) was used to study if the measured variables varied significantly between the different days of sampling. Since $CHCl_3$ was the only component detected in the collected samples, $CHCl_3$ was the only component included in the modelling of the air concentration. The concentration of $CHCl_3$ was positively skewed and was ln-transformed prior to statistical analysis. To account for the correlation between the repeated measures, the concentration of $CHCl_3$ was modelled using a linear mixed effects model. Judging from the likelihood ratio test, the covariance structure of the first-order autoregressive (AR (1)) model for the repeated samples produced the best fit for the data ($p \le 0.05$). Determinants were treated as fixed effects and kept in the model if the p-value was <0.05 and if they could justify the more complex model, as judged by the likelihood ratio test ($p \le 0.05$). The interest of this study was not in the effects present only at individual sampling locations but rather in the effects present within the poolroom. Sampling locations were therefore treated as a subject, including the random specific intercept of location, in the model. To estimate the variance components, the method of restricted maximum likelihood (REML) was used since this method is considered to be more precise, ice, it reduces the standard error, for mixed effects modelling compared to maximum likelihood (Leech et al., 2015; Baayen et al., 2008). The contribution of the fixed effects was estimated by comparing the variance component of the final model to the variance components estimated in the initial model, in which only the subject-specific intercept was included. The final model included $ACH_{freshair}$, height above the water surface, day of the week, concentration of combined chlorine and RH.

The linear mixed effect model with random subject-specific intercept predicting the contamination of the ln-transformed $CHCl_3$ can be back-transformed to estimate the exposure levels of different

combinations of predictor variables using the following formula:

$$E = e^{intercept} \times e^{determinat\ 1} \times e^{determinant\ 2} \times \ldots. \times e^{determinant\ n},$$

where E is the estimated geometric mean exposure, the intercept represents the true underlying concentration level (fixed) over all subjects (here, sampling locations) and the determinant n represents the identified significant determinates of exposure.

3. Results

All water quality parameters obtained in this study were in accordance with the Norwegian regulations. In Table 1, the quantified air quality parameters are presented as mean ± standard deviation (SD), along with their sampling locations. In general, $CHBr_3$ was not detected in any of the collected air samples, and $CHClBr_2$ was either not detected or below the limit of qualification. $CHCl_2Br$ was quantified in 53 of the 93 collected air samples. In these 53 samples, $CHCl_2Br$ accounts for 0.05%–2.6% of the tTHM, while the rest of the quantified tTHM was $CHCl_3$.

All variables, except the number of bathers and air and water temperatures, differ significantly according to day of sampling. ACH represents how many times the air is exchanged per hour in the poolroom, regardless of whether the air consists of fresh air, recycled air, or a mixture of the two. $ACH_{freshair}$ represents how many times per hour the air in the poolroom is exchanged with outside air. This value is estimated based on the valve position opening recorded in the ventilation log and information from the ventilation supplier, who were able to read off the exact fresh air supply from their logging system. ACH and $ACH_{freshair}$ for the different days of sampling are listed in Table 2, along with information on the mean $CHCl_3$ and $CHCl_2Br$ concentration measured in the morning and afternoon.

As shown in Table 2, the ACH was always lower than the Norwegian recommended ACH of 4-7. During night-mode ventilation, from 8 PM to 6 AM, between 2.5 and 2.9 ACH was supplied to the swimming facility, and, of this, between 0% and 33% was fresh air. The first day of sampling (October 2nd), there was an issue with the fresh air dampers, and almost no fresh air was supplied to the pool facility (0.4 ACH fresh air) during the morning. Day-mode ventilation was switched on at 6 AM, and the supplied air volume increased slowly from 6 AM to 8 PM in the evening.

The linear mixed effects model for the concentration determinants for $CHCl_3$ is presented in Table 3. Before any of the fixed variables were accounted for, i.e., only the subject-specific intercept was included in the model, the estimated between and within location variabilities were $\sigma_b^2 = 0.015$, and $\sigma_w^2 = 0.12$, respectively. The interclass correlation among locations was also highly dependent, with an AR (1) rho value of 0.30 ($p = 0.01$) and scores for each location highly dependent on one another. After the determinants improving the fit of the model were adjusted for, σ_b^2 decreased to 0.008 and σ_w^2 decreased to 0.079, hence, it is clear that σ_w^2 has greater weight than σ_b^2. Approximately 47% and 34% of the between and within variability observed, respectively can be attributed to the determinants identified in Table 3.

Table 3
Significant determinants for $CHCl_3$ estimated using a linear mixed effects model.

Effect	Estimate (SE)
[a]Intercept	2.69 (0.57)**
Height above water	
0.05 m	0.24 (0.03)**
0.60 m	0
Day of the week	
Monday	0.20 (0.06)**
Wednesday	0
$Cl_{combined}$	1.67 (0.55)**
$ACH_{freshair}$	−0.13 (0.04)**
RH	0.04 (0.01)**
	Variance (SE)
Between-location variance	0.008 (0.03)
Between samples covariance (rho)	0.668 (0.12)**
Within-location variance	0.079 (0.03)**
% of between variance explained by fixed effects	46.7%
% of within variance explained by the fixed effects	34.2%

Abbreviations: SE = standard error; $Cl_{combined}$ = combined chlorine; RH = relative humidity.
[a] Intercept represents the true underlying concentration level (fixed) over all sampling locations.
** $p \le 0.001$.

Sample calculation based on estimated exposure to $CHCl_3$ (E) 0.05 m above the water surface on a Monday, with a concentration of $Cl_{combined}$ of 0.24 mg/l, $ACH_{freshair}$ of 2 and a RH of 55%:

$$E = e^{2.69} \times e^{0.24} \times e^{0.20} \times e^{(1.67\times0.24)} \times e^{(-0.13\times2.0)} \times e^{(0.04\times55)} = 237.7\ \mu g/m^2$$

4. Discussion

4.1. The distribution of $CHCl_3$ among heights and locations in the poolroom

This study describes the variation in repeated samples of $CHCl_3$ obtained from different stationary sampling locations within the same poolroom. In some previous studies, results have been based on a limited number of air samples, often collected from only one stationary sample location above the swimming pool (Erdinger et al., 2004; Nitter et al., 2017). However, the assumption that one sampling location

Table 2
ACH, $ACH_{freshair}$, and mean concentration of $CHCl_3$ and $CHCl_2Br$ (mean of both heights and all sampling locations) obtained by sampling date.

Date	Time	ACH	$ACH_{freshair}$	n	Mean $CHCl_3$ (range) ($\mu g/m^3$)	Mean $CHCl_2Br$ (range) ($\mu g/m^3$)
02.10[a]	Morning	3.0	0.4[c]	8	274.9 (164.7–457.0)	n. d.
	Afternoon	3.4	2.9	6	172.9 (87.2–358.9)	n. d.
04.10[b]	Morning	3.1	2.5	10	120.8 (80.7–159.8)	n. d.
	Afternoon	3.6	3.6	6	150.9 (110.8–199.1)	2.8 (1.5–4.0)
09.10[a]	Morning	3.2	2.4	10	165.1 (124.0–285.8)	2.8 (0.3–6.6)
	Afternoon	3.7	3.7	6	196.7 (132.6–308.5)	3.9 (1.5–7.1)
16.10[a]	Morning	2.9	2.2	10	216.3 (152.4–362.6)	2.8 (n.d-6.0)
	Afternoon	3.4	3.4	6	218.0 (157.6–355.5)	3.0 (0.9–7.3)
18.10[b]	Morning	3.1	2.5	10	169.9 (97.9–251.0)	1.2 (0.1–2.5)
	Afternoon	3.6	3.6	6	182.7 (110.8–267.0)	2.1 (0.4–3.3)
06.11[a]	Morning	3.0	1.9	9	204.6 (147.7–308.4)	3.9 (2.0–7.6)
	Afternoon	3.0	2.1	6	241.0 (146.5–371.9)	5.1 (1.6–10.0)

n. d. = not detected or below the calculation limit.
[a] Monday.
[b] Wednesday.
[c] A fault with the fresh air dampers.

can represent the air quality for the entire facility may be incorrect. In a recently published study of one indoor swimming pool in Canada, results showed that some zones have appropriate air-renewal, while others are poorly ventilated or even over-ventilated (Lebon et al., 2017). It is also known that parameters such as water temperature, water turbulence, water surface, RH and air temperature can impact air quality (Shah, 2014). As this pool facility consists of swimming pools with different surface areas, water temperatures and activity levels, it is reasonable to assume that local air contamination will vary, despite ventilation system efficiency.

During the morning, air samples were collected from locations 1 and 4 by the therapy pool. As shown in Table 1, the average concentration of $CHCl_3$, RH, and air temperature were always slightly higher at location 4 versus location 1, although not significantly. As shown in Table 1, there was a greater difference between the air quality parameters measured at locations 2 and 3 by the sports pool. However, when considering heights, only 37% higher values of $CHCl_3$ were obtained 0.6 m above water surface at location 2 compared to location 3, and the variability shows no significant difference between the two locations at this height. When we looked at samples collected 0.05 m above the water surface, 88% higher values were obtained at location 2 compared to location 3, a statistically significant result. This finding suggests that there is a dead zone by location 2, where the mean age of air is greater compared to the mean age of the air observed at location 3. Although the evaporation mass flow increases with decreasing RH (Asdrubali, 2009), the concentration of $CHCl_3$ was found to increase with increasing RH. RH was also found to be one of the most important predictors of exposure to air contamination levels of $CHCl_3$.

Another important predictor identified for the concertation level of $CHCl_3$ was height above the water surface. On average, between 8% and 57% higher concentrations of $CHCl_3$ were obtained at 0.05 m than 0.60 m. Higher concentrations have also been measured closer to the water surface in previous studies in which samples at different heights have been collected (Nitter et al., 2017). However, in a French study, in which the air concentrations of tTHM were measured from two different heights (0.25 m and 1.5 m) above the water surface, the authors did not find any statistically significant difference between the chosen sampling locations (Bessonneau et al., 2011). This might be explained by the difference in chosen heights and possibly a different ventilation strategy. Even though air velocity was not measured in the present study, the ventilation strategy is designed to deliver low air velocities above the water surface to reduce the evaporation rate from the water. This might result in a layer above the water surface where the air is not changed as often as the air in the rest of the poolroom. To collect representative information about the exposure among the swimmers, it is therefore essential to collect air samples as close to the water surface as possible.

4.2. Predictor variables for the concentration of $CHCl_3$

Limited information about the importance of proper ventilation in preventing the accumulation of DBPs above the water surface exists. In a previous study, it was found that the ventilation rate was strongly associated with the measured level of the volatile NCl_3 in the air. The authors estimated that >2 $ACH_{freshair}$ was necessary in order to keep the level of NCl_3 below the French limit value of 0.3 mg/m^3 (Levesque et al., 2015). In our study, the ACH in the pool facility was below the Norwegian recommendations of 4–7 ACH per hour, but this variable was not found to be an important predictor variable for the air concentration of $CHCl_3$. $ACH_{freshair}$, however, was estimated to be an important determinant and a minimum requirement for $ACH_{freshair}$ is considered to be necessary in order to ensure proper air quality in the swimmers' breathing zone. No upper acceptable contamination limit for tTHM in the air of indoor swimming pool facilities exists in Norway. The German Federal Environmental Agency recommends that the concentration of $CHCl_3$ in a swimming pool facility be ≤200 μg/m^3 air (VDI 2089, 2010). In our study, 33% of the air samples exceeded this value, and, of these, 75% were observed 0.05 m above the water surface. If we are exposed 0.05 m above the water surface together with five other bathers on a Monday, with a combined chlorine concentration in the water of 0.24 mg/l and an RH of 58%, we need an $ACH_{freshair}$ of approximately 3.1 to keep the concentration of $CHCl_3$ below 200 μg/m^3.

The filters and dehumidification unit in the ventilation system manage, to some extent, to remove particles and keep the humidity and the air temperature in the recirculated air under control, and the variability observed in these variables was low compared to the variability observed in $CHCl_3$. Gases off-gassing from the pool water will pass through the filters and therefore may be recirculated back into the room with the recirculated air (Hery et al., 1995). Considering the determinants of concentration identified in Table 3, the supplied air should be balanced with respect to the water quality as well as the bather load, and not just the RH and air temperature, as it is today. The variations obtained within the pool room highlight the need for a new ventilation strategy, as supplied ventilation air should provide proper air quality in the users' breathing zone and not along the window facade. For future studies, the use of absorbent filters in the air handling unit should also be tested to see if they reduce the gas concentration in the recirculated air sufficiently.

One of the main advantages of using a linear mixed effects model is the ability to account for the correlation between the repeated measures using covariance structures. The determinants identified in Table 3 explained about 35.5% of the total variability observed in $CHCl_3$, and these determinants should also be prioritized if hazard control is considered necessary. When all determinants improving the model were accounted for, the correlation between the repeated measures was estimated to be 0.69 using AR (1). Therefore, the observations are highly dependent and, in order to enhance the precision in the estimates of exposure, handling this dependence is important in terms of preventing biased estimates of the point estimate and confidence interval. Another advantage is the model's ability to adjust for factors that might unfold during the experiment, such as the free and combined chlorine and fresh air supply. Being able to make adjustments allows us to investigate in naturalistic settings and not just under controlled experimental conditions (Baayen et al., 2008). Adjusting for variables that might influence the variable of interest is important for the credibility of the study and for estimating the influence from different effects.

5. Conclusion

The concentration of $CHCl_3$, RH, and air temperature vary within the pool facility and around the same swimming pool, and the within-location variability suggest that repeated samples over time are necessary in order to understand the long-term mean concentration. The chosen ventilation strategy does not ensure the same air exchange for all locations in this pool facility, and, based on the identified predictor variables, hazard control should focus on increasing the air renewal of the layer above the water surface. ACH did not explain the variability in the observed concentration of $CHCl_3$; however, $ACH_{freshair}$ did. Based on the identified determinants of contamination, the supplied air should be balanced with respect to bather load and water quality, and not just RH and air temperature, as it is today.

Conflict of interest

The authors have no competing interests to declare.

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