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Can CO_2 sensors in the ventilation system of a pool facility help reduce the variability in the trihalomethane concentration observed in indoor air?

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ABSTRACT

Volatile and hazardous compounds are formed during the chlorination of pool water. Monitoring components in the air, such as the four trihalomethanes; chloroform, dichlorobromomethane, dibromochloromethane and bromoform (tTHM), is challenging. Carbon dioxide (CO_2) sensors are used for controlling air quality in different buildings and can be installed in ventilation systems for continuous surveillance and monitoring purposes. However, such sensors are not used in indoor swimming facilities. In this study, samples of tTHM and CO_2 were collected and analysed, along with other air and water quality parameters such as combined chlorine, to evaluate whether CO_2 sensors could be used to explain the observed variability in the tTHM concentration in an indoor swimming facility and thereby reduce the exposure of individuals utilising the pool to tTHM. Random intercept models were built for the tTHM and CO_2 concentrations, respectively, and the results show that the relationships between combined chlorine in the water, CO_2 in the air and number of occupants explain 52% of the variability in tTHM. The correlation between occupancy and CO_2 concentration ($\rho = 0.65$, $p \leq 0.01$) suggests that CO_2 sensors should be used so that the air supply corresponds to the demand of the users.

1. Introduction

People in developed countries spend an average of 80–90% of their time indoors (ASHRAE, 2016), and sufficient indoor air quality (IAQ) is necessary to maintain a healthy indoor environment. However, due to the evaporation of potentially hazardous gasses from the pool water's surface, indoor swimming facilities introduce unique IAQ challenges compared to those observed in offices and residential buildings (Lebon et al., 2017). In pool facilities, there are increased risks of moisture damage, bacterial growth and corrosion (Ciuman and Lipska, 2018; Liu et al., 2018), and in many facilities, the occupants complain regularly about thermal comfort, respiratory irritations and skin problems (Nitter et al., 2019).

Although improper disinfection is associated with outbreaks of fatal contaminants in the water (World Health Organization, 2006), the reaction between free chlorine and precursors in the pool water, introduced by swimmers and from filling water (Deutsches Institut für Normung (DIN), 2012), also leads to the formation of disinfection by-products (DBPs) (Daiber et al., 2016). Volatile DBPs, such as trihalomethanes (THM), can be potentially hazardous to human health if individuals are exposed to high concentrations over a long period of time (Font-Ribera et al., 2018; Gouveia et al., 2019). Typically the following four THM, referred to as total THM (tTHM) are formed as a result of chlorination: bromoform, dibromochloromethane, chloroform and dichlorobromomethane, of which the last two are characterized as potentially carcinogenetic to humans by the International Agency for Research on Cancer (IARC) (World Health Organization, 2017). In previous studies, the air concentrations of tTHM have been found to correlate with the volatile trichloramine (NCl_3) concentration (Cossec et al., 2016; Nitter and Svendsen, 2019a), which is related to the increased prevalence of respiratory irritations amongst swimmers and lifeguards (Chu et al., 2013; Jacobs et al., 2007; Lévesque et al., 2006; Andersson et al., 2018).

In order to control the relative humidity (RH) and air temperature in the poolroom, the room is ventilated mechanically. The air supply grills are typically located at floor level, and the air is supplied to the room at

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Abbreviations: ACH, air changes per hour; AR(1), first order autoregressive; CO_2, carbon dioxide; DBP, disinfection by-product; IAQ, indoor air quality; RH, relative humidity; tTHM, sum of the four most common trihalomethanes; UV, ultra violette

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relatively high velocities to mix the air by jets up along the window façade. However, the distribution of air in such facilities is often complex and inadequate (Lebon et al., 2017; Nitter and Svendsen, 2019b). Worldwide, the most common measure for the concentration of precursors in swimming pool water is combined chlorine, a product of the reaction between ammonia and free chlorine. Combined chlorine is also the only DBP for which a pool water limit value exists in Norway; no other DBPs are being controlled either in the air or in the water (Norwegian Ministry of Health, 1996). The German Federal Environmental Agency suggests that the concentration of chloroform (one of the four THMs) in the air should never exceed 200 µg/m^3, as this value indicates improper air and/or water quality (Verein Deutsher Ingenieure, 2010).

The absence of required limit values for DBPs in the air of pool facilities makes it difficult to judge whether the air renewal is adequate. Monitoring the most hazardous components is also challenging, as no easy measurement techniques, such as sensors for characterizing NCl_3 and tTHM concentrations in the air, exist.

Carbon dioxide (CO_2) is exhaled when people breathe, and this component is considered to be a good indicator of the number of occupants in a given room (Dougan and Damiano, 2004; Seppänen et al., 1999). The development of different sensors for the continuous surveillance and measurement of CO_2 have also made it easy to monitor this gas (Norbäck et al., 1995; Qiao et al., 2019). In Norway, it is recommended that the air supply be controlled in sport halls with the use of sensors for CO_2 and air temperature (Ministry of Culture, 2016). Such sensors, however, are not used in swimming facilities.

Findings from previous studies show that the concentration of CO_2, in addition to the occupancy level, could function as an indicator for other components that are related to illness (Norbäck et al., 1995; Padhi et al., 2012; Rodríguez et al., 2018). Studies have also identified insufficient ventilation, such as condensation on window surfaces, high CO_2 concentrations and occupancy level, to be associated with high tTHM concentrations (Gabriel et al., 2019). Based on knowledge from previous studies, the aim of the present study is to investigate whether the measured CO_2 concentration can be used as an effective indicator for predicting tTHM concentration in a swimming pool facility.

2. Materials and methods

2.1. Pool dimensions, air handling and water treatment

In this study, one poolroom built in 2018 and containing one swimming pool (12 m × 8 m) was investigated. The total air volume in the poolroom was approximately 1050 m^3. The swimming pool was filled with freshwater and disinfected using sodium hypochlorite (NaOCl) in addition to UV treatments. During the sampling days, the air change rate (ACH) varied between 5.1 and 5.7 h^{-1}, with a fresh air rate of between 70 and 100%. During night-mode ventilation, the ACH was reduced to 60–70% of the day-mode ventilation. The air supply was controlled using set points of RH and air temperature and was preheated in the ventilation unit before being supplied to the room. The air was supplied to the room by grills located on the floor and up along the window façade. To mix the air in the room, the air was supplied at relatively high velocity. During air sampling, the swimming pool was being used mainly for swimming education.

2.2. Sampling strategy

Due to the sampling and analytical procedures, each tTHM sample had to be collected over 20 min. In total, 65 samples of tTHM were collected, simultaneously with CO_2, RH and air temperature, over the course of three Tuesdays and four Thursdays during a four-week period. CO_2, RH and air temperature were collected at intervals of two minutes and were logged continuously while present in the poolroom. One 20-minute sample of tTHM was collected every 30 min from 10:00 to 15:00, except for the final day, when samples were collected from 12:00 to 14:00. All air quality parameters (tTHM, CO_2, air temperature and RH) were collected from 0.30 m above the floor level using a test stand. The location of the test stand is shown in Fig. 1. In a previous study, no differences in tTHM concentration were found between 0.05 m and 0.30 m, and the concentrations measured from 0.30 m were therefore assumed to be representative of the concentration in the breathing zone of the occupants in the pool (Nitter and Svendsen, 2019a). The test stand was placed approximately 2.8 m from the pool edge to prevent interference with the activity in the room. Before sampling was carried out, the air temperature and RH were measured from two different locations in the room to investigate whether the air in the room could be considered fully mixed. The two locations are shown in Fig. 1.

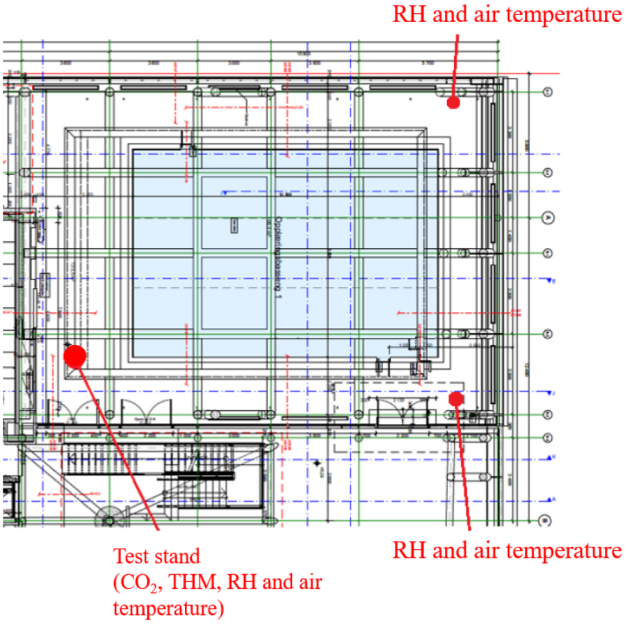

Fig. 1. Sketch of the pool facility with its sampling locations.

2.3. Air samples and analysis

Samples were collected using the active air sampling method, by which air is pulled into an automatic thermal desorption (ATD) tube using a pump. The ATD tubes contained 200 mg of Tenax TA 35/60 (Markes Int, 2019b) and were fastened to one Acti-Voc low-flow sampling pump (Markes Int.) (Markes Int, 2019a). The pump was calibrated to deliver a flow rate of 40 ml/min for 20 min, which has been found to provide satisfactory results with regards to both safe sampling volume and uncertainty (Nitter and Svendsen, 2019b). The pump was calibrated in the poolroom before and after each sample. The ATD tubes were sealed with Swagelok fittings with PTFE ferrules and packed in uncoated aluminium foil, both before leaving the lab and immediately after sampling. To prevent the ATD tubes from being contaminated, they were always stored in an airtight container with charcoal when not in use. The sampling, analysis, and quality assurance for collecting samples of tTHM in the air were based on the methods published in US EPA TO-17 (United States Environmental Protection Agency, 1999) and the ISO standard 16017 (International Organization for Standardization, 2000). Samples of tTHM were identified and quantified using a GC/MSD in the laboratory of Health Safety and Environment at the Department of Industrial Economics and Technology Management, NTNU, Norway. The analysis setup is explained elsewhere (Nitter et al., 2018).

The air temperature and RH were recorded every two minutes using one EasyLog USB (EL-USB-2). The concentration of CO_2 was measured every second minute using a KIMO AQ 200. Information on tube number, time, flow rate, water activity and number of occupants was logged for each sample of tTHM collected. The water concentration of

Table 1
Mean for physical and chemical parameters and number of occupants for the different sampling days.

Day	Number of Occupants	Cl_{Comb} (mg/l)	T_{air} (°C)	RH (%)	tTHM (µg/m^3)	CO_2 (ppm)	ACH (h^{-1})	n†
1	7	0.12	29.0		112.0	626	5.7	10
2	14	0.15	29.0		116.3	641	5.1	10
3	14	0.13	28.4	56.9	116.8	639	5.6	10
4	15	0.10	28.6	55.0	88.9	649	5.7	10
5	13	0.19	28.5	60.0	134.6	668	5.5	10
6	5	0.20	28.7	56.1	126.8	620	5.6	10
7	14	0.20	29.0		184.0	659	5.1	5

Abbreviations: Cl_{Comb} stands for combined chlorine, T_{air} stands for air temperature.

† Based on the number of tTHM samples collected.

free and combined chlorine was logged continuously in the facility. To calibrate the logging instrument, the concentrations of free and combined chlorine were measured manually at least three times per day during open hours, in accordance with the Norwegian regulations (Norwegian Ministry of Health, 1996). After each day of sampling, the concentrations of free and combined chlorine, pH and water temperature were provided by the technical staff who performed these measurements.

2.4. Statistical analysis

All variables observed in this study were interpreted and analysed using the statistics software package STATA 15.1. The average measured CO_2 concentration, RH and air temperature for each tTHM sample (lasting for 20 min) was used in the statistical analysis. Descriptive data for the different variables measured in this study are presented in Table 1. Due to some skewness in the data, tTHM and CO_2 concentrations were transformed using the natural logarithm function before parametric methods were applied. The residuals for the tTHM and CO_2 concentrations were tested for normality using the Shapiro-Wilk test and plotted using histograms. Based on the results, the null hypothesis of normality could not be rejected.

The dataset consisted of both continuous variables (such as tTHM and CO_2 concentrations, number of occupants, air temperature, RH, ACH and combined chlorine) and ordinal cyclic variables (such as day of the week and time during the day). To estimate the independence and variability of the collected data, random intercept models for tTHM and CO_2 concentrations were built, where day was used as cluster unit, and time was used as unit for repeated measures. In the random intercept model, the natural logarithm transformations of the two components ($\ln C_{ijk}$) were used as dependent variables. In the model for tTHM concentration, the number of occupants, the concentration of combined chlorine and the CO_2 concentration were interpreted as fixed effects. The same approach was used for CO_2, but, in this second model, the tTHM concentration was included as a fixed effect, and the concentration of combined chlorine was excluded, as this variable did not explain any of the observed variability. The geometric mean exposure, as determined by the identified variables, can be estimated by back transformation of the regression coefficients using the following formula:

$$E = e^{c+b_1+b_2\cdots} = e^c \times effect_{determinant_1} \times effect_{determinant_2}, \qquad (1)$$

where E is the exposure, c is the intercept of the regression model and b_1 and b_2 are the regression coefficients of the predictor variables. The final model was estimated using the method of restricted maximum likelihood. Other variables, such as the interaction between combined chlorine and number of occupants, RH, air temperature and ACH, were tested for both models, but, as they were not statistically significant (at $p \leq 0.05$), they were taken out of the model again. IAQ parameters are often autocorrelated as a result of limited mixing of contaminants and insufficient air exchange (Luoma and Batterman, 2000). To account for the potential correlation between the repeated samples collected on the same day, different covariance structures were tested using the log likelihood ratio test. The covariance first-order autoregressive (AR (1)) structure was used for both models. The AR (1) structure assumes that the correlation function decays exponentially as the intervals between the measurements increase (Peretz et al., 2002).

3. Results

In Table 1, an overview of the mean values for the different variables measured in this study is shown. The water temperature, concentration of free chlorine and pH value were stable throughout the study period at 31 °C, 0.8 mg/l and 7.2, respectively; therefore, these values are not included in the table. As shown, the average daily concentrations of tTHM and CO_2 measured ranged from 88.9 µg/m^3 to 184.0 µg/m^3 and 620 ppm to 668 ppm respectively. Except for dibromochloromethane, which was not quantifiable on three samples, all four tTHM were quantified in all samples, in which chloroform accounted for 82% of the quantified tTHM, while bromodichloromethane, dibromochloromethane and bromoform accounted for 9.5%, 1.0% and 7.5% respectively. During the period of sampling, the mean outdoor air temperature, measured from the city weather station, varied between −9.2 °C and 7.7 °C. The measured air temperature was very stable, and the difference between the lowest and highest measure was only 0.6 °C.

In Table 2, the parameters that were significantly correlated with CO_2 and THM concentrations are shown. As expected, a statistically significant correlation between the measured level of CO_2 and number of occupants in the room was obtained ($\rho = 0.645, p = 0.01$). A significant Pearson's correlation was also obtained between the natural logarithmically transformed tTHM concentration and the natural logarithmically transformed CO_2 concentration ($r = 0.38, p \leq 0.01$). Both the CO_2 and tTHM concentrations are significantly and positively correlated with RH; i.e. when RH increases, air contamination rises. A significant negative correlation between tTHM concentration and ACH was also found.

Table 2
Significant Spearman's correlations (ρ) with tTHM and CO_2 concentrations.

	Number of Occupants	Cl $_{comb}$	tTHM	CO_2	RH	ACH	T_{air}
Number of Occupants		−0.11	0.22	0.65**	0.25	−0.03	−0.26*
Cl_{comb}	−0.11		0.61**	0.02	0.22	−0.44**	−0.00
THM	0.22	0.61**		0.34**	0.53**	−0.33**	−0.10
CO_2	0.65**	0.02	0.34**		0.46**	0.02	0.25*
RH	0.25	0.22	0.53**	0.46**		−0.18	−0.35*
ACH	−0.03	−0.44**	−0.33**	0.02	−0.18		−0.14
T_{air}	−0.26*	−0.00	−0.1	−0.25*	−0.35*	−0.14	

Abbreviations: T_{air} stands for air temperature, Cl_{comb} stands for combined chlorine.

* $p \leq 0.05$.

** $p \leq 0.01$.

Table 3
Random intercept model for Ln tTHM with estimates of random effects.

Parameter†	Estimate‡	95% Confidence interval	
Intercept	3.036	2.34	3.73
Number of occupants	0.005	0.00	0.01
Combined chlorine	4.299	0.91	7.69
CO_2 concentration	0.002	0.001	0.003
Random effects†	Variance explained by random effects		
Within day variability (σ_w^2)	0.021	52%	
Between day variability (σ_b^2)	0.012		
Correlation between repeated measures	0.73		

† All parameters are significant at $p < 0.05$.

‡ The estimates are for each one unit increase in the parameters and how much this increases the tTHM concentration. Example: One ppm increase in CO_2 gives an $e^{0.002} = 1.002$ or a 0.2% increase in tTHM. The estimated model parameters may only be valid for the observed values.

The parameter estimates for tTHM concentration using a random intercept model are shown in Table 3. Before the variables were added to the model, the estimated total variability was 0.070. After the three significant variables (i.e. CO_2 concentration, number of occupants and concentration of combined chlorine in the water) were included in the model, the total variability was reduced to 0.033, meaning that three variables thereby explained 52% of the total variability observed. The correlation between the repeated observations within the same day was estimated as 0.73, meaning that ignoring the correlation between the repeated observations might lead to incorrect parameter estimates.

In Table 4, the random intercept model for the CO_2 concentration is shown. For this component, only two explanatory variables (tTHM concentration and number of occupants) contributed significantly to the model. These two variables explained 44% of the observed variability. The correlation between the repeated observations was low (0.081), meaning that the observations of CO_2 concentrations can be assumed to be approximately independent of these variables and that other independent observations might be useful in analysing the results.

The CO_2 concentration can be estimated using Eq. (1) and the regression coefficient in Table 4. For example, if the concentration of tTHM is 200 μg/m^3 and the number of occupants is 20, results in an estimated geometric mean CO_2 concentration of:

$$E = e^{c+b_1+b_2\cdots} = e^{6.3365} \times e^{(0.00426\times 20)} \times e^{(0.00063\times 200)} = 698 \quad \text{ppm}$$

4. Discussion

Epidemiological evidence suggests that there is an association between exposure in swimming pool facilities and health effects such as irritations to the skin, eyes and respiratory tract and even cancer (Gouveia et al., 2019; Fantuzzi et al., 2010; Hery et al., 1995; Jacobs et al., 2007). To protect people who are regularly exposed in such environments from increased risk of disease, the implementation of guidelines and control strategies is considered necessary. Volatile compounds, such as NCl_3 and tTHM, in the air of indoor swimming facilities have been studied in previous literature (Afifi and Blatchley, 2015; Hsu et al., 2009; Nitter and Svendsen, 2019a); however, these components are difficult and expensive to measure and analyse, and no sensor technology allowing for continuous monitoring exists. Air concentrations of tTHM may be used as an indicator for the air concentration of NCl_3 (Nitter and Svendsen, 2019a; Cossec et al., 2016). If sensors for CO_2 could be used to predict the tTHM concentrations in the air, controlling the air quality in swimming facilities would become less complex. In this study, the indoor concentration of CO_2 was measured in parallel with the tTHM concentration in order to investigate whether CO_2 could be used to estimate the number of occupants and function as an indirect indicator for the tTHM concentration in the air.

Table 4
Random intercept model for Ln CO_2 with estimates of random effects.

Parameter†	Estimate	95% Confidence interval	
Intercept	6.337	6.28	6.40
Number of occupants	0.004	0.003	0.006
tTHM	0.001	0.0001	0.001
Random effects†	Variance explained by random effects		
Within day variability (σ_w^2)	0.003	44%	
Between day variability (σ_b^2)	0.000		
Correlation between repeated measures	0.081		

† All parameters are significant at $p < 0.05$.

4.1. Can CO_2 be used to estimate contamination by tTHM?

The highest value of tTHM, 184 μg/m^3, was measured the final day of sampling and is close to the threshold value of 200 μg/m^3 recommended by the German Federal Environmental Agency (Verein Deutsher Ingenieure, 2010). In a recent study, where mean air concentrations of tTHM was measured to be 205 μg/m^3, the cancer risk among elite swimmers was found to be unacceptably high (Gouveia et al., 2019), and therefore keeping the concentrations below 200 μg/m^3 is considered necessary to protect the occupants in the poolroom. Pearson's correlation between the air concentrations of CO_2 and tTHM shows a statistically significant relationship between the two ($r = 0.38$, $p \leq 0.01$). However, this relationship is far from linear, and the CO2 concentration is not considered an optimal means for controlling the air concentration of tTHM. As shown in Table 3, the concentration of tTHM depends on the water concentration of combined chlorine, occupancy level and CO_2, and these variables combined explained 52% of the observed variability in tTHM concentration. If one assumes that the concentration of combined chlorine in the water is stable around 0.15 mg/l and that the pool capacity is 20 people, then one can allow the CO_2 concentration to be around 700 ppm while keeping the geometric mean concentration of tTHM below 200 μg/m^3. This limit value may only help control the IAQ in poolrooms of the same size, same water quality, same occupancy level and same ventilation strategy as in the investigated poolroom.

As of today, the air supply in this facility is controlled using sensors for RH and air temperature. Controlling these parameters is necessary to control the energy use and to protect the building construction (SINTEF Byggforsk, 2003), and these sensors allow the amount of recirculated air to be adjusted. The dehumidification unit makes the system robust towards changes in outdoor and indoor conditions concerning RH. However, as shown in Table 2, a negative correlation between ACH and tTHM was observed, meaning that when the ACH increases, the tTHM concentration decreases. Adjusting the amount of recirculated air or ACH to adjust RH will therefore cause changes in the level of tTHM or other DBPs. Overall, little variation of CO_2 and tTHM were observed, which is likely to be a result of the high ACH and fresh air supply used in this poolroom. The investigated poolroom is also small, consisting of only one swimming pool, and the chosen ventilation strategy is assumed to be effective (Nitter and Svendsen, 2019a). In larger pool facilities, however, the ventilation efficiency might not be considered equally good (Nitter and Svendsen, 2019b), and lower ACH, which is related to the accumulation of tTHM in the air and an increase in reported health issues, is common (Bessonneau et al., 2011; Nitter et al., 2019).

tTHM is a product of the reaction between precursors from the number of occupants in the pool, precursors in the filling water and chlorine, and the formation rate depends on the water circulation system, the disinfecting strategy, water temperature, pH value and the concentration of bromine (World Health Organization, 2017). While CO_2 is generated by the occupants in the room and thereby will be reduced to outdoor concentrations when no occupants are present (Dougan and

Damiano, 2004), tTHM will be transported from the water to the air even after the occupants have left the swimming pool. This fact also explains the large correlation obtained between the repeated measures of tTHM (see Table 3), as the concentration levels are not only dependent upon the occupancy level, as is the case for the concentration of CO_2. Despite the complex nature of swimming facilities, with their varying sizes, ceiling heights and different user groups, a minimum requirement for ACH and the implementation of CO_2 sensors are assumed to make the system more robust towards sudden changes in occupancy or activity level as well as reducing the observed variability in tTHM.

4.2. Can CO_2 be used to predict the number of occupants in a poolroom?

In a previous study that used a cross-sectional study design, CO_2 concentrations were measured in the air of 20 swimming facilities, and these concentrations where found to vary significantly between the facilities, ranging from 351 ppm to 1553 ppm (Gabriel et al., 2019). In this study, the CO2 concentrations in the poolroom investigated decreased quickly after each swimming session and when no people were present, which indicates that the ventilation system replaced the air in the room effectively (Lu et al., 2015). As shown in Table 4, effective air exchange is also confirmed by the lack of correlation observed between the repeated measurements of CO_2 (Luoma and Batterman, 2000).

The main predictors for energy consumption in a swimming facility are floor area, surface of the swimming pool and number of visitors (Kampel et al., 2016; Nitter et al., 2019). During the days of sampling, the bather load varied from 0 to 30 people in the pool. While the ACH is controlled after design criteria and therefore varies little over the day, the bather load varies significantly. Considering bather load to be one of the main predictors for energy consumption, creating a more dynamic system corresponding to the user demand can potentially reduce the energy use as well as improve the air quality.

As shown in Table 2, a statistically significant correlation was obtained between CO_2 concentration and the number of occupants ($\rho = 0.654, p \leq 0.01$), which corresponds to the correlation between the number of occupants and CO_2 concentration found in previous studies (Gabriel et al., 2019; Lu et al., 2015; Rodríguez et al., 2018). The results obtained in this study might indicate that the air supply should be controlled with respect to the CO_2 level so that more fresh air could be distributed to the poolroom during periods of occupancy. However, such a tactic might only be suitable for rooms where the air can be considered well mixed, which might not be the case for larger pool facilities and water parks. It also requires having a relatively high ACH for the sensors to detect concentrations of CO_2 representative of that in the users' breathing zone. For buildings where the ACH is low (0.2–0.5 h^{-1}), there might be a delay between the response from the ventilation system and supply of fresh air, which, in some cases, might result in fresh air being supplied to the room after the occupants have left the location. In previous studies, correlations have been found between the number of occupants and the respiratory irritant NCl_3, and between tTHM and NCl_3 in the air (Nitter and Svendsen, 2019a; Cossec et al., 2016). Adjusting the air supply based on the number of occupants using CO_2 censors might therefore also control the concentration of NCl_3. This assumption, however, should be investigated further before any conclusions are made.

When CO_2 concentration is used as an indicator to predict the number of occupants in a room, then the underlying assumption is that the occupants have the same metabolic rate, diet and activity level (Dougan and Damiano, 2004). A poolroom, however, is typically used by individuals in different age groups, for different purposes and with dissimilar metabolic rates. Therefore, individuals might differ significantly in terms of the release of CO_2. Controlling the supply airflow rate based on the CO_2 level will increase the fresh air supply when the need for fresh air increases, regardless of the level of occupancy. The integration of CO_2 sensors into the ventilation system might make the ventilation strategy more dynamic and better able to correspond to visitor and activity level patterns.

5. Conclusions

The aim of this study was to investigate whether the measured CO_2 concentration can be used as an effective indicator for predicting tTHM concentration in a swimming pool facility. The results show that the CO_2 concentration alone may not function as an optimal indicator for predicting the air concentration of tTHM. Rather, the CO_2 concentration, in combination with the occupancy level and water concentration of combined chlorine can improve the control of the air exposure to tTHM in this swimming facility and these predictor variables explained 52% of the variability observed in tTHM. The correlation between occupancy level and CO_2 ($\rho = 0.65$, $p \leq 0.01$) also suggests that CO_2 sensors should be used to increase the air supply during occupancy and reduce the air supply during non-occupancy periods to save energy. A significant negative correlation between ACH and tTHM was obtained, and a minimum requirement of ACH and fresh air supply should be implemented to prevent tTHM to accumulate in the air.

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CRediT authorship contribution statement

Therese B. Nitter: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - review & editing, Visualization, Project administration. **Morten S. Grande:** Conceptualization, Investigation, Writing - review & editing, Project administration. **Kristin V.H. Svendsen:** Conceptualization, Methodology, Validation, Resources, Writing - original draft, Writing - review & editing, Supervision. **Rikke B. Jørgensen:** Conceptualization, Resources, Writing - original draft, Writing - review & editing, Supervision. **Salvatore Carlucci:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision. **Guangyu Cao:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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