



Covariation amongst pool management, trichloramine exposure and asthma for swimmers in Norway

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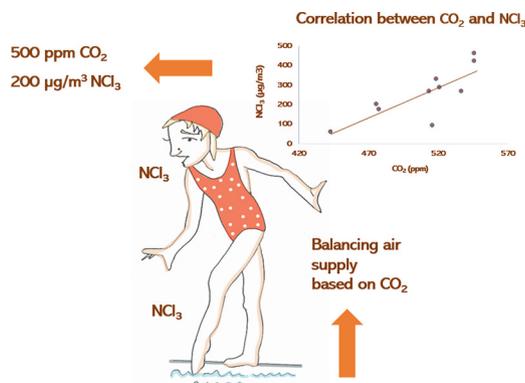
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HIGHLIGHTS

- Air exposure to trichloramine in swimming facilities is associated with asthma.
- No sensor for monitoring air concentrations of NCl_3 exist.
- The prevalence of asthma amongst the most-exposed swimmers in Norway was 36%.
- CO_2 concentration explained 52% of the variation observed in NCl_3 .
- CO_2 sensors can improve air quality and balance the air supply to occupancy level.

GRAPHICAL ABSTRACT



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ABSTRACT

The association between asthma and exposure to the air in swimming facilities has been acknowledged. However, the variation in, long-term exposure to and management of the respiratory irritant trichloramine (NCl_3) is not well understood. In this study, 313 swimmers above 18 years of age licensed by the Norwegian Swimming Association answered a questionnaire about health and swimming. The prevalence of asthma amongst the most-exposed swimmers was 36%. Two facilities, those with the highest and lowest reported prevalence of asthma, were chosen for further investigation. For each facility, a one-week-long monitoring campaign was performed, during which pool management, air and water quality were investigated. The results of this study showed that time of day, occupancy and pool management affect the concentration of NCl_3 , which ranged from $58 \mu\text{g}/\text{m}^3$ to $461 \mu\text{g}/\text{m}^3$. Furthermore, in one of the facilities, the concentration of CO_2 was measured to evaluate whether this contaminant could be used to predict the number of pool occupants as well as the concentration of NCl_3 in the air. The concentration of CO_2 was significantly correlated with occupancy level ($\rho = 0.82$, $p = 0.01$) and NCl_3 concentration ($r = 0.80$, $p = 0.01$). Furthermore, according to the random intercept model the concentration of CO_2 explained 52% of the variation observed in the air concentration of NCl_3 . CO_2 sensors to control the air supply can help reduce the air concentrations of NCl_3 and balance the air supply based on occupancy level.

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Abbreviations: ACH, Air changes per hour/air change rate; CO_2 , Carbon dioxide; DBP, disinfection by-product; HRT, hydraulic retention time; NCl_3 , trichloramine; OA, outdoor air; OR, odds ratio; RH, relative humidity.

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1. Introduction

In Norway, swimming has become increasingly popular which can be linked to the implementation of mandatory swimming education in schools (Det kongelige kulturdepartementet, 2013) and increased socioeconomic status. For most people, swimming promotes health, and, in many studies published on swimmers' health, especially before 1980, swimming was recommended for people struggling with asthma due to the lower respiratory heat loss experienced in environments with high humidity (Chen and Horton, 1977; Inbar et al., 1980). To maintain hygienic conditions, the water in the approximately 250 training and competitive pools in Norway are disinfected with hypochlorite and UV treatment. However, during swimming, the occupants release cosmetics and body fluids into the water (Keuten et al., 2012), which reacts with chlorine and forms inorganic chloramines with trichloramine (NCl_3) as the dominating inorganic chloramine in the indoor air (Richardson et al., 2010; Wastensson and Eriksson, 2019). The association between regular swimming pool attendance and increased prevalence of asthma has been confirmed in several previous studies (Lévesque et al., 2006; Thickett et al., 2002), and the prevalence of respiratory irritations reported amongst poolroom users is most often associated with exposure to volatile NCl_3 (Hery et al., 1995; Parrat et al., 2011). Respiratory problems, such as bronchial hyperactivity, which is a feature of bronchial asthma, appear to be greater amongst professional swimmers compared to healthy individuals (Bougault et al., 2010; Bougault et al., 2009; Romberg et al., 2012; Langdeau et al., 2000).

1.1. Asthma in Norway

In the last few years, the overall prevalence of asthma in Norway has increased, with an incidence of 4.1% amongst adult females and 2.9% amongst adult males from 1984 to 2008 (Langhammer and Brumpton, 2014). The best approximation of the prevalence of asthma in Norway amongst young adults can be obtained through the Norwegian prescription Database (NorPD). Numbers from 2018 show that the prevalence of asthma amongst adults varies from 4.8% (20–24 years old) to 5.5% (35–39 years old) (Folkehelseinstituttet, 2018).

1.2. Exposure to, and control of, NCl_3 in the pool room

High pulmonary ventilation, in addition to higher concentrations of contaminants in the air above the water surface (Nitter et al., 2018; Nitter and Svendsen, 2019a; Nitter and Svendsen, 2019c), renders professional swimmers the most exposed users in the poolroom. In Norway, an upper limit for inorganic chloramines, also called combined chlorine, in the water exists (0.5 mg/l). Aside from this limit, there are no upper limits for exposure to inorganic chloramines in the air. However, in a recent report published by the Nordic Expert Group, a health-based occupational exposure upper limit for NCl_3 in the air of $200 \mu\text{g}/\text{m}^3$ as an 8-hour time-weighted average was recommended for stationary measurements in swimming pool facilities (Wastensson and Eriksson, 2019).

1.3. Characterizing long-term exposure

Intense, long-term training in indoor chlorinated swimming pools is associated with airway changes similar to those seen in mild asthma (Bougault et al., 2012). In previous studies in which surveys have been used to collect information about respiratory health amongst swimmers or lifeguards, the concentrations of NCl_3 have been measured using cross-sectional designs (Parrat et al., 2011; Andersson et al., 2018; Thickett et al., 2002). Although these studies have strengthened the association between the increased prevalence of respiratory irritations and exposure to NCl_3 in the poolroom, the information of exposure and outcome is collected only once. Therefore, cross-sectional studies are not considered suitable for establishing dose-response relationships

as the timing of sampling may not be representative with long-term conditions (Sedgwick, 2014).

When considering the limitations of a cross-sectional study design, it is clear that variations in exposure plus the ventilation criteria and pool management necessary to ensure low air concentrations in the poolroom require more attention (Lévesque et al., 2006; Löfstedt et al., 2016). Considering that the exposure concentration may be time-dependent, varying with the days of the week and times during the day, this time dependency should be considered prior to creating exposure categories amongst the different exposure groups for epidemiological investigations (Nitter and Svendsen, 2019a). Monitoring NCl_3 requires skilled personnel, is expensive and time consuming. To the best of the authors' knowledge, this study represents the first time that a one-week-long monitoring campaign has been designed and performed to investigate the covariation amongst pool management, air exposure and asthma for competitive swimmers while taking into consideration exposure's time-dependent nature. The aims of this study were to:

1. Estimate the prevalence of respiratory irritations amongst active swimmers above the age of 18.
2. Determine whether there is a covariation amongst pool management, reported health effects and air quality.
3. Study the possibility of using CO_2 sensors in poolroom ventilation systems to predict the concentrations of NCl_3 in the air above the water surface.

2. Materials and methods

2.1. Questionnaire

To determine the prevalence of respiratory irritations amongst active and competitive swimmers, a questionnaire, created in Select Survey, was distributed to swimmers via e-mail through the Norwegian Swimming Association. Some of the questions concerning respiratory irritations and doctor diagnosed- and self-reported asthmatic symptoms were taken from the Norwegian Longitudinal Health Study (HUNT) and are considered to be standardized questions. Additional questions concerning the name of swimming facility used for training, use of medication, swimming background, sex, age, body weight, height, tobacco habits were also included. All members above the age of 18 licensed by the Norwegian Swimming Association were invited to complete the questionnaire ($n = 1109$). Prior to distribution, the questionnaire was approved by the Regional Ethical Committee in Norway (REK), with application ID 29689, as well as the Norwegian Institute for Data Research (NSD), with reference 577380. The survey was first distributed to the swimmers in May of 2019, and the non-respondents were reminded to participate in August of 2019.

2.2. In-depth analysis of two facilities

Based on the response rate from the questionnaire as well as the reported prevalence of doctor-diagnosed asthma, two facilities were chosen for further investigation in terms of air and water quality, ventilation and disinfection strategies and technical installations. Facility 1 is a water park consisting of eight swimming pools as well as jacuzzies, springboards and fountains. This facility was opened in 2001 and has approximately 385,000 visitors per year. The facility is used from Monday to Sunday for organized training as well as public swimming and the technical staff works full-time. The water in the sports pool contains approximately 15% seawater. The target population for this study rent the sports pool (21 m \times 50 m) in this facility between 7 PM and 11 PM. However, some of the swimmers also have individual training sessions during other periods of the day. Facility 2 was built in the 70s and consists of only one sports pool (12 m \times 25 m), filled with fresh water. The facility is operated by one swimming club and technical staff is available only for a shorter time during the day. The target

population for this study use the swimming pool from 6 AM to 9 AM in the morning, and from approximately 3 PM in the afternoon until 6 PM. However, the swimming pool is occupied most hours from 6 AM to 10 PM, Monday to Sunday, by school children and training groups.

In both swimming facilities, liquid sodium hypochlorite (15%) (NaOCl) and UV treatment is used to disinfect the pool water. The facilities use the same ventilation strategy, where air is supplied up along the window façade, and return air is extracted from extract grills on the wall opposite to the window façade in the facility.

2.3. Sampling strategy

The samples of NCl_3 were collected from Monday to Friday over two different weeks; Facility 1 was sampled during the first week, the Facility 2 was sampled during the second week. Samples were collected using a stationary test stand, and samples were collected at a height of 0.3 m above the floor next to the pool. The test stand was pointed away from the pool to prevent water droplets from entering the filter. Samples were collected while the most-exposed swimmers were present in the pool, i.e., from 7 PM to 10 PM in Facility 1 and from 6 AM to 9 AM and 3 PM to 6 PM in Facility 2. In previous studies conducted by the authors, it was demonstrated that, for smaller pool rooms containing only one swimming pool with a high air change rate (ACH), the air in the room can be considered to be well mixed (Nitter and Svendsen, 2019b). However, in larger pool facilities, where multiple swimming pools are located in the same room, the mean age of the air might not be the same for all sampling locations (Nitter and Svendsen 2019). To account for the different sizes of the two chosen swimming facilities, one sample of NCl_3 was collected simultaneously from each long side of the sports pool in Facility 1, while samples of NCl_3 were only collected from one long side of the pool in Facility 2.

Each sample was collected on impregnated filters in 37 mm closed face filter cassettes for 3 h with a flowrate of 1 l/min using pumps from SKC Ltd. (one SKC Sidekick and one SKC Universal). The flow rate through the filter was checked at least once every hour.

Additional information on air temperature and air relative humidity (RH) was collected at two-minute intervals using Easy Loggers (EL-USB-2), which were also fastened to the test stand at a height of 0.30 m above the floor. Information about free and combined chlorine as well as pH value was collected from the logging systems in the pool facilities, and the number of swimmers was counted continuously during sampling. Information on the ventilation system in Facility 1 was obtained from the ventilation supplier, and the fresh air ratio was calculated based on the valve openings. In most facilities, some air is recirculated, meaning that the air supplied to the poolroom is a mix of fresh air from outside and recirculated air. Both facilities use the same ventilation system; however, the ventilation system in Facility 2 is older, and no log detailing the valve openings and air supply exists. To estimate the fresh air supply in this facility, CO_2 sensors (Elma CA1510) were placed in the supply channel, return channel and fresh air channel of the facility, with the logging interval set to every 5 min. Based on the information from the CO_2 sensors, the fresh air supply was calculated using the following formula:

$$\%OA = \left(\frac{X_R - X_S}{X_R} - X_O \right) \times 100\%, \quad (1)$$

where OA is the outdoor air supply, X_R is the CO_2 concentration in the return air/extracted air, X_S is the CO_2 concentration in the air supply and X_O is the CO_2 concentration in the outdoor air. The air flow rate in m^3/h was collected from the ventilation room. Although some variations in air flow rate will occur during the day in order to balance the RH and air temperature in the poolrooms, the variations in air supply can be assumed to be approximately constant, as both ventilation systems operate according to settings, i.e., day mode (from 6 AM to 10 PM) or night mode (from 10 PM to 6 AM) ventilation.

2.4. Analysis of NCl_3

The analysis of NCl_3 was done in accordance with the method published by Hery et al. (1995). In brief, air passes through a filter impregnated with sodium carbonate and diarsenic trioxide. The chloramines collected on the filter are reduced to chloride ions. After sampling, the filters are desorbed in water, sonicated and filtered, and the collected material is analysed in an ion chromatogram. For each set of ten samples collected and analysed, two blank samples were used as control samples. The samples were sent to Sweden, to the department of Occupational and Environmental Medicine at Umeå University, for analysis.

2.5. Statistical analysis

To analyse the degree of association between two variables, Pearson's correlation coefficient was used for parametric variables; for non-parametric variables, Spearman's correlation was used. To test for the difference reported amongst the swimmers in the two selected pool facilities, the Mann-Whitney U test for independent samples was used, using facility as grouping variable. When analysing the responses from the swimmers, the odds ratio (OR) of irritation between the two selected facilities was calculated using multiple logistic regression analysis. This method allows adjustments to be made for possible confounding variables or multiple independent variables determining the observations. The OR represents the odds that an outcome will occur given a particular determinant, or exposure, compared to the odds of the outcome occurring in the reference group (Szumilas, 2010).

To determine the possible covariation between CO_2 and NCl_3 observed in Facility 2, a random intercept model was built using day as the subject and time during the day as the unit for repeated measures. This method was used as repeated samples collected over the course of the same day are likely to be more correlated compared to samples collected on different days. The NCl_3 concentration was ln-transformed, and it was found to be normally distributed via the Shapiro Wilk test (with a check conducted via histogram). The only variable significantly correlated with the NCl_3 concentration was the CO_2 concentration in the extraction channel. Other variables, such as swimmer load and water quality, also varied significantly between the different days of sampling, but no pattern with NCl_3 concentrations could be observed, assumingly due to the limited number of samples of NCl_3 collected. The CO_2 concentration was treated as a fixed effect, and timepoints (morning and afternoon) from the same day were treated as random effects.

The random intercept model is specified by the following expression

$$\gamma_{ij} = \beta_0 + \beta_1 x_{ij1} + \zeta_j + \epsilon_{ij}, \quad (2)$$

where i is the cluster unit (day), j is the unit for repeated samples (time), ζ is the random intercept and ϵ represents the error term. Both ζ and ϵ are assumed to be normally distributed with zero means. The variance of ζ represents the between-day variance (σ_b^2), and the variance of ϵ represents the within-day variance (σ_w^2). Finally, β_0 represents the intercept, and β_1 is the regression coefficient of the CO_2 concentration. To account for the potential correlation between the repeated samples collected on the same day, the covariance structure's compound symmetry (CS) was used, as only two samples, one in the morning and one in the afternoon, were collected each day. This covariance structure assumes the correlation is constant regardless of how far apart the samples are (Peretz et al., 2002). The statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) 25.

2.6. Dealing with error and uncertainty related to the data collection

The question concerning "physician-diagnosed asthma" has been measured previously to a specificity of 99% (Torèn et al., 1993), meaning

that, even when the prevalence of illness is high, the number of false negatives due to misclassification is assumed to be low. In general, the greater proportion of non-responses is often related to increased risk of estimation bias (Rönmark et al., 2009), especially in cases where the missing responses are related to the topic (Schouten et al., 2009), which is the case in this study. In this study, the association between exposure and disease was strongest amongst the swimmers spending >16 h in the water per week; therefore, this group is considered to have been more likely to respond to the survey compared to swimmers spending only a few hours in the water per week. If the response rate had been higher, it is likely that the estimated prevalence of disease would be reduced for the group of swimmers spending <16 h in the water per week.

If the percentages in the responses and follow-up were to be the same, it is then more likely that the responses are representative of the responses from the whole population (Tyrrer and Heyman, 2016). Between the first and second round of survey distribution, the prevalence of reported doctor-diagnosed asthma decreased from 23% to 22.4%. The mean reported age of the swimmers, weekly exposure hours in the pool, percentage of females and percentage experiencing respiratory irritations during or after swimming did not change between the first (n = 209) and second (n = 104) round of survey distribution.

3. Results

3.1. Prevalence of respiratory irritations amongst swimmers above the age of 18

Of the 1109 swimmers who received the survey via the Norwegian Swimming Association, 313 swimmers completed the survey, resulting in a response rate of 28.2%. However, the response rate is assumed to differ between the different exposure groups. The numbers provided by the Norwegian Swimming Association show that around 60 people, from 18 to 26 years old, qualified to participate the national competitions (NMs) in 2019. These swimmers are characterized as the most-exposed swimmers in Norway, as they spend 16 h or more in the water every week. In this survey, 64 of the respondents reported being between 18 and 26 years old and swimming >16 h every week. Therefore, it is assumed that the estimates reported for this group are representative for the most-exposed swimmers in Norway.

The overall reported prevalence of doctor-diagnosed asthma amongst all the respondents in this study was 22.4%, 84% of whom had been swimming for >10 years. The prevalence of doctor-diagnosed asthma was greater amongst those who swim for >16 h a week (35.4%, n = 65) compared to those who swim <16 h a week (19.2%, n = 248).

In Fig. 1, the prevalence of skin, nose and respiratory problems during or after training reported amongst swimmers with asthma,

swimmers who suspect they have asthma and swimmers who do not have asthma is shown.

As shown in the figure, one or more health irritations were reported, during or after swimming training, by 67.5%, 65.4% and 36% of the swimmers diagnosed with asthma, suspecting asthma and with no asthmatic symptoms, respectively. A significant Spearman's correlation coefficient was found between asthma diagnoses and coughing daily during periods of the year ($\rho = 0.38$, $p = 0.01$) and one or more attacks of heavy breathing during the last 12 months ($\rho = 0.37$, $p = 0.01$). A significant positive correlation was also found between asthma diagnosis and facility ($\rho = 0.14$, $p = 0.05$), age of swimmer ($\rho = -0.13$, $p = 0.05$), increased prevalence of airway irritation with increasing activity level ($\rho = 0.46$, $p = 0.01$) and spending >16 h in the water every week ($\rho = 0.16$, $p = 0.01$).

In Table 1, the prevalence of reported symptoms during or after training is shown for different exposure groups. The increasingly dark shades of red indicate progressively increasing percentages of health problems. Using the Kruskal Wallis test and Mann-Whitney test for independent samples, a significant difference ($p \leq 0.05$) was found between the swimmers spending <16 h in water per week and >16 h in water per week for all questions in Table 1, excluding the question about red and itchy eyes ($p = 0.061$). The difference between the two lowest exposure groups was statistically insignificant for all questions listed in Table 1.

3.2. In depth-analysis of the two selected facilities

The 313 swimmers answering the questionnaire represent 82 different swimming facilities. The two facilities selected for in-depth analysis were chosen based on the number of responses as well as the difference in reported prevalence of doctor-diagnosed asthma and respiratory irritation. For Facility 1, 40 swimmers completed the survey, and the reported prevalence of doctor-diagnosed asthma was 17.5%. For Facility 2, 33 swimmers completed the survey, and 36% of these swimmers reported being diagnosed as having asthma by a doctor. The average reported hours spent in the water at the two facilities were approximately the same (7.0 h/week for Facility 1, and 7.3 h/week for Facility 2) as were the number of swimmers spending >16 h in the water per week and between 6 and 14 h in the water per week. However, the mean age of the swimmers differed between the two facilities; therefore, an adjustment was made for age when the OR was calculated. For Facility 1, 9, 16 and 15 swimmers reported swimming 16 h or more, between 6 and 14 h and <6 h every week, respectively. These numbers correspond to the number of active swimmers given by the club leaders; hence, it is assumed that the most-exposed swimmers using Facility 1 filled out the questionnaire. For Facility 1, the response rate was 40/203. For Facility 2, the response rate was higher (33/84), and the percentage of reported doctor-diagnosed asthma was twice as high as that in Facility 1. From the survey, 8, 10 and 15 swimmers reported

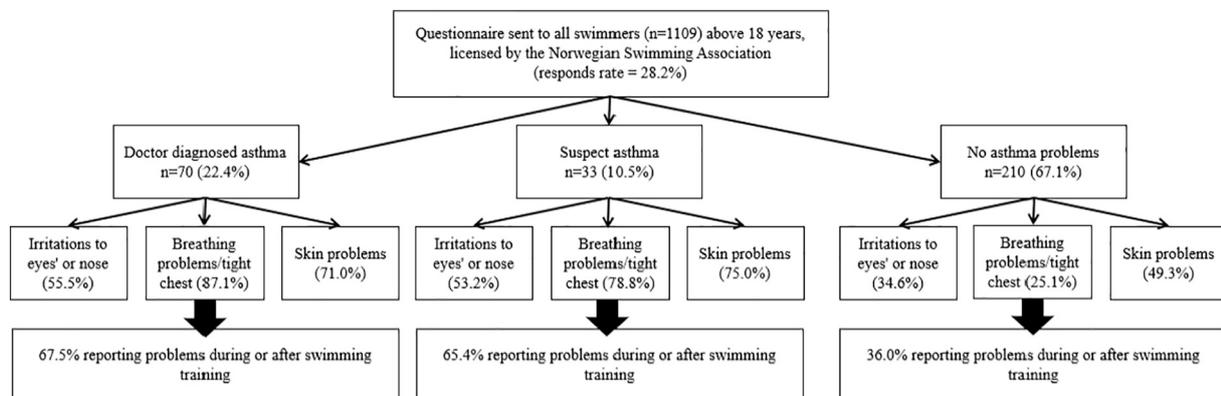


Fig. 1. Reported prevalence of health problems during or after training amongst swimmers diagnosed with asthma, suspecting asthma and having no problems with asthma.

Table 1
Reported health problems for different exposure groups (n = 312).

| | Less than 6 h (n=104) | Between 6 and 14 h (n=143) | More than 16 h (n=65) |
|---|-----------------------|----------------------------|-----------------------|
| Average hours in water per week | 2.4 h | 7.1 h | 16.4 h |
| Do you ever experience red, itchy or runny eyes during or after training? (%) | 29.1 | 37.4 | 46.9 |
| Do you ever experience a red or itchy nose during or after training? (%) | 42.3 | 40.1 | 62.5 |
| Do you ever experience chest tightness during or after training? (%) | 33.7 | 41.4 | 70.8 |
| Do you ever experience skin irritations during or after training? (%) | 46.2 | 54.6 | 78.5 |
| Do your breathing problems increase with increasing activity level? (%) | 34.0 | 32.9 | 61.5 |
| Do your breathing problems affect your performance? (%) | 27.9 | 26.4 | 52.5 |

Note: One swimmer did not report weekly exposure hours.

swimming 16 h or more, between 6 and 14 h and <6 h every week, respectively. Based on these matching criteria, it is assumed that the two facilities are comparable with respect to the participating individuals, despite the differing response rates.

As shown in Table 2, there are negligible differences between the two facilities in terms of irritation of the eyes (0.4 percentage point difference), nose (6 percentage point difference), skin (1.2 percentage point difference) and medication (4 percentage point difference). However, using the Mann Whitney *U* test, the reported prevalence of chest or respiratory tightness during or after swimming differed significantly between the two facilities (28.1 percentage point difference) ($p = 0.02$), and, after adjusting for age, the calculated OR for respiratory irritations and chest tightness was 8.7 (95% CI: 2.0–37.2, $p = 0.00$) for Facility 2 compared to Facility 1. The OR for diagnosed and suspected asthma, after adjusting for age, was 2.5 (95% CI: 0.7–8.5, $p = 0.145$), which was not statistically significant.

Technical data on ventilation and disinfection strategies, as well as the arithmetic mean values of physical-chemical parameters measured in the two facilities, is shown in Table 3. The hydraulic retention time (HRT) is a measure of the average time that the pool water remains in the swimming pool before it is treated in the water treatment system. The air exchange rate (ACH) is a measure of how many times per hour the air (combination of fresh air and recirculated air) in the room is removed divided by the volume of the room. The ACH (h^{-1}), HRT, percentage of outdoor air (%OA), free chlorine, combined chlorine, RH and air temperature differed significantly between the two selected facilities. The water volume (m^3 water) in the two sports pools also differed, and, in order to render the swimmer density at the two facilities comparable, m^3 water per swimmer was used. These values are presented in Table 3. As shown in the table, the density of swimmers was almost four times greater in Facility 2 compared to Facility 1.

According to Norwegian regulations, the level of combined chlorine should never exceed 0.5 mg/l. Furthermore, the combined chlorine should never be >50% of the measured concentration of free chlorine

(Norwegian Ministry of Healthcare, 1996). The measured exposure concentrations in Facility 1 and 2 is shown in Table 4. In Facility 1, the measured levels of free and combined chlorine never exceeded the Norwegian regulations. The concentration of NCl_3 ranged from 245 $\mu\text{g}/\text{m}^3$ to 265 $\mu\text{g}/\text{m}^3$, and the concentration measured simultaneously from the two sampling locations only varied by 10 $\mu\text{g}/\text{m}^3$, suggesting homogenous concentrations across this swimming pool, despite the low ACH.

In Facility 2, the level of combined chlorine was always >50% of the measured concentration of free chlorine, and 50% of the measured values of combined chlorine exceeded the Norwegian limit of 0.5 mg/l. While the measured RH level and air temperature were stable, the air concentrations of NCl_3 varied significantly from day to day, ranging from 58 $\mu\text{g}/\text{m}^3$ to 327 $\mu\text{g}/\text{m}^3$ in the morning and 92 $\mu\text{g}/\text{m}^3$ to 461 $\mu\text{g}/\text{m}^3$ in the evening. On Thursday during the week of measurement, low concentrations of NCl_3 were measured, with 58 $\mu\text{g}/\text{m}^3$ in the morning and 92 $\mu\text{g}/\text{m}^3$ in the evening being recorded. On this particular day, the chlorine machine stopped working, and free chlorine levels as low as 0.15 mg/l was measured in the pool water. In general, the concentrations were always lower in the morning compared to in the evening, which is perhaps explained by increased swimmer load during the day.

In Facility 1, almost no air is recirculated, and, on average, 91% of the air supply is fresh air from the outdoors. However, the ACH was low (0.95 h^{-1}). The average percentage of fresh air in Facility 2 was 69, which was calculated based on the measured CO_2 concentrations. The ACH was also much higher (9.55). In Facility 2, the HRT was high, and so was the swimmer load. In some periods during the day, up to 60 people were present in the pool at the same time. During the evening, the area around the pool was used for warm-ups, strength training and by parents waiting for their kids to finish swimming. Despite the high occupancy level, the concentration of CO_2 measured in the extraction channel never exceeded 750 ppm as a result of the high air exchange rate and fresh air supply.

Table 2
Prevalence of irritation in all respondents and the two selected facilities.

| | Facility 1 (% yes) | Facility 2 (% yes) | All facilities (% yes) |
|--|--------------------|--------------------|------------------------|
| Do you sometimes experience red, itchy or runny eyes†? | 35.9 | 35.5 | 36.8 |
| Do you sometimes experience an itchy or runny nose†? | 42.5 | 48.4 | 45.4 |
| Have you ever experienced chest or respiratory tightness†? | 32.5 | 60.6 | 45 |
| Have you ever experienced skin irritations/skin problems†? | 55 | 56.2 | 56.6 |
| Have you been diagnosed with asthma by a doctor? | 17.5 | 36.4 | 22.4 |
| Do you suspect you have asthma? | 5 | 23.8 | 13.8 |
| Have you ever used medications to prevent/reduce asthmatic or allergic symptoms? | 47.5 | 51.5 | 44.5 |

† during or after training.

The increasingly dark shades of red indicate progressively increasing percentages of health problems.

Table 3
Technical data on ventilation and disinfection strategy, plus chemical-physical parameters for the two facilities.

| Facility | HRT (h) | m ³ water | ACH | %OA | Cl _{comb} | Cl _{Free} | pH | RH | T _{air} (°C) | m ³ /swimmer | T _{water} (°C) |
|----------|---------|----------------------|------|-----|--------------------|--------------------|------|------|-----------------------|-------------------------|-------------------------|
| 1 | 4.6 | 2450 | 0.95 | 91% | 0.17 | 0.64 | 7.12 | 71.3 | 27.1 | 28.3 | 28.0 |
| 2 | 7.2 | 450 | 9.55 | 69% | 0.52 | 0.78 | 7.02 | 45.1 | 28.4 | 7.7 | 26.5 |

Abbreviations: %OA = percentage of outdoor air, Cl_{comb} = Combined chlorine, Cl_{Free} = Free chlorine, T_{air} = Air temperature, T_{water} = water temperature.

3.3. Using CO₂ sensors to predict the concentrations of NCl₃ in the air

A significant Pearson's correlation was found between the NCl₃ concentration in the air and the concentration of CO₂ (average over 3 h) measured in the extract channel ($r = 0.80$, $p = 001$). A significant Spearman's correlation was also found between the CO₂ concentration and occupancy load ($\rho = 0.82$, $p = 0.01$). The covariations between the number of occupants and the measured concentration of CO₂ in the extract, supply and fresh air channels are shown in Fig. 2.

As shown in Fig. 2, during the night, the CO₂ concentrations measured in the extract channel are below the CO₂ concentration measured in the fresh air channel, suggesting that some of the CO₂ in the room is absorbed by the pool water during the night. In Table 5, the random intercept model for ln NCl₃ with the CO₂ concentration as a fixed effect is shown.

The CO₂ concentration was a significant predictor variable ($p = 0.004$), and, after this component was included into the random intercept mode, the total variability ($\sigma_v^2 + \sigma_b^2$) was reduced by 52.3%. However, as the sample size is small, the model cannot be generalized for values other than those observed in this study. Despite the small sample size, the relationship between NCl₃ and CO₂ concentrations is significant. In Fig. 3, a scatterplot between CO₂ and NCl₃ concentrations is shown. The star represents the predicted concentration of CO₂ necessary to keep the concentration of NCl₃ below 200 µg/m³, based on the estimates in Table 5. According to the plot and the random intercept model, the CO₂ concentrations should be below 500 ppm in order to keep the concentration of NCl₃ below 200 µg/m³. This is illustrated in Fig. 3.

4. Discussion

4.1. Prevalence of respiratory irritations amongst swimmers above 18 years of age

The prevalence of irritation to the eyes, nose, skin and respiratory tract was greatest amongst swimmers with asthma and who were suspected of having asthma as well as those who have been swimming for >10 years or >16 h per week. Amongst all swimmers, the overall reported prevalence of doctor-diagnosed asthma was 22.4%. However, this estimate might be biased due to the low response rate, as we expect that swimmers who spend limited time in the pool water or do not experience any health issues related to swimming would be less likely to participate in this type of study. It should be noted that amongst swimmers spending >16 h in the water per week, the prevalence of asthma was 36%, with 71% reporting respiratory irritations or chest tightness during or after training. As the response rate amongst swimmers

Table 4
Exposure concentrations of NCl₃ measured in the morning and evening in Facility 1 and 2 spread over five days.

| Facility | N | Time | AM (µg/m ³) | GM (µg/m ³) | SD (µg/m ³) | Range (µg/m ³) |
|----------|----|---------|-------------------------|-------------------------|-------------------------|----------------------------|
| 1 | 10 | Evening | 250 | 250 | 9.4 | 240–270 |
| 2 | 5 | Morning | 205 | 200 | 101.3 | 58–327 |
| 2 | 5 | Evening | 305 | 286 | 145.6 | 92–461 |

Abbreviations: N = number of samples, AM = arithmetic mean, GM = Geometric mean, SD = Standard deviation, Range shows the lowest and highest value observed in NCl₃ during morning and evening.

spending >16 h in the water per week is assumed to be approximately 100%, these estimates are also considered representative. The same prevalence of doctor-diagnosed asthma (36.6%) was reported in a Swedish study including 101 elite swimmers from 13 to 23 years old who swam between 10 and 30 h per week (Romberg et al., 2012). In a Finnish study, which included 200 competitive swimmers, a lower prevalence of doctor-diagnosed asthma (16%) was reported (Päivinen et al., 2009).

In Table 2, selected questions are shown to compare the responses from the two facilities to the responses from all the 313 swimmers. As shown, 203 swimmers using Facility 1 received the questionnaire, but only 40 of these swimmers participated in this study. In order to increase the response rate, the leaders of the two swimming clubs using Facility 1 were contacted and asked to distribute the survey to the members by e-mail once more. The largest club, consisting of approximately 180 licensed student members refused, as they had not asked for permission to contact their members by e-mail. The Norwegian Ethics Committee also imposed some restrictions on recruiting respondents. Amongst others, the researcher was not allowed to ask the swimmers to respond to the survey directly unless the swimmers contacted the researcher themselves. The coaches were also not allowed to encourage the swimmers to answer the questionnaire, as doing so could be perceived as pressure. Despite the low response rate, the most-exposed swimmers filled out the survey in both facilities, and, based on the matching criteria's exposure hours as well as the distributions of male and females and exposure groups, the two facilities are comparable.

The difference in reported prevalence of doctor-diagnosed asthma might be caused by several factors, such as air inhaled during training (Langdeau et al., 2004; Kippelen et al., 2012) and selection bias. However, more severe cases of bronchial hyperreactivity (BHR) and asthma have been found amongst swimmers compared to cross-country skiers (Stang, 2017) and healthy individuals (Romberg et al., 2012); thus, the high prevalence of asthma is not likely to be caused by the intensity level alone (Romberg et al., 2012; Päivinen et al., 2009), rather endurance exercise itself can disrupt the airway epithelium and lead to an increase in vascular leakage of inflammatory cells (Williams, 2011). In this study, a significant association was found between asthma diagnosis and facility, and the results from this study also show that the prevalence of reported asthma symptoms, as well as irritation of the eyes, skin and nose, increases with increasing weekly exposure time as well as years of exposure. Based on these results, both pool management and exposure duration are likely to affect the prevalence of irritations reported by swimmers.

4.2. Pool management and air quality in the two selected swimming facilities

When chlorine is added to a pool, it reacts with free ammonia to form combined chlorine, which is known to cause allergic dermatitis (Cohen and Wolff, 2000). In the two selected facilities, no difference in the prevalence of skin irritations was reported, despite the difference in combined chlorine. However, the difference in the reported prevalence of airway irritations was significant, and the estimated OR between the two facilities was 8.7 after adjusting for age.

The mean air concentrations of NCl₃ measured in the evening in Facility 1 and Facility 2 were 250 µg/m³ and 305 µg/m³, respectively. While the concentrations of NCl₃ in Facility 1 varied from 245 µg/m³ to 265 µg/m³, the concentrations of NCl₃ measured in Facility 2 varied from 92 µg/m³

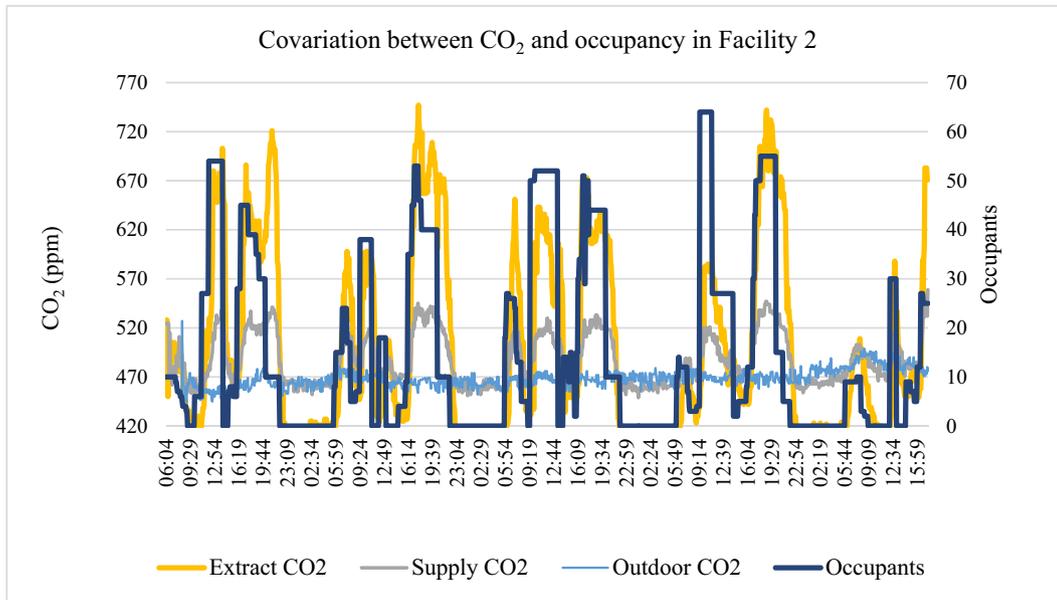


Fig. 2. Number of occupants and measured concentrations of CO₂ in the extract, supply and fresh air channels of Facility 2.

m³ to 461 µg/m³. Although higher concentrations of NCl₃ were measured in Facility 2 compared to Facility 1, this difference is not likely to explain the great difference in doctor diagnosed asthma prevalence reported between the two facilities. In a previous study, it was found that the OR for respiratory, asthma-related and ocular symptoms increased when the concentration of NCl₃ was above 500 µg/m³. However, these results are based on only one sample of NCl₃ collected from each of 20 swimming facilities included in the study (Fantuzzi et al., 2013). The highest concentrations of NCl₃ observed in Facility 1 might explain the high reported prevalence of respiratory irritations and thereby the high estimated OR from this facility. However, considering the variability observed in Facility 2, both with respect to the air and water quality, estimating the long-term exposure in this pool facility might require more samples. The variations measured in Facility 2 also highlight how important it is to collect samples over a longer period in order to understand the real long-term exposure, especially when the water quality varies as much as it did in Facility 2.

In Facility 1, the measured values of free and combined chlorine never exceeded the Norwegian limits. However, this was not the case in Facility 2, where 50% of the combined chlorine was unacceptably high. In addition, the concentration of combined chlorine was always >50% of the concentration of free chlorine. A few weeks before the inspection, the chlorine machine in Facility 2 stopped working and values as low as 0.01 mg/l of free chlorine were measured in the pool water. On one day during the week of sampling, the chlorine machine stopped working once again, which is assumed to be the main reason for the low concentrations of NCl₃ (58 µg/m³ in the morning, and 92 µg/m³ in the evening) observed on this day.

Table 5
Random intercept model for ln NCl₃ using the CO₂ concentration as a fixed effect.

| Determinant | Random intercept model for ln NCl ₃ | Sig. |
|---|--|-------|
| Constant | 1.1799 | 0.185 |
| CO ₂ | 0.0083 | 0.004 |
| Variance explained by random effects | | |
| Within day (σ_w^2) | 0.013 | |
| Between day (σ_b^2) | 0.109 | |
| % variance explained by CO ₂ concentration | 52.3% | |

In Facility 1, the technical staff work full-time, which makes the facility more robust in the event of failures. However, in most smaller facilities, such as Facility 2, the technical staff is only present for short periods during the day. As of now, no specific requirements for pool management exists in Norway, and a minimum amount of training is devoted to learning how to keep the water and air quality within the requirements. Considering the reported prevalence of irritations in this study, keeping within the requirements is especially important for facilities hosting competitive swimmers.

4.3. Using CO₂ sensors to predict the concentration of NCl₃ in the air

The air exchange rate for fresh air was significantly higher in Facility 2 (5.6) compared to Facility 1 (0.9); however, a higher fresh air supply is necessary in Facility 2 due to higher swimmer density. Despite the high amount of fresh air in Facility 2, the concentrations of NCl₃ varied extensively, both within and between the sampling days, with the highest concentrations measured in the evening. This variability is associated with varying chlorine levels, low HRT levels and high swimmer load. The stable concentrations of NCl₃ observed in Facility 1 are associated with better pool management, despite varying swimmer load. According to the Nordic Expert Group, however, the concentrations of NCl₃ should not exceed 200 µg/m³ in stationary air samples. Of the 20 NCl₃ samples collected in this study, 16 exceeded this value. In Facility 1,

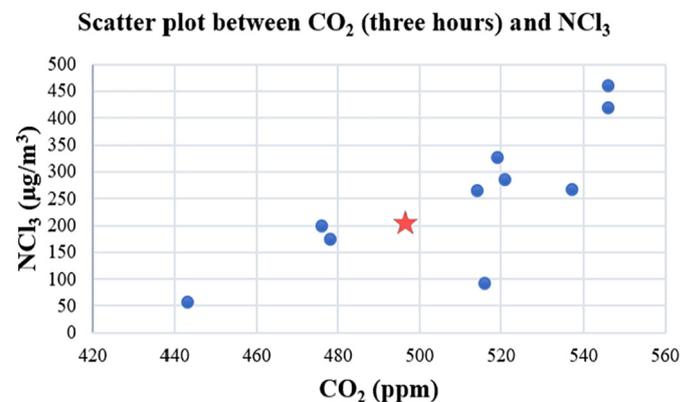


Fig. 3. Scatterplot of the CO₂ measured in the extract and NCl₃.

reducing the mean concentrations of NCl_3 might be accomplished by increasing the ACH level.

In Facility 2, the concentrations of CO_2 were measured in the extraction channel, air supply channel and fresh air channel. According to the random intercept model and scatter plot, the concentration of CO_2 should not exceed 500 ppm (average over 3 h) in order to have an NCl_3 concentration below 200 $\mu\text{g}/\text{m}^3$. To achieve this goal without improving the water management, a greater exchange of fresh air would be required, which is not a sustainable suggestion considering the already high fresh air supply in this facility. In accordance with the Norwegian regulations, the lowest acceptable concentration of free chlorine in water with a temperature below 27 °C is 0.4 mg/l. At this value, the maximum allowable concentration of combined chlorine is 0.2 mg/l. If the microbiological water quality is maintained, reducing the concentrations of chlorine in the water, reducing the water HRT or the maximum allowable swimmer load would probably also reduce the concentration of NCl_3 observed in the air.

As of today, no sensor for the continuous monitoring of NCl_3 exists. Based on the random intercept model, the CO_2 concentration explained 52% of the variability observed in the NCl_3 concentration. A strong correlation was also found between the CO_2 concentration and occupancy load ($\rho = 0.82$, $p = 0.01$), and between the CO_2 and NCl_3 concentrations ($r = 0.80$, $p = 0.01$), meaning that the CO_2 concentration might function as a marker for both these variables. Based on these results, a CO_2 sensor could be used in the ventilation system to control the concentration of NCl_3 as well as create a more dynamic air flow rate corresponding to the occupancy load in the room. Although no dose-response relationship was found in this study, it is considered likely that if the air concentrations of NCl_3 are kept below 200 $\mu\text{g}/\text{m}^3$, the prevalence of respiratory irritations would decrease as the proposed health-based exposure limit is based on irritations from the respiratory tract.

Higher concentrations were always measured in the afternoon when more swimmers were present in the pool. Time of exposure (morning or afternoon), swimmer load and pool management are variables that should be considered to reduce the exposure amongst swimmers.

5. Conclusion

The prevalence of doctor-diagnosed asthma amongst competitive swimmers in Norway was 36% in this study. Predictor variables, such as years of swimming, weekly exposure and type of facility, are significantly associated with asthma. Even though some of the asthma cases may be exercise induced, some are related to the air contamination in the poolroom. Time of day, occupancy and pool management affect the concentration of NCl_3 , and characterizing which strategies are more beneficial in terms of reducing air exposure might be crucial for the health, wellbeing and performance of the swimmers. In swimming facilities hosting active swimmers, stricter requirements for pool management as well as air and water quality should be implemented, as varying water quality also leads to varying air quality. However, monitoring NCl_3 concentrations requires skilled personnel, is expensive and time consuming. The concentration of CO_2 is significantly correlated with both occupancy level ($\rho = 0.82$, $p = 0.01$) and NCl_3 concentration ($r = 0.80$, $p = 0.01$). Furthermore, the concentration of CO_2 explained 52% of the variation observed in the air concentration of NCl_3 , suggesting that using CO_2 sensors to control the air flow rate can help reduce the air concentrations of NCl_3 , as can increasing the air flow rate when the occupancy load increases.

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CRediT authorship contribution statement

Therese Bergh Nitter: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Project administration.
Kristin v. Hirsch Svendsen: Conceptualization, Methodology, Validation, Resources, Writing - original draft, Writing - review & editing, Supervision.

Declaration of competing interest

The authors have no conflicts of interest to declare.

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