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Therese Bergh Nitter

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Thesis for the Degree of
Philosophiae Doctor
Faculty of Economics and Management Dept. of
Industrial Economics and Technology
Management

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THESIS FOR DEGREE OF PHILOSOPHIAE DOCTOR

Strategies for assessing exposure to and managing air concentrations of disinfection by-products in indoor swimming facilities

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Department of Industrial Economics and Technology Management
NTNU NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
Trondheim, Norway 2020

PREFACE

From 2015-2017 I finished my master's degree in Health, Safety and Environmental Management (HSE) at the Department of Industrial Economics and Technology Management (IØT). During these two years I had courses in indoor climate and air quality, occupational hygiene, work environment and ventilation. These courses aroused an engagement in me, and I decided that I wanted to do research on air quality and exposure, which are two of the focus areas at HSE. It was therefore a real pleasure to get the opportunity to work with air quality in swimming facilities in my master thesis, and an even greater pleasure that I was allowed to continue this work as a Ph.D. student, from 2017-2020.

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for the partial fulfilment of the requirements for the degree of Philosophiae Doctor. This thesis consists of a summary of the Ph.D. project including five original, research papers published in per reviewed scientific journals.

This Ph.D. work was funded by the Center for Sports Facilities and Technology (SIAT) at the Department of Civil and Environmental Engineering (IBM) and performed at the Department of Industrial Economics and Technology Management (IØT), NTNU, Trondheim. Professor Kristin von Hirsch Svendsen has been the main supervisor, Professor Rikke Bramming Jørgensen and Professor Salvatore Carlucci has been involved in this research as co-supervisors, and Bjørn Aas as mentor.

ACKNOWLEDGEMENTS

Substantial efforts and motivation hides behind the conclusions of scientific journal papers. For the last three years, I have been given the trust and opportunity to walk the steps in the process of research, from developing research questions to my own conclusions, and this, for me, has been extremely rewarding. The project would not be possible without the kindness and support of many people, and it is my pleasure to acknowledge the role of individuals who have given me the trust, support, and help I have needed to complete this journey.

First, I would like to thank Bjørn Aas at SIAT/IBM, who initiated the project and who has been an essential link between me and the different swimming facilities and companies. I also wish to thank Carl Thodesen, the former head of department at IBM, Professor Amund Bruland, and Bjørn Åge Berntsen at SIAT/IBM for their trust in me to develop this project as I wanted.

I wish to sincerely thank my main supervisor, Professor Kristin von Hirsch Svendsen, who has been the most important person during these three years. I admire her engagement and creativity. Thank you for keeping me inspired and motivated through the project. A great thanks to my co-supervisors Rikke Bramming Jørgensen and Salvatore Carlucci, for fruitful discussions, advice, and support. Thanks to Arne-Vidar Sjønøst for his patience and help at the lab.

In the beginning, I thought this Ph.D. journey would be an individual, sometimes lonely, experience. However, it takes place in a community of sharing, support, extreme joy, and sometimes frustration. I really must thank some of my friends, colleagues, and the administration at IØT/IBM. A special thanks to Anna for being such a great friend and for helping me with posters, presentations, and graphical abstracts. A great thanks to Camilla, who is responsible for the project “godeidrettsanlegg.no,” where SIAT/IBM publishes research, reports, and tools on different types of sports facilities and makes this information available for the public. I also must acknowledge Snorre, Sondre, Viviann, Siri, Linda, Bernhard, and Ola from SIAT/IBM. I also wish to thank my office mate at IØT, Paritosh, and Matteo, Shabnam, Yeganeh, Carine, Atle, Tone, Kjerstina, Maria, Olav and Vikas from IBM. Dear Amin, thank you for all your help and support. I admire your kindness, willingness to help others, and hard work.

These acknowledgments would not be complete without mentioning all the workers and swimmers who have contributed to this work. Thank you for giving me easy access to the facilities and for providing me with all the information I needed. Thanks to Thomas for answering all my emails and for giving me all the requested information. Thanks to the Norwegian Swimming Federation for collaborating on sending the survey to the swimmers.

Finally, my most profound appreciation to my family, mamma Anne-Bianka, pappa Einar, my twin sister Cathrine and my brother Bjørnar. I highly suspect you have not read my papers, but thanks for always being so proud of me and for cheering for me.

ABSTRACT

Norway has approximately 900 public, private, and leisure swimming facilities used for swimming education, recreation, and sports. Chlorine is the most common disinfectant used in swimming pool water to prevent the growth of microorganisms. However, while maintaining the chlorine concentration in a pool, continuous reactions between chlorine and organic and inorganic materials take place, which leads to the formation of inorganic chloramines and other disinfection by-products (DBPs) such as trihalomethanes (THM). The only group of DBPs which is controlled in Norwegian swimming pool waters is inorganic chloramines, often referred to as combined chlorine. To mitigate the water concentration of combined chlorine, UV treatment is often used as a secondary disinfectant in addition to chlorine. However, the results of some studies suggest that UV treatment increases chlorine reactivity and the formation of chlorinated DBPs in pool water.

An increased prevalence of asthma and other respiratory irritations has been found among users who visit swimming pools on a regular basis. These health effects are most often linked to long-term exposure to a volatile inorganic chloramine, trichloramine (NCl_3). In 2019, the Nordic Expert Group proposed an occupational health-based limit value for air exposure to NCl_3 of 0.2 mg/m^3 (stationary air samples). Another important group of DBPs is the trihalomethanes (THM), as represented by the four components chloroform ($CHCl_3$), bromoform ($CHBr_3$), bromodichloromethane ($CHBrCl_2$), and dibromochloromethane ($CHBr_2Cl$). The four components are referred to together as total THM (tTHM), and all are formed in the pool water when chlorine reacts with natural organic matter. The tTHM are volatile and can penetrate the skin easily, making both inhalation and dermal absorption important pathways of exposure. Long-term health effects, such as adverse reproductive outcomes, cancer, and stillbirth, have been associated with exposure to tTHM. As of today, no limit value for exposure to these compounds exists in Norway, and the determinants causing the exposure concentrations to vary over time have not received much attention. The main purpose of this Ph.D. thesis is to identify strategies to assess and manage air exposure in indoor swimming pool facilities and to estimate the prevalence of health effects amongst the most exposed swimmers in Norway.

The method of repeated measures was used to quantify the within and between variability of different predictor variables on air concentrations of tTHM and identify the most important determinants for exposure assessment. The method of repeated measures was also used to assess how strategies for air and water quality determine the variability observed in the air concentration of $CHCl_3$. An exploratory study was conducted to study how the use of UV treatment in pool water affects the overall air concentrations of tTHM and NCl_3 and the covariation between these two exposure variables.

Monitoring components in the air, such as tTHM and NCl_3 is time-consuming, expensive, and requires skilled personnel. While carbon dioxide (CO_2) sensors are used for controlling air quality in different buildings and can be installed in ventilation systems for continuous monitoring purposes, such sensors are not used in indoor swimming facilities. Also, the

strategies for air and water treatment are more or less static and do not correspond to the dynamic bather load observed in swimming pools. The concentration of CO_2 was measured to evaluate whether this component could be used to predict the number of occupants as well as the concentrations of tTHM and NCl_3 in the air. In addition, the prevalence of health effects was studied amongst the most exposed swimmers in Norway.

For normally distributed data for which information was collected repeatedly over time, a mixed effect model was applied to analyse the results. This tool enables the within and between variance components in air concentrations to be estimated while adjusting for fixed and random effects. As a result, we can identify which determinants are affecting the variance components. Multiple logistic regression was used to estimate the odds ratio (OR) for health effects. The statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) 25 and Statistics and Data (STATA) MP 15.

One main conclusion of this thesis is that the air concentrations vary extensively, both in terms of different times of the day and days of the week. To collect representative samples, it was necessary to monitor concentrations during different exposure scenarios; otherwise, our exposure estimates could have been no more valid than random guesses. In cases where repeated samples were collected, methods accounting for the dependency between the repeated observations were used, as a correlation between the repeated samples collected of tTHM and NCl_3 was found. Even when the water quality is within the required limit values, the air concentration of NCl_3 and tTHM may vary extensively, with the concentration of NCl_3 possibly exceeding the concentrations proposed by the Nordic Expert Group (0.2 mg/m^3). The results also showed that when the water concentration of combined chlorine increases, the air concentration of tTHM also increases. Furthermore, when the concentration of free chlorine decreases, the air concentration of NCl_3 decreases. Therefore, a recommendation is that the concentrations of free and combined chlorine should be kept well below their upper acceptable limit values. The results suggest that the use of any UV treatment should be carefully evaluated, as using such a treatment may increase the overall air exposure to tTHM. Rather, other methods for reducing the concentration of combined chlorine in the water should be implemented. As the air quality is highly dependent on the water quality, air and water quality should be treated as one system in which the air supply is controlled based on bather load and water concentrations of combined chlorine. Both tTHM and NCl_3 should be monitored regularly in the air, and limit values for these components should be implemented. Considering that the concentration of CO_2 significantly correlates with occupancy and NCl_3, CO_2 sensors can be used to create a more dynamic air supply, on that corresponds to the need of the users in the poolroom and, at the same time, reduces the variability observed in the air concentrations of NCl_3 and tTHM. The prevalence of health problems is greatest amongst the most exposed swimmers in poolrooms. Facilities hosting swimmers spending more than 16 hours in the water every week should have stricter requirements for pool water management and air quality than other facilities.

Through this thesis work, six research questions have been answered and new knowledge was created.

DECLARATION OF AUTHORSHIP

The thesis author is the main author of this thesis, responsible for the study design development, data collection, laboratory work, statistical analysis, the results and discussion, writing, editing and reviewing of paper I, paper II, paper III, paper IV and paper V appended this thesis. Except for the air samples collected in paper IV, all samples were collected by the main author of this thesis. All papers have been published before the thesis submission. The role of co-authors of the appended papers are as follow:

Kristin von Hirsch Svendsen as the main supervisor contributed to discussions regarding the study design, obtained results, statistical methods, scientific input from her expertise, quality control on the scientific content, and proofreading of **paper I, paper II, paper III, paper IV** and **paper V**.

Rikke Bramming Jørgensen as co-supervisor and co-author, provided inputs on the design, scientific input from her expertise, inputs on the analysis of the results, and proofreading of **papers IV**.

Salvatore Carlucci as co-supervisor and co-author, provided inputs on the design, scientific input from his expertise, inputs on the analysis of the results, and proofreading of **paper IV**.

Morten Sæther Grande as co-author, collected the air samples and helped proofreading **paper IV**.

Guangyu Cao, as co-author supervised, together with the main author of this thesis, master student Morten Sæther Grande. He helped in the discussions of study design, provided materials for data collation, contributed with scientific input from his expertise, and proofreading **paper IV**.

LIST OF APPENDED PAPERS

This thesis is based on the following academic publications:

Paper I:
T. B Nitter and K. v H. Svendsen. «Determinants of Exposure and Variability of Trihalomethanes in the Air of Three Indoor Swimming Pools.» *Annals of Work Exposures and Health.* 2019; 63(5):560-567. Doi: https://doi.org/10.1093/annweh/wxz024

Paper II:
T. B Nitter and K. v H. Svendsen. «Modelling the concentration of chloroform in the air of a Norwegian swimming pool facility- A repeated measures study.» *Science of the Total Environment.* 2019; 664:1039-1044.Doi: https://doi.org/10.1016/j.scitotenv.2019.02.113

Paper III:
T. B Nitter and K. v H. Svendsen. «UV treatment and air quality in a pool facility.» *Water Science and Technology*. 2019; 80(3):499-506. Doi: https://doi.org/10.2166/wst.2019.291

Paper IV:
T. B Nitter, M. S Grande, K. v H. Svendsen, S. Carlucci, R. Jørgensen, and G. Cao. «Can CO_2 sensors in the ventilation of a pool facility reduce the variability in the trihalomethane concentration in indoor air?» *Environment International*. 2020. Doi: https://doi.org/10.1016/j.envint.2020.105665

Paper V :
T. B Nitter and K. v H. Svendsen. « Covariation amongst pool management, air exposure and asthma for competitive swimmers in Norway.» *Science of the Total Environment.* 2020; 723. Doi: https://doi.org/10.1016/j.scitotenv.2020.138070

CONTENTS

ABBREVIATIONS

ACH	Air changes per hour/air change rate
$CHBr_3$	Bromoform
$CHCl_2Br$	Bromodichloromethane
$CHClBr_2$	Dibromochloromethane
$CHCl_3$	Chloroform
CO_2	Carbon dioxide
DBP	Disinfection by-product
HRT	Hydraulic retention time
NCl_3	Trichloramine
NH_2Cl	Monochloramine
$NHCl_2$	Dichloramine
OR	Odds ratio
THM	Trihalomethanes
tTHM	The set of the four most common THM in chlorinated water ($CHCl_3$, $CHCl_2Br$, $CHClBr_2$, $CHBr_3$)
WHO	World Health Organization
US EPA	United States Environmental Protection Agency
UV	Ultra Violet

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Swimming dates back to the Stone Age, but it did not truly become an organised sport until 1896, when it was included in the Olympic games for the first time. Since then, its popularity has increased, and swimming is now considered to be an important worldwide sport. Due to Norway's geography, with its long coastline and many fjords, rivers, and lakes, learning to swim is essential to prevent drowning. Therefore, swimming education is a mandatory component of primary schools' sports curricula (1). However, swimming is also used for recreational and exercise purposes, and the Norwegian Swimming Federation currently has 62,000 active members, representing all age groups.

To prevent infectious illnesses caused by exposure to microorganisms, the water in Norwegian pool facilities is disinfected with hypochlorite, often in combination with UV treatment. However, during swimming, bathers release cosmetics and body fluids into the water (2). These products, along with the dissolved organic matter present in the filling water, react with chlorine and form numerous unwanted disinfection by-products (DBPs) (Figure 1). The exposure to certain DBPs is widespread, as inhalation, dermal absorption, and accidental oral ingestion are potential exposure pathways. As certain DBPs have been found to be toxic and carcinogenic, they have generated a great deal of interest (3, 4). The most common health issues related to exposure in swimming facilities are irritations of the respiratory tract, skin, eyes, and nose (5).

To prevent irritations, the most commonly measured concentrations of precursors in swimming pool water are for three inorganic chloramines, namely, monochloramine (NH_2Cl), dichloramine ($NHCl_2$), and trichloramine (NCl_3), which are referred to in combination as combined chlorine. The formation of inorganic chloramines occurs when ammonia reacts with free chlorine. In Norway, water limit values for free and combined chlorine exist (6). However, no limit values for the control of any other DBPs exist for the air or in the water. Pool water treatment is further described in Section 2.1.

One of the quantitatively most important groups of DBPs are four trihalomethanes, often summarized as total trihalomethanes (tTHM), which includes $CHCl_3$ (chloroform), $CHCl_2Br$ (dichlorobromomethane), $CHClBr_2$ (dibromochloromethane), and $CHBr_3$ (bromoform). The International Agency for Research on Cancer has classified both $CHCl_3$ and $CHCl_2Br$ as possibly carcinogenic to humans (2B) (7). The tTHM are volatile, and their total relative concentration is higher above the water surface compared to in the pool water (8, 9). The tTHM can also penetrate the skin easily, making both inhalation and dermal absorption relevant pathways of exposure (10, 11). Long-term health effects, such as adverse reproductive outcomes, low birth weight, stillbirth, and cancer, have been associated with exposure (12-15), but the evidence is inconsistent. Another volatile DBP is inorganic NCl_3, and when considering air exposure in swimming facilities, NCl_3 and tTHM concentrations are the most essential concentrations to consider (see Figure 1) (16). NCl_3 is not classified as carcinogenetic to humans (group 3); however, the component is associated with the increased prevalence of respiratory irritations, such as asthma, reported amongst swimmers and lifeguards (17-19). The main objective of this Ph.D. work is to find strategies to assess and manage air exposure in swimming facilities, and, for this work, air concentrations of tTHM and NCl_3 were measured. Health effects and existing limit values related to tTHM and NCl_3 are described further in Section 2.3.

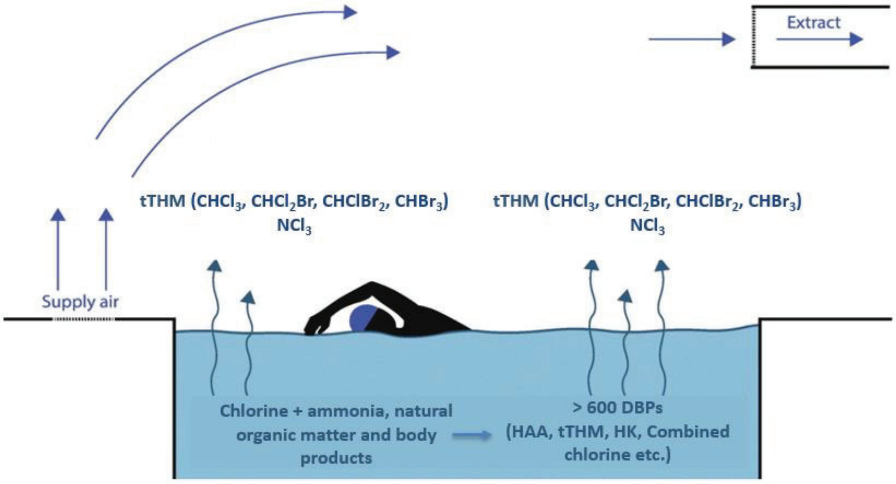

Figure 1: Formation of DBPs in swimming pool water

To save energy and reduce the loss of water, both the water and air are recycled and controlled via fixed set points for relative humidity (RH), air and water temperatures, and water concentration of combined chlorine. This process leads to long residence times for compounds in the pool system and recirculation of air contaminants. The air and water are treated as two independent systems. Water quality is controlled based on the measurements of water quality parameters, and air quality is controlled via measurements of air quality expressed as temperature and RH. With regard to volatile tTHM and NCl_3, inhalation is considered to be the most critical exposure pathway. Still, information about fresh air supply and air exchange rate is rarely provided in the published literature, and no requirements for air exchange rates exist in Norway. Air handling in Norwegian pool facilities is described in Section 2.2.

Existing epidemiological investigations, which are elaborated upon further in Section 2.4, focus mostly on hazard identification, in which the prevalence of disease amongst lifeguards and exposure to NCl_3 have been estimated using cross-sectional study designs (18-24). Considering that an increased body of evidence exists for the association between exposure to NCl_3 and respiratory irritations, in 2019, the Nordic Expert Group proposed an occupational guideline limit value for eight hours of air exposure to NCl_3. However, measuring tTHM and NCl_3 is expensive and requires skilled personnel, and, currently, no sensor technology for continuous monitoring of these compounds exists.

The health issues related to exposure in the poolroom are caused by long-term exposure. Therefore, to characterize such exposure, there is a need for methods able to identify the long-term exposure pattern (25). To the knowledge of the candidate, the determinants of exposure variability required for assessing and managing concentrations of tTHM and NCl_3 in the air are not well understood. Currently, a more holistic understanding of the relationship between ventilation and disinfection strategy, pool water management, and variability in air concentrations is lacking, along with effective measures for reducing the air concentrations of these compounds in existing facilities.

1.1 RESEARCH OBJECTIVES

Based on the identified gaps in the knowledge, which are summarized in Section 2.5, the purpose of this Ph.D. project is to identify strategies to assess and manage air concentrations of DBPs in indoor swimming facilities and to estimate the prevalence of health effects amongst the most exposed swimmers in Norway. This work was accomplished by performing repeated measures of variables, such as ventilation strategy, disinfection technology, occupancy load, as well as air and water quality, in several pool facilities. The covariations between self-reported health problems amongst active swimmers, swimming facility, pool water management, and air concentrations were also investigated, and methods for assessing and managing exposure are proposed. In particular, the following two research objectives (RO) were addressed:

> *Assessing air exposure:* The work ought to identify which determinants causing spatial and temporal variability in air concentrations of DBPs essential to consider when determining air exposure.
>
> *Managing air exposure:* The work ought to identify strategies to manage air concentrations of DBPs that can be implemented to reduce exposure in indoor swimming pool facilities.

The research objectives were then developed into the following research questions:

1. What is the prevalence of respiratory irritations amongst active swimmers above the age of 18 years in Norway? (Paper V)
2. What are the most important determinants to consider to produce a reliable sampling strategy for assessing the air concentration of tTHM in the air? (Paper I)
3. Can the observed variability in air concentrations of $CHCl_3$ be estimated via a statistical model taking into account both air and water quality? (Paper II)
4. Does a medium-pressure UV lamp used in the water circulation system have a significant impact on the air concentrations of tTHM and NCl_3? (Paper III)
5. Could monitoring CO_2 in swimming facilities be used as an effective method for predicting the air concentrations of tTHM and NCl_3 in the air of swimming facilities? (Papers IV and V)
6. Are there covariations amongst ventilation strategy, pool water management, and NCl_3? (Paper V)

Assessing exposure (see Figure 2) includes the identification of the population at risk, air concentrations, exposure pathways, and strategies for exposure quantification. Exposure quantification consists of the identification of the determinants causing exposure variability and the magnitude of that variation, both of which are explored in this thesis. Once the determinants of exposure are identified, potential solutions for effective hazard control can be identified, which will enable us to propose different alternatives for managing exposure.

Figure 2: Steps in assessing and managing exposure

1.2 SCOPE AND LIMITATIONS

The thesis focuses on strategies to assess and manage the concentration of NCl_3 and tTHM in the air, and it is assumed that these air concentrations function as markers for the total exposure concentrations in the poolroom. Bathers are also exposed through dermal penetration and accidental oral ingestion. Regarding the health effects caused by exposure to tTHM, dermal penetration is considered a vital exposure pathway; however, this method of exposure is not accounted for in this thesis. Microorganisms are not reviewed, and, in general, no measures should be implemented unless the microbiological water quality can be maintained. Other primary disinfection methods, such as bromine, and secondary disinfection methods, such as ozone and UV/ozone combinations, also exist. These methods are, however, not applied in Norway, and, for this reason, they are not discussed or addressed in this thesis.

1.3 RESEARCH OUTCOMES

The work done for this thesis resulted in five papers addressing the assessment and management of air concentrations in indoor swimming facilities which have provided the following contributions:

1. Estimated the prevalence of health effects amongst active swimmers in Norway and its covariations with pool water management, asthma, and NCl_3 in the air (paper V- assessing exposure).
2. Identification of the determinants of importance in terms of assessing the air concentrations of tTHM and the magnitude of the variability observed within and between different swimming facilities (paper I- assessing exposure).
3. Identification of the determinants related to the air and water explaining the variation observed in the air concentrations of $CHCl_3$ in the air and development of a model explaining the relationship between air and water quality (paper II- assessing and managing exposure).
4. Identification of the effects on airborne concentrations of NCl_3 and tTHM when a medium-pressure UV lamp is used in the water and the relationship between these two air concentrations (paper III- managing exposure).
5. Assessment of whether CO_2 sensors in the ventilation system can help reduce the variability observed in the air concentrations of NCl_3 and tTHM, thereby allowing the creation of a more dynamic ventilation strategy corresponding to poolroom user demands (papers IV and V- managing exposure).

1.4 STRUCTURE OF THE THESIS

The framework of this Ph.D. work is shown in Figure 3, where the activities and outcomes of this project are divided into exposure assessment and management. The research questions and issues addressed in each of the published papers are based on the knowledge gaps identified in the review of existing literature (see Section 2.5). The results of this Ph.D. work are based on case studies and field observations. Data were collected repeatedly using stationary test stands and field observations (papers I-V). In paper V, a cross-sectional study was used to estimate the prevalence of health problems amongst active swimmers in Norway above 18 years of age. Statistical methods, such as descriptive statistics, linear mixed effect models, and multiple logistic regression, relied on the analytical software tools SPSS and STATA.

Chapter 1 introduces the research problem, questions, scope and limitations, and outcome of the thesis. Chapter 2 describes the theoretical background and emphasis on topics pertinent to the research questions. Chapter 3 elaborates on the methods used for exposure assessment and analysis. In chapter 4, the main results are presented under each research question, and a discussion follows in chapter 5. The discussion is divided into sections on the two research objectives, exposure assessment and management. Chapter 6 presents the overall conclusions, and chapter 7 identifies some needed research.

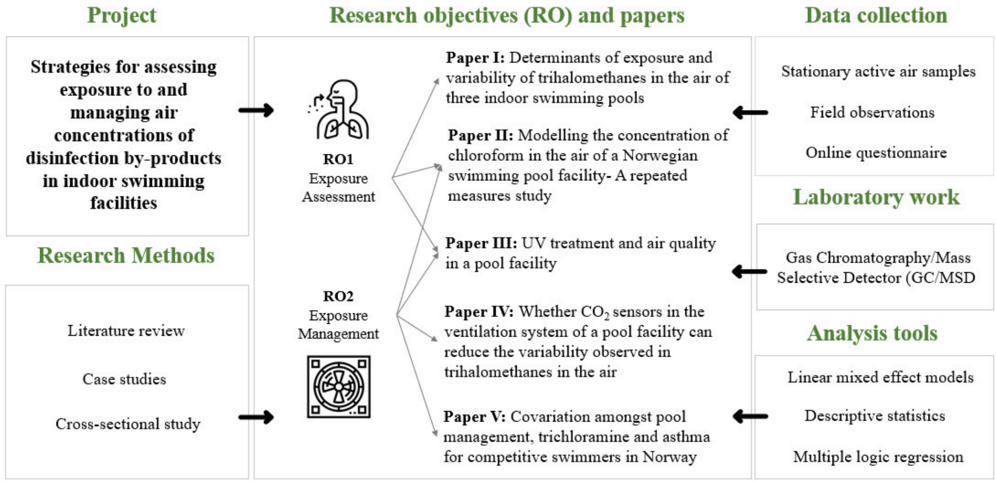

Figure 3: Thesis framework

2 THEORETICAL BACKGROUND

2.1 POOL WATER TREATMENT

There are approximately 900 public, private and leisure pool facilities in Norway. Swimming pools in Norway are commonly filled with freshwater or, in rare cases, a mixture of freshwater and seawater. According to the Norwegian Institute for Water Research (NIVA), the filling water should be of the same hygienic quality as drinking water (26), meaning that, in a 100 mL water sample, no pathogenic microorganisms can be quantified. Naturally, freshwater and seawater contain different types of organic and inorganic matter, and, when bathers enter pools, additional material is added to the water, such as cosmetics, urine, sweat, skin, particles, and so forth. These precursors, along with high water temperatures, create optimal conditions for the growth of microorganisms. In addition, pool water is recycled to save energy and water, and, depending on the water temperature, between 30 L (≤34 °C) and 60 L (≥34 °C) of water should be added per bather. The water, therefore, has a high residence time; typically, it takes between 4 and 8 hours before all the water in a pool has been treated by the water treatment system. A simplified pool water circulation system is shown in Figure 4 and consists of an equilibrium tank, filter, UV treatment, and chlorination.

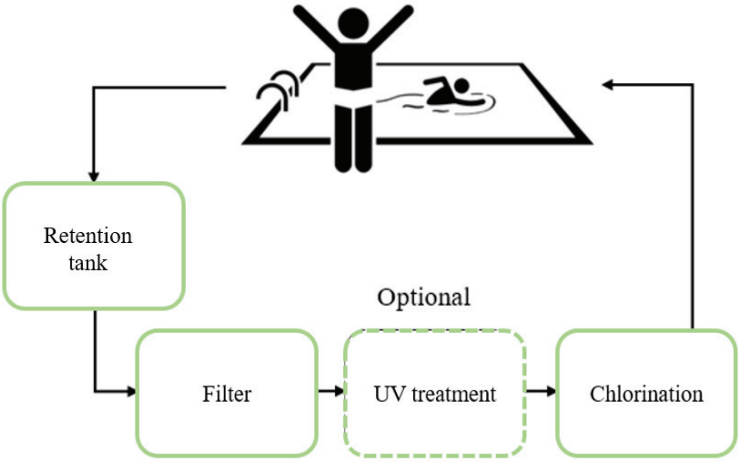

Figure 4: Pool water circulation system. Modified from Soltermann, 2015 (27)

To maintain hygienic conditions, the water must be disinfected. The most common strategy for water disinfection in Norway is hydrochlorination (sodium or calcium), often accompanied by UV treatment. In this section, the mechanisms for free and combined chlorine and UV treatment are described briefly, along with existing laws and regulations for pool water quality.

2.1.1 Free chlorine

The disinfection properties of hypochlorite are determined by the concentrations of free and combined chlorine in the water. Free chlorine is the combination of hypochlorite acid (HOCl) and hypochlorite ion (OCl^-), both of which are formed when hypochlorite is added to the water, see equation 1 (28).

$$HOCl \leftrightarrow H^+ + OCl^- \qquad (1)$$

Of the two, HOCl is significantly more active than OCl^-. Therefore, it is favourable to keep the concentration of HOCl as high as possible. However, the pH value, together with the water temperature, affects the equilibrium between the two, with more HOCl present when the pH value and water temperature are low (28). Considering that low pH values irritate the skin and mucous membranes of humans, the pH value should be maintained between 7.2 and 7.6. At these pH values, the concentrations of HOCl and OCl^- are approximately the same (6, 26). To ensure proper inactivation of pathogenic microorganisms, the minimum requirement for free chlorine is 0.4 mg/l at water temperatures of 27 ºC and 1.0 mg/l at water temperatures above 37 ºC (6).

2.1.2 Combined chlorine

Urea (CH_4N_2O) is the final product of human protein metabolism. Bathers release this component to the pool water through skin, sweat, and urine, making it the main nitrogenous compound found in swimming pool water (29). When free chlorine reacts with ammonia and nitrogenous compounds, combined chlorine is formed (30). Combined chlorine also has some disinfection properties, but these are slower and weaker compared to those of free chlorine (26). Combined chlorine is the combination of the three inorganic chloramines NH_2Cl, $NHCl_2$, and NCl_3 (17). Of the three, NH_2Cl is the dominant compound in pool water (26). At 20 ºC, NCl_3 is estimated to be 966 and 286 times more volatile than NH_2Cl and $NHCl_2$, respectively, and when combined chlorine is measured in the air, 90% of it consists of NCl_3 (31). No evidence of cancer or increased toxicity has been found in studies in which animals have been exposed to NH_2Cl and $NHCl_2$ (5). On the contrary, NCl_3 is characterized as causing substantial irritation of the airways and is suspected of being the leading cause of the increased prevalence of asthma observed amongst professional swimmers and lifeguards (17, 18, 23). Epidemiological investigations, health effects, and limit values for air exposure to NCl_3 are further described in Subsection 2.3.2.

Existing technology (N,N-dietyl-p-fenyldiamin (DPD)) allows for the continuous monitoring of combined chlorine in swimming pool water, and this compound is used as a marker for the concentrations of contaminants in swimming pools (26). According to Norwegian pool water regulations, the combined chlorine concentration should never exceed 50% of the concentration of free chlorine. The maximum accepted concentration of combined chlorine is 0.5 mg/l (6). According to the WHO, the level of combined chlorine should ideally be less than 0.2 mg/l, as higher levels suggest too many bathers and low water circulation (32). Currently, free and combined chlorine are the only chemicals for which pool water limit values exist in Norway.

2.1.3 UV treatment

The most commonly used UV lamp in Norway is a medium-pressure UV lamp which emits wavelengths between 200 nm and 600 nm. Combined chlorine, especially NCl_3, is very photosensitive, and a common strategy for combined chlorine mitigation is to use UV treatment in combination with chlorination (33). The use of UV treatment is optional; however, this method is used as a secondary disinfectant in almost all pool facilities across Norway. Although the concentration of combined chlorine is mitigated when the water is treated via UV lamp, the results of some studies suggest that the levels of $CHCl_3$ and $CHCl_2Br$ may increase significantly (34, 35). These increases have been explained by the observed increase in active chlorine and by radicalizing mechanisms initiated by UV treatment (35). Findings from lab-scale studies have shown that the concentration of tTHM remains constant in the UV reactor (27); however, UV treatment makes the organic compounds in the water more reactive towards chlorine, making them act as precursors to the formation of tTHM, leading to increased concentrations (36, 37).

2.2 AIR HANDLING

The general purpose of ventilating a room is to improve indoor air quality by both diluting and removing harmful compounds. In Norwegian swimming facilities, air is mechanically (forced) supplied to the pool room using air handling units with blowers for fresh air and exhaust. The most common air distribution strategy is called mixing ventilation. Mixing ventilation is characterized by air being supplied to the room at velocities high enough to impact the total air volume, so that the air temperature, RH, and air concentrations of compounds are assumed to be more or less uniformly distributed throughout the room volume (38, 39). In the swimming facilities studied in this Ph.D. thesis, the supply grills were located at floor level, and the air was supplied to the room up along window façades to prevent condensation on the window surfaces. The air was extracted from grills located on one of the walls of each poolroom, see Figure 5. To prevent humidity and heated air from leaking out of the room, negative air pressure is created by extracting a higher air volume than that being supplied.

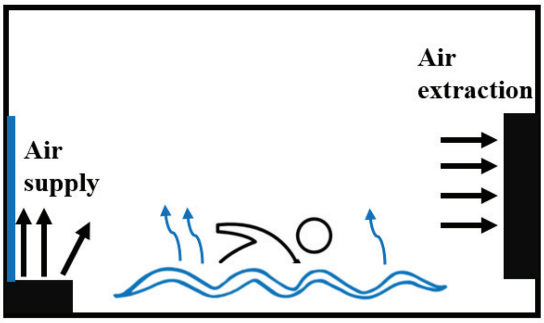

Figure 5: Sketch of mixing ventilation strategy in swimming facilities

Swimming facilities constitute one of the most energy-consuming building categories (40); hence, to save money on heating the air, the air is recycled. Dehumidification is energy demanding, and, to reduce water evaporation, it is recommended that the air velocity above the water surface be limited (maximum 0.15 m/s). The air temperature should also be kept 1-2 ºC higher than the water temperature (41). In order to maintain a satisfying indoor climate for the users and to reduce the evaporation from the pool surface, the RH is normally kept in the range of 50-60%. Air changes per hour (ACH) represents how many times, theoretically, the air is exchanged per hour in a room, regardless of whether the air consists of fresh air, recycled air, or a mixture of the two. The mean age of the air is a term used to describe how long an interval exists from when an air particle enters the room until it exits that room. Sometimes the mean age of air differs within the room due to low ventilation effectiveness, which means that some parts of the room may be over ventilated while other parts of the room are under ventilated (38). Ventilation efficiency can be evaluated by measuring air concentrations, which was done in this Ph.D. thesis.

Although it is not a requirement, SINTEF suggests that the ACH be between 4 - 7 times per hour for conventional pool facilities; further, for rooms with hot water pools (water temperatures above 34 ºC), the ACH should be between 8 - 10. The recommended fresh air supply per m^2 water surface is 10 m^3/h (41), which is well below the WHO's recommendation of 36 m^3/h (5).

In Norwegian swimming facilities, the feedback control method used to maintain indoor air quality involves adjusting the air supply based on setpoints for air temperature and RH (42). The air quality can also be adjusted based on concentrations of carbon dioxide (CO_2), which is exhaled when people breathe. CO_2 is considered to be a good indicator for the number of occupants present in the room, as well as for other air concentrations which are related to illness (43-46). In sports halls, it is recommended that CO_2 sensors be used to control the air supply (47); however, such sensors have not been proposed for swimming facilities. In general, the air concentrations of CO_2 have not been a focus in swimming facilities except for in a recent study, where the authors found a correlation between the measured CO_2 concentration; insufficient ventilation, as indicated by such factors as condensation on window surfaces; occupancy level; and air concentrations of tTHM (48).

2.3 DISINFECTION BY-PRODUCTS

Since the beginning of the 20th century, disinfecting drinking water with chlorine has mostly defeated the outbreaks of deadly waterborne diseases, making the chlorination of drinking water one of the greatest public health achievements, saving billions of lives worldwide (49). However, in 1974, Rooks discovered that when free chlorine reacts with natural organic matter in water, the formation of undesired halogenated disinfection by-products (DBPs) occurs (50). Since then, more than 600 DBPs have been identified in chlorinated water (16). Although the results remain uncertain (51), the most studied health effects caused by exposure to DBPs in chlorinated drinking water are bladder cancer and congenital disabilities (52, 53).

The reactions of free chlorine with precursors in swimming pool water are illustrated in Figure 6. In chlorinated freshwater pools, chlorinated DBPs, such as $CHCl_3$, $CHCl_2Br$ and NCl_3 dominate. However, if bromide is present, then brominated, as well as chlorinated DBPs, will be produced (54). As described in Section 2.1, the only chemicals for which limit values exist for Norwegian pool water are free and combined chlorine (highlighted in Figure 6). The variation in concentration of DBPs in pool water depends on several factors, including reaction period, organic material content (55, 56), chlorine dose, number of swimmers, bromide content, off-gassing of volatile DBPs (57, 58), pH value, and water temperature (59).

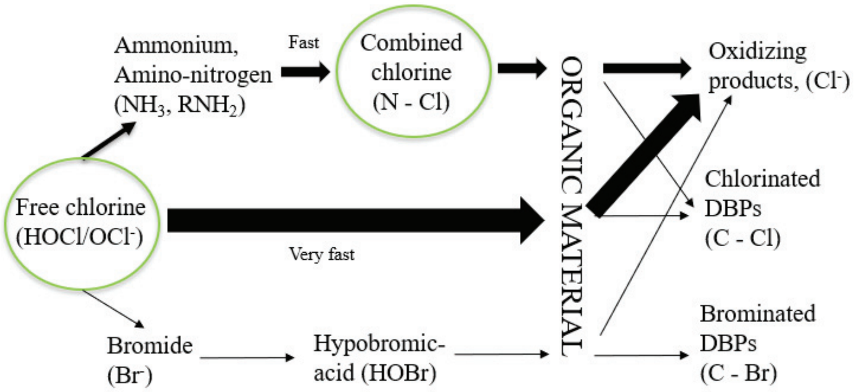

Figure 6:Schematic overview of the reactions of free available chlorine with organic matter, modified from Pickup, 2010 (30).

In studies of chlorinated drinking water, tTHM and haloacetic acid (HAA) are the most frequently targeted DBPs, not necessarily due to their toxicities, but because they are the quantitatively most essential DBPs and serve as indicators of water quality (16, 51). In swimming pool water, the water concentrations of DBPs are likely to be much higher compared to those found in drinking water (56, 60). However, the health effects observed for long-term exposure to chlorinated drinking water may not be relevant for exposure in chlorinated pool water, mainly due to the exposures being significantly different. While the health-based limited values derived for chlorinated drinking water reflect tolerable risks over a lifetime and assumed an intake of 2 litres of water per day (5), oral ingestion during swimming can vary between 20 mL and 100 mL, making this exposure pathway essentially negligible (61). For non-volatile DBPs with a low ability to penetrate the skin, such as HAA (62), exposure might be significant when drinking chlorinated water, making it even less relevant when the exposure occurs in a swimming facility.

In previous studies in which dermal, inhalation, and oral exposures using tTHM or just $CHCl_3$ as indicators, have been estimated amongst swimmers, inhalation was assumed to be the main route of absorption, accounting for between 56% and 76% of the total exposure (9, 10, 63-65).

To identify strategies for assessing and managing air exposure in indoor swimming facilities, tTHM and NCl_3 are considered to be the most relevant compounds, as these DBPs are characterized as relatively to extremely volatile. In the following subsections, exposure pathways and health effects, as well as available limit values for tTHM and NCl_3, are described briefly.

2.3.1 Trihalomethanes (tTHM)- Health effects and limit values

The tTHM are formed through reactions involving chlorine and naturally occurring material in the water, and tTHM is one of the dominant groups, representing up to 20% of the DBPs present in pool water (16). The tTHM are characterized as being from relatively to extremely volatile, with $CHCl_3$ being the most volatile (31, 66). The relative concentration of tTHM is higher above the water's surface compared to the concentration found in the pool water (11, 60, 67)). $CHCl_3$ and $CHCl_2Br$ are both characterized as potentially carcinogenic to humans (2B). In some previous studies, the hazard index and carcinogenetic risk related to active swimmers have been estimated using formulas for multi-pathway exposure to tTHM. In many of these studies, the estimated cancer risk exceeds 10^{-6}, which indicates that carcinogenetic effects related to swimming cannot be neglected for lifeguards or other people who swim regularly (8, 68, 69). However, these calculations are based on a number of assumptions, and, in most of these studies, the air concentration of, and multi-pathway exposure to, tTHM has been estimated based on concentrations measured in the water.

Currently, there is no limit value for the pool water concentration of tTHM in Norway; however, a limit value for tTHM (50 µg/l) has been proposed in the revised version of the Norwegian pool water regulations. In other countries, such as Denmark, Germany, and Sweden, a limit value for tTHM (sometimes counted as $CHCl_3$ equivalents) in swimming pool water exist and range from 20 µg/l to 100 µg/l (70, 71).

In Norway, occupational air exposure limit values for $CHCl_3$ (10 mg/m^3) and $CHBr_3$ (5 mg/m^3) exist (72). These are, however, not considered to be optimal reference values for swimming facilities, as occupational health effects, such as irritative ocular and respiratory symptoms, have been observed at median air concentrations of tTHM as low as 76 $\mu g/m^3$ (81.1 ±. 45.5 $\mu g/m^3$) (73). In another study, where mean air concentrations of tTHM were measured to be 205 $\mu g/m^3$, the cancer risk among elite swimmers was found to be unacceptably high (8). Based on results from animal studies on dogs, a tolerable daily intake value for oral exposure to $CHCl_3$ based on the increase observed in hepatic cysts of 0.015 mg/kg body weight per day was suggested, which corresponds to a tolerable concentration for inhalation of 140 $\mu g/m^3$. According to a risk assessment conducted by the WHO, pool users could potentially exceed the proposed acceptable daily intake value for $CHCl_3$ (32). InVerein Deutscher Ingenieure (VDI) 2089, the German Federal Environmental Agency suggests that the air concentration of $CHCl_3$ should never exceed 200 $\mu g/m^3$. Although this is not a health-based limit value, it was proposed as a marker for insufficient water quality (74).

2.3.2 Trichloramines (NCl_3)- Health effects and limit values

As described in Subsection 2.1.2, chlorine reacts rapidly with the ammonia introduced to the water mainly by the bathers to form inorganic chloramines (NH_2Cl, $NHCl_2$, and NCl_3), of which NCl_3 is exceptionally volatile. With the exception of one study, airborne levels of NCl_3 have been assumed to be the main trigger of work-related asthma or irritative symptoms (17-19, 23, 75, 76). From a health perspective, NCl_3 is considered to be the most essential DBP (16). Experiments carried out in mice have shown that NCl_3 is an upper airway irritant which is as powerful as chlorine. Based upon concentration-response curves, a short-term limit value of 1.5 mg/m^3 and a long-term limit value of 0.5 mg/m^3 for NCl_3 have been proposed (77). This last study may be the main reason why the WHO proposed a privational guideline limit value of 0.5 mg/m^3 for swimming pool atmospheres in 2006 (5). However, in 2019, the Nordic Expert Group proposed occupational limit values for an 8-h air exposure to NCl_3 of 0.2 mg/m^3 for stationary air samples and 0.1 mg/m^3 for personal air samples (4).

2.4 EXPOSURE GROUPS

Theoretically, the warm and humid air of indoor swimming pools constitutes a beneficial environment for asthmatic subjects, as explained by the lower respiratory heat loss experienced in environments with high ambient humidity (78, 79). However, the prevalence of health problems amongst the most exposed users in the poolroom has been acknowledged, and air concentration is an essential determinant for the respiratory irritations observed (80). In Section 2.3, it was established that inhalation is considered the most critical exposure pathway in the poolroom. Furthermore, when considering air exposure, the volatile compounds tTHM and NCl_3 are the most relevant compounds.

In swimming pool facilities, there are three main exposure groups: the lifeguards, visitors, and active swimmers. Considering the different exposure times and pulmonary ventilation both between and within each of these exposure groups, the risk related to exposure differs significantly. In this section, the results from previous critical reviews, meta-analysis, and epidemiological investigations of air exposure and health effects amongst children, lifeguards, and swimmers is presented. If management strategies are to be implemented successfully, it is important to understand which exposure groups should be targeted.

2.4.1 Exposure amongst children

In addition to the mandatory school swimming education, the Norwegian Swimming Federations had, in 2016, 52106 active members aged from 0 to 19 years (81). The risk related to swimming and children is ambiguous. Some studies show that swimming pool exposure in early life is associated with a significantly higher risk of pre-school onset asthma (82, 83). Children with asthma have been found to report substantially more irritative eye symptoms and worsened asthma compared to controls (84). Nickmilder and Bernard concluded that the prevalence of childhood asthma and wheezing rises around 2 to 3% for every indoor swimming pool per 100,000 individuals in the populations across Europe after accounting for the gross domestic product (GDP) of a country (n=21), as well as its climate and altitude (85). However, in a meta-analysis published in 2016 which excluded studies done in vivo and in vitro as well as accidental exposure, it was concluded that there is no significant difference in asthma development between children utilizing swimming pools and controls (86). This conclusion supports the findings from other studies suggesting that swimming does not increase the risk of asthma or allergic symptoms in children (87-89).

2.4.2 Occupational exposure

The exposure time amongst lifeguards depends on the routines of the swimming facility. In Norway, the exposure time in the poolroom varies from 3 to 8 hours during an 8-hour shift. It has been found that occupational exposure in the poolroom can be a trigger for both pre-existing asthma and the onset of work-related asthma (90). In a previous study, environmental and biological monitoring of lifeguards was included. The authors found that employees with mean levels of tTHM in their alveolar air higher than 21 µg/m^3 had higher risks of red and itchy eyes, dyspnoea/asthma, and blocked nose compared to subjects with lower exposure. At poolside, the mean air concentrations of tTHM were measured as 81.1 ± 45.5 µg/m^3 (73). In most previous studies which investigated the prevalence of health effects via questionnaires while measuring occupational air exposures, NCl_3 was used as an indicator of air quality. In these studies, the air concentrations measured ranged from 0.017 mg/m^3 to 1.34 mg/m^3. In most previous studies, air concentrations of tTHM and NCl_3 were collected using stationary air samples. However, in one previous study, personal air samples of tTHM and NCl_3 were obtained; in this study, the authors found that the relationship between personal and stationary air samples was 1:2, suggesting that to compare stationery samples with personal occupational exposure, the sample concentrations should be divided by two (91, 4). In addition, higher air concentrations of NCl_3 have been measured in leisure pools compared to conventional swimming facilities (17, 20, 76).

2.4.3 Exposure amongst competitive swimmers

The most exposed swimmers in Norway spend more than 16 hours in the water every week while engaging in high pulmonary ventilation (exceeding 200 L/min) (92). Thus, they are inhaling the same amount of air as a lifeguard during an 8-h shift in less than two hours, and the mean uptake of tTHM after a 1-hour swimming period for these individuals has been estimated to be seven times higher compared to their uptake at rest (93). High pulmonary ventilation, in addition to the exposure through dermal penetration during swimming, makes these swimmers the most exposed group in the swimming facility.

Previous literature has shown that athletes who regularly use chlorinated swimming pools may have a higher risk of developing respiratory health problems compared to non-swimming healthy individuals or other athletes (94-98). In two previous studies from Norway, including 24 and 29 competitive swimmers, respiratory symptoms were reported amongst 83% and 48% of these swimmers, respectively (99, 100). In two studies in which air exposure to NCl_3 was estimated while swimmers where present in the pool, concentrations between 0.26 mg/m^3 and 0.41 mg/m^3 were measured. However, in these studies, a limited number of samples were collected (97, 101).

2.5 IDENTIFIED GAPS IN THE KNOWLEDGE

To summarize, inhalation is considered the most critical exposure pathway, both amongst the lifeguards and swimmers. The tTHM and NCl_3 are characterized as being relatively to extremely volatile, and the relative concentrations of these compounds are higher in the air than in the pool water. Yet, no limit values for air supplies or air exposure for the concentrations of tTHM and NCl_3 exist for indoor swimming facilities. Based on the air concentrations measured in previous studies and the reported health effects of recent epidemiological investigations, the exposure concentration of tTHM should be somewhere between 140 µg/m^3 and 200 µg/m^3. In 2019, the Nordic Expert Group proposed a health-based occupational exposure limit value for an 8-h air exposure to NCl_3 which corresponds to 200 µg/m^3 for stationary measurements in swimming pool facilities (4).

In previous epidemiological investigations in which the prevalence of health symptoms amongst swimmers and lifeguards was estimated, the air concentrations of NCl_3 and tTHM have been measured mainly through cross-sectional study designs. Air samples were collected over one or two days, often during the winter season, using high bather loads to characterize worst-case conditions. However, according to Rappaport, using “worst-case” sampling to estimate chronic exposure is a biased sampling strategy (102). The risk of chronic diseases, such as asthma, depends upon mean exposure over time. Considering the fact that air concentrations tend to vary extensively, it is essential to adapt sampling strategies that recognize the long-term behaviour of the concentrations of interest (102). In previous studies of exposure in swimming facilities, it was highlighted that longitudinal studies are necessary to establish a possible dose-response relationship between exposure to NCl_3 and the potential risk of airway irritations among persons who are regularly exposed in the poolroom (18, 76). It has also been highlighted that the air should be as carefully monitored as the water (75, 103).

To the knowledge of the candidate, the focus in published research has been on hazard identification, that is, the prevalence of health problems related to exposure in the poolroom has been estimated for various exposure groups. Limited attention has been given to the determinants causing the variability observed in air concentrations in the poolroom. These determinants are, however, essential for both exposure control (exposure management) and valid and precise assignment of exposure levels (exposure assessment) (104).

Based on the identified knowledge gaps, the two research objectives, along with their research questions, presented in Section 1.1 were developed.

3 METHODS

Exposure assessment can be defined as the science that describes how an individual or population comes into contact with a substance, including the quantification of that amount across space and time for individuals and communities (105, 106). The aim of an exposure assessment varies from assessing the risk related to exposure, to testing compliance with existing limit values, to epidemiological investigations, to source identification, to the identification of determinants of exposure.

Over the last 50 years, however, the methods and terms used in occupational epidemiology have undergone a shift from general to specifics due to the fact that new risks, or risks yet unknown, are difficult to detect (107). When the prevalence of a disease or the number of exposed people is low, even a small confounding variable or measurement error might prevent the discovery of an association between exposure and disease. The exposure estimates must, therefore, be accurate and reliable (106) and optimized in such a way that the study design, sampling strategy/collection of data, and methods for exposure analysis reduce the chance of estimation error (107). Reducing the consequences of uncertainty and measurement error is only possible if an understanding of how to collect representative air concentrations and what types of statistical methods to use for exposure analysis exists.

Assessing exposure includes the identification of the population at risk; relevant exposure pathways; exposure quantification, including exposure frequencies across time and space and dose-response relationships; and determinants of exposure.

Determinants can be defined as factors causing a reduction (such as fresh air supply) or elevation (such as increasing concentrations of precursors) in the outcome variable (108, 109). When important determinants are identified, managing exposure becomes less complicated, as these determinants explain the observed variation, thus allowing for effective hazard control. The relationship between different determinants and the outcome variable is illustrated in Figure 7.

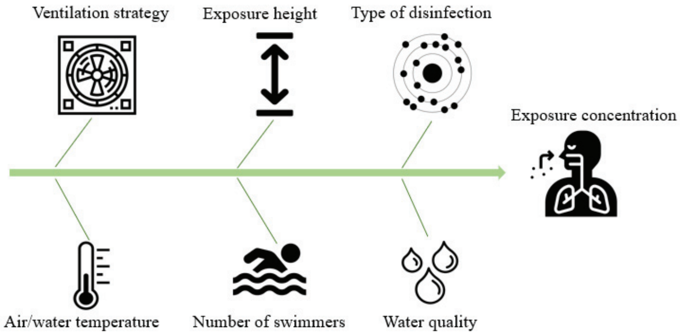

Figure 7: Determinants explaining the variation observed in air concentrations

In this chapter, the methods used in this thesis for assessing air concentrations, including sampling strategies for assessing air exposure (Section 3.1) and the prevalence of health effects (Section 3.2), are described and discussed.

3.1 ASSESSING EXPOSURE

As described in Section 2.5, the covariation between air exposure and the prevalence of health effects amongst different users of pool facilities has mainly been studied using a cross-sectional study design. In cross-sectional studies, measurements are obtained at a single point in time (110). Although these studies are considered suitable for estimating the prevalence of a disease or exposure status, it is not possible to evaluate how the outcome variable unfolds and varies over time. The lack of understanding of the observed variability in poolrooms threatens the representativeness of the air concentration(s) measured. By limiting these threats, the determinants of exposure and the contributors to the observed variability can be assessed by measuring the concentrations of interest, along with other variables of importance, repeatedly over time (111-113).

When quantifying the variation observed in exposure concentration over time, we often refer to the total variation (σ_t^2), which is defined as the sum of the between variation (σ_b^2) and the within variation (σ_w^2). Understanding the contributions made by within and between variations is essential, as each of these terms provides different types of information. For example, if the aim is to identify long-term air concentrations, the between-day variability or variability over time is most important, as short-term peak concentrations may not be relevant for the health outcome. However, if the primary interest is to identify determinants for effective hazard control, then identifying the determinants causing air concentrations to fluctuate within the same day is essential (25, 114-116).

3.1.2 Selection of sampling locations

For air quality monitoring, different sampling strategies can be applied, such as using stationary samples, where samples are collected from one or multiple fixed positions in the room, or personal samples, where the sampling device is placed in the breathing zone of the exposed subject. Depending on the available techniques and the goal of the assessment, samples can be collected continuously for a short time (e.g., using sensors) or discontinuously, in which case, an average value over a given time interval is used (e.g., using thermal absorption tubes (ATDs) or filter cassettes). Air sampling can be either active, where the air is pumped into the sampling medium, or passive, where the air is collected in the sampling medium according to the diffusion and kinetic energy of the gas molecules.

In this Ph.D. work, active air sampling was used for collecting samples of tTHM and NCl_3. These samples were collected using test stands in fixed sampling locations within the poolroom (papers I-V), which was considered to be the most appropriate sampling method due to the adsorbent used to collect air concentrations of tTHM (see Section 3.4). In a paper published by the candidate with co-authors prior to the work done for this Ph.D., the air concentration of tTHM was measured simultaneously from three different heights, namely, 0.05 m, 0.60 m, and 1.5 m, above the surface of the water. No significant difference was found between the samples collected 0.60 m and 1.5 m above the surface; hence, for this thesis,0.60 m was assumed to be representative of the air concentration in the breathing zone of people standing by the poolside, whereas, in papers I and II, the sampling heights 0.05 m and 0.60 m were used to represent the air concentration in the breathing zone of the swimmers and lifeguards.

As described in Subsection 3.4.2, the filter cassettes used for sampling NCl_3 in the air were prepared and analysed at Umeå University in Sweden. Following the sampling strategy used by the lab in Sweden, air samples of NCl_3 were collected 0.30 m above the water's surface. In paper III, air concentrations of tTHM and NCl_3 were collected simultaneously using fixed, stationary test stands. The concentrations of tTHM were collected at both 0.05 m above the water's surface, representing the breathing zone of the swimmers, and 0.30 m above the water's surface, in parallel with the air samples collected for NCl_3. The results, however, showed no differences in the tTHM concentrations measured from the two heights, that is, 0.05 m and 0.30 m above the water's surface. Hence, in paper IV, the concentrations of tTHM were measured at 0.30 m only and used to represent the air concentrations in the breathing zone of the swimmers. Sensors were used to collect information concerning CO_2 concentrations (papers IV and V), air temperature, and RH (papers I-V). The sensors for air temperature, RH, and CO_2 (paper IV) were placed on the test stands in a manner parallel with that used for the samples of tTHM and NCl_3. In paper V, sensors measuring CO_2 concentrations, air temperature, and RH were placed in the air supply, extraction, and fresh air channels.

Monitoring all the air particles in a room is impossible. When collecting information about air concentrations from fixed sampling locations, assumptions are made regarding the air distribution in the room which depend on the ventilation strategy as well as the distribution of the sources, such as swimming pools. These assumptions, however, may bias the representativeness. For example, in a room where mixing ventilation is used, it is often assumed that the air concentration in a room is evenly distributed and that the concentration is the same for all sampling locations. In a thoroughly mixed room, the variability observed between (σ_B^2) different fixed sampling locations would be close to zero, meaning that the air collected from all sampling locations represents the air quality in the room (117). This situation, however, is most likely not the case within a swimming facility, especially when several different swimming pools are located within the same room, because different swimming pools have different water temperatures, different chlorine levels, and different bather loads, resulting if differing emissions within the facility, regardless of ventilation effectiveness. In cases in which the σ_B^2 differs from zero, the assumption of a thoroughly mixed room is no longer valid (104), and representativeness can only be achieved by collecting information for various sampling locations within the room.

For the above reasons, in this Ph.D. work, repeated measures were performed several times a day on different days of the week and over several weeks on variables such as air concentration, ventilation strategy, disinfection technology, occupancy load, and air and water quality in several pool facilities. Air quality parameters, such as air concentration, RH, and air temperature, were collected from several fixed sampling locations within the pool facilities (papers I-V). Repeated measures was used to quantify the within and between variability of facilities, days, and heights, and so forth and to identify the most important determinants of exposure variability.

Due to the limitations in the sampling of tTHM (see Section 3.4), 20-minutes samples were collected. When short-term air samples are collected repeatedly from fixed sampling locations within the same pool room, the air samples are likely to be correlated. Hence, dealing with correlated data is described in Section 3.3. This sampling strategy is, however, considered most suitable for improving both the accuracy and representativeness in cases in which repeated samples are correlated (113). In the following section, the method used in paper V to collect information about the prevalence of health effects is described.

3.2 ASSESSING THE PREVALENCE OF HEALTH EFFECTS

In paper V, information about the prevalence of health effects was collected from active and competitive swimmers in Norway. This paper followed a cross-sectional study design in which data was obtained from the swimmers using an online questionnaire created in Select Survey. To increase the response rate, the Norwegian Swimming Federation distributed the survey to the respondents via e-mail. 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 the swimming facility used for training, use of medication, swimming background, sex, age, body weight, height, and tobacco habits were also included. The questionnaire was administered in Norwegian; however, the translated version can be found in appendix 1. All members above the age of 18 licensed by the Norwegian Swimming Federation were invited to complete the questionnaire (n = 1109), and 313 swimmers completed the survey. The survey was distributed twice, and, based on the responses from the swimmers, two facilities with the highest and lowest reported prevalence of asthma were chosen for the further investigation of pool water management and air quality.

There are some advantages and disadvantages to distributing a survey online. One concern is access to the internet; however, the internet coverage in Norway is good, and numbers from 2019 show that 93% of people between 16 and 79 years used the internet to read e-mail (118). The survey was distributed anonymously, meaning that it was not possible to detect possible misunderstandings related to the survey questions. On the contrary, anonymity may also increase the likelihood of respondents being honest. When using internet-based surveys, the response rate is typically low (119), which was the case for our study as well, which reached a response rate of 28.4% after being distributed twice. A low response rate raises questions as to whether the results can be trusted, as a high proportion of non-responses is often related to an increased risk of estimation bias (120), especially in cases in which the missing responses are related to the topic (121). However, the Norwegian Ethics Committee has 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 of as pressure.

In a previous study, where late and non-responses to a survey concerning respiratory health were examined for 29,218 subjects, the results showed no significant difference in the prevalence of airway disease or symptoms when compared to those for the respondents (120). If the percentages in the responses and follow-up are the same, it is then more likely that the answers are representative of the responses from the whole population (122). Between the first and second rounds of survey distribution, the prevalence of reported doctor-diagnosed asthma decreased from 23.0% to 22.4%. Despite the low response rate, the most-exposed swimmers filled out the survey in both the selected facilities. Thus, based on the matching criteria's exposure hours as well as the distributions of males and females and exposure groups, the two facilities were considered comparable.

The mean reported age of the swimmers, weekly exposure hours, percentage of females, and percentage of swimmers experiencing respiratory irritations during or after swimming did not change between the first (n = 209) and second (n = 104) survey distribution rounds. For this reason, the responses received from the swimmers spending more than 16 h in the pool every week were considered to be representative. All parts of this study were conducted following current international ethical standards. Before the survey used in paper V was distributed, the study was approved by the Norwegian Center for Data Research (NSD), with reference code 577380, and the Regional Ethical Committee (REK), with application id 29689. For further details, please see paper V.

In the following section, the statistical methods used to analyse the prevalence of health effects reported amongst the swimmers and to deal with the correlations between the repeated samples when identifying the determinants of exposure are explained.

3.3 STATISTICAL METHODS FOR EXPOSURE ANALYSIS

3.3.1 Analysing non-parametric data

The type of statistical analysis used hinges on the dependency in the collected data as well as the distribution of that data. In paper V, in which information about disease and exposure status was collected using a survey, the collected information is assumed to be independent, as data from each swimmer was collected just once. The questions in the questionnaire were either ordinal (ranked answer options) or binomial (yes/no) and did not follow any specific distribution.

The odds ratio (OR) represents the odds that an outcome, such as asthma, will occur given a particular determinant, or exposure, compared to the odds of the outcome happening in the reference group (123). The OR was estimated for the occurrence of health effects between the two different facilities using multiple logistical regression. This method allows adjustments to be made for possible confounding variables, such as age, or multiple independent variables which determine the observations. To analyse the association between two non-parametric variables (papers I-V), Spearman's correlation was used, whereas Pearson's correlation coefficient was used to analyse the degree of association between two variables following normal distributions (papers I-V).

3.3.2 Analysing parametric data

For air concentrations following a normal distribution, different analytical methods can be applied, depending on whether the information is independent or dependent of other information. However, in many studies, dependent data is analysed using methods designed for independent data. This analysis error is one of the most common mistakes made in exposure and medical studies. While statistical methods, such as linear regression models, rely on independent sampling, the estimation of within and between variability can only be utilized if repeated samples have been collected (116). Repeated samples collected from the same cluster unit, such as a pool facility or sampling location, are, however, likely to be correlated. Unless the potential correlation between repeated observations is accounted for, under- or over-estimation of p-values and incorrect estimates of the standard errors might result (115, 124, 125). To estimate the air concentrations while adjusting for different predictor and confounding variables and accounting for the potential correlations between repeated observations (115, 125, 126), linear mixed effect models were used in papers I-V. When using such models, the intercept (random intercept model) or/and slope (random coefficient model) can be allowed to vary across clusters and units of repeated measures.

Linear mixed-effect models are accommodated hierarchically (112). The basic idea behind such a model is that fixed determinants can partially explain the variance observed in the exposure concentration. Fixed determinants/effects are those determinants affecting the overall mean exposure concentration such as the fresh air supply, height above the water surface, and so on. When adjusting for these determinants, factors that unfold during the period of analysis, such as bather load and chlorine concentrations, can be accommodated, making the results from these real-life studies more reliable (127). The remaining random variance, which is not explained by the fixed effects, will thus be reduced (109). Linear mixed-effect models are also flexible in terms of being able to accommodate missing (unbalanced) data, which is problematic in, for example, linear regression models, where cases with missing values are excluded (128). In the linear mixed effect model, parameters are estimated using maximum likelihood (ML) or restricted maximum likelihood (REML) (112, 127). For unbalanced data, using the REML method to estimate the variance components is considered to be more valid than ML (128).

To account for the potential correlations between the repeated samples collected within the same cluster, different covariance structures specifying the structure of the variance-covariance matrix can be applied (128). The covariance structure is essential because it is used to estimate the starting point (intercept) of the model parameters. If the choice of structure is not apparent, it is recommended that models with different covariance structures be run and scored based on goodness of fit (129). The covariance structure whose goodness to fit is closest to zero is thus the best covariance structure (130)—as judged by the significance of the likelihood ratio tests ($p \leq 0.05$). Log-likelihood ratio (- 2LL) analysis was used in papers I-V to compare the fit across models, taking into consideration different determinants as well as covariance structures, as judged by the significance of the likelihood ratio tests ($p \leq 0.05$) (131).

Indoor air quality parameters are often autocorrelated, and the correlation varies with ventilation rate and effectiveness (113). In the appended papers, in the cases where multiple samples were collected close in time, the first-order autoregressive (AR (1)) model provided the best model fit. This structure assumes that the correlation function decays exponentially as the interval between the measurements increases (112). In the cases in which only two samples were collected on the same day, compound symmetry (CS) fit the data best. This covariance structure assumes that the correlation is constant irrespective of the time interval separating the measurements (115).

One of the assumptions made when using a linear mixed effect model is that the residuals of the air concentrations are normally distributed with a constant variance and a mean of zero. When the air concentrations are complicated, time-consuming, and expensive to measure, limited samples are often collected, sometimes resulting in significant observed variations in these concentrations. In such cases, the probability distributions are often better described with the natural log (ln) transformations of the air concentrations (116). In this thesis, the air concentrations were always tested for normality via the Shapiro Wilk test and histograms. As the distributions were either positively or negatively skewed, this skewness was accounted for by the ln transformations of the air concentrations. The following expression specifies the general interpretation of the random intercept model:

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

where i is the cluster unit, j is the repeated sample unit, 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 for the outcome variable.

Prior to the work done on this thesis, the candidate, together with the technician Arne Vidar Sjønøst, developed a method for sampling, analysing, and maintaining the quality control for the tTHM. This method, along with the sampling, analysis, and quality control method used for NCl_3, is described briefly in Section 3.4.

3.4 LABORATORY ANALYSIS OF tTHM AND NCL_3

As described in Section 3.1, active air sampling was used for both tTHM and NCl_3. Active sampling consists of pumping a defined air volume through a bed of sorbent(s) in a tube/filter cassette, which retains the analytes. Active sampling onto sorbents is the most versatile option (132), and several official methods, including US-EPA TO 17 and ISO 16017/16000, which were used in this work, have been established based on this technique.

3.4.1 Sampling, analysis and quality assurance for tTHM

The selection of the sampling flow rate and sampling time depends on the sorbent used, the environment in which the samples are to be collected, and the GC detection limits. According to US-EPA Method TO-17, the pump flow rate should be above 10 mL/min to minimize the errors due to the ingress of VOCs via diffusion. Additionally, a sampling volume between 1 L and 4 L is recommended, as long as it is consistent with safe sampling and breakthrough volumes (133).

For the air sampling of tTHM, different sorbents can be used, such as Chromosorb, Carbopack B, Tenax TA, or charcoal, or a combination of these sorbents can be used in the same tube. In some previous studies, samples of tTHM were collected over a 20-minute span using an airflow rate of 7 mL/min (3, 9, 11, 134). In other studies, samples were collected using Tenax TA for two and three hours using airflows of 10 mL/min and 12 mL/min, respectively (135, 136). In this thesis, Tenax TA was used because it was available in the lab. Although there are limitations and advantages related to the different sorbents, regarding the aim of this thesis, short-term samples were preferable, for which Tenax TA performs well. In cases where personal exposure amongst lifeguards is of interest, other sorbents allowing for greater sampling volumes are preferable.

Of the four tTHM, $CHCl_3$ is the component most sensitive to high sampling volumes since its theoretical sampling volume is 19 L per gram of Tenax TA at an ambient air temperature of 20 ºC. In this work, the sorbent tubes contained approximately 0.20 g Tenax, providing a theoretical sampling volume of 3.8 L at 20 ºC. For every ten ºC increase in ambient air temperature, the theoretical sampling volume is halved (137). However, RH also affects the sampling volume.

Breakthrough occurs when 5% or more of the target analyte is observed in any of the back-up tubes (133). When determining the optimal sampling volume for tTHM, two tubes were coupled in series, and different flow rates (7 mL/min, 20 mL/min, 40 mL/min, 50 mL/min, and 100 mL/min) where tested over a sampling period of 20 minutes. The airflow rates 7 mL/min and 50 mL/min were tested at the same time and produced the same results for $CHCl_3$, but not $CHBr_3$. This result is assumed to be related to retention time, which is around 10 minutes for $CHBr_3$ and only 3 minutes for $CHCl_3$. With a flow rate of 100 mL/min, a significant breakthrough was observed in the backup tube. Considering the recommendations of the United States Environmental Protection Agency (US EPA) and the result of the tests for sampling volume, a pump flow rate of between 40 mL/min and 50 mL/min for 20 minutes was used for sampling the tTHM.

Sampling in the swimming facility

The low-flow pumps (Markes International) were calibrated in situ in the pool facilities with a TSI 4100 before and after each sample. When the tubes were not in use, they were always capped using Swagelok caps combined with PTFE ferrules. The tubes were also wrapped in uncoated aluminium foil and placed in an airtight container with charcoal to avoid contamination and losses. The samples were always handled using cotton gloves. For each group of ten air samples collected, one field blank and one laboratory blank were prepared and analysed together with these samples.

Laboratory analysis

Determination of tTHM in the air was performed by using a Unity Thermal Desorber (Markes International) coupled with an 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 to a cold trap packed with Tenax TA. Secondary desorption was carried out with a carrier gas flow rate of 20 ml/min from the trap. The tTHMs were submitted using a 3.7:0.7 split ratio. The separation was performed on a capillary column (DB-1; ID 0.25 mm and 0.25 µm film thicknesses). The oven temperature was elevated with a temperature program from 35 °C to 90 °C using 5 °C/min steps, and a post-run was conducted at 230 °C. Identification and quantification of the tTHM were performed in a selected ion monitoring (SIM) mode. The analysis of tTHM was performed immediately after sampling in the laboratory of the Department of Health, Safety, and Environment at the Institute of Industrial Economics and Technology Management at NTNU. During the work on this thesis, between 400 and 500 samples were collected in the poolrooms.

The samples of tTHM was always analysed on the same day that they were collected. At the beginning (papers I and 11), a limited number of Tenax tubes were available. Thus, to collect as many samples as possible during the same day and same week, the sampling tubes were quantified and conditioned in the same session. Doing so resulted in the loss of three samples due to tube leakage. When the work for paper III started, more Tenax TA tubes were made available. To avoid sample loss, all samples were analysed prior to the start of conditioning.

Method validation and quality assurance

Both external and internal calibrations were performed. For internal calibration, the sorbent tubes were spiked with 250 ng 8260 Internal Standard Mix 2 (Supelco) containing fluorobenzene, chlorobenzene-d5, and 1.4- dichlorobenzene-d4 in methanol. For external calibration, a five-point calibration curve was created, ranging from 0.5 ng to 500 ng, for each of the tTHM using the Trihalomethanes Calibration Mix (Supelco) in dilute with methanol (n = 30). This process was followed before each sampling campaign. Using this method, a limit of quantification (LOQ) of 0.5 µg/m^3 and a linear range from 0.5 µg/m^3 to 500 µg/m^3 was obtained for each of the tTHM. In accordance with US EPA Method TO-17, all duplicate measures and volume pairs of tubes were within 5% precision. Breakthrough was tested weekly to verify that less than 5% of the target analytes were observed on any of the back-up tubes.

3.4.2 Sampling, analysis and quality assurance for NCl_3

Sampling in the swimming facility

In total, 56 samples of NCl_3 were collected during the work done for this thesis (papers III and V), and all samples were analysed by the Department of Occupational and Environmental

Medicine at Umeå University, Sweden. The preparing, sampling, and analysing of the NCl_3 was done following the method established by Hery et al. (17). In brief, ambient samples are collected on filters, which were impregnated with sodium carbonate and diarsenic trioxide, then placed in 37mm closed-face filter cassettes. The principle behind the method is based upon the reduction of chloramines to chlorides. After sampling, the filter cassettes were stored at room temperature in a closed plastic bag and sent to Umeå University for analysis. The samples were never stored for more than one month after being collected. In the lab at Umeå University, the filters were desorbed in water, sonicated and filtered, and the collected material was analysed in an ion chromatogram. For each set of ten samples collected, two blank samples were used as field control samples.

In this study, samples were collected for three hours with a flow rate of 1 l/min (180 L) using pumps from SKC Ltd. The pumps were calibrated in situ in the pool facilities with a TSI 4100 both before and after each sample, as well as at least once every hour during sampling.

3.4.3 Dealing with random errors

All samples of tTHM were spiked, sampled, and analysed by the candidate herself, except for the samples collected for paper IV, which were collected by a master student, Morten Sæther Grande. The candidate also collected all samples of NCl_3; however, these samples were prepared and analysed by Dr. Annika Hagenbjörk in Sweden. Sampling by the same people reduces the random errors related to procedures and personal behaviour. Following US EPA TO-17, samples were to be invalidated if the pump sampling flow rate measured at the end of sampling varied more than 10% from the flow rate measured at the beginning of sampling (133). The samples included in this Ph.D. work never varied more than 10% in flow rate. For the NCl_3 samples, the flow rate was controlled at least once every hour, and, at the end of sampling, the volume collected on the filter was calculated based on the average flow rate measured during the three-hour sampling period. For the tTHM samples, which were collected over 20 minutes, the average of the flow rates measured at the beginning and end of collection was used to calculate the total air volume collected in the Tenax TA tubes.

The candidate remained close to the test stands during sampling, making field observations and observing the test stands. Posters were used to inform the people in the poolroom about the research and to make people aware of the test stands. The candidate's presence in the poolroom made it possible to count the number of bathers continuously and to observe the activities in the room.

4 MAIN RESULTS

This Ph.D. project had two main research objectives in which six research questions (RQs) were formulated. This chapter provides the main results in six different sections in accordance to the RQs.

4.1 RQ 1- THE PREVALENCE OF HEALTH EFFECTS AMONGST SWIMMERS

In paper V, the prevalence of health effects amongst active swimmers above the age of 18 licensed by the Norwegian Swimming Federation was estimated. Responses from the swimmers were collected using an online questionnaire (see Section 3.2). The methods used for analysis of the data are described in Section 3.3.

The overall results from the respondents in this study show that the reported prevalence of doctor-diagnosed asthma was 22.4%. Of those with doctor-diagnosed asthma, 84% had been swimming for more than 10 years. Considering the low response rate (28.2%), the estimated prevalence of doctor-diagnosed asthma may not be representative of prevalence in the population. Numbers provided by the Norwegian Swimming Federation 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 hours or more in the water every week. Our survey included 64 swimmers from this group. Hence, the response rate amongst the most exposed swimmers is assumed to be 100%.

In general, the prevalence of doctor-diagnosed asthma was greater amongst those who swim for more than 16 hours a week (35.4%, n=65) compared to those who swim less than 16 hours a week (19.2%, n=248). In Figure 8, the prevalence of health effects during or after training reported amongst swimmers diagnosed with asthma, swimmers who suspect they have asthma, and swimmers without asthma symptoms are shown. The reported prevalence of health effects was significantly higher amongst swimmers diagnosed with asthma or suspected of having asthma (67.5% and 65.4%, respectively) compared to swimmers without asthmatic symptoms (36.0%).

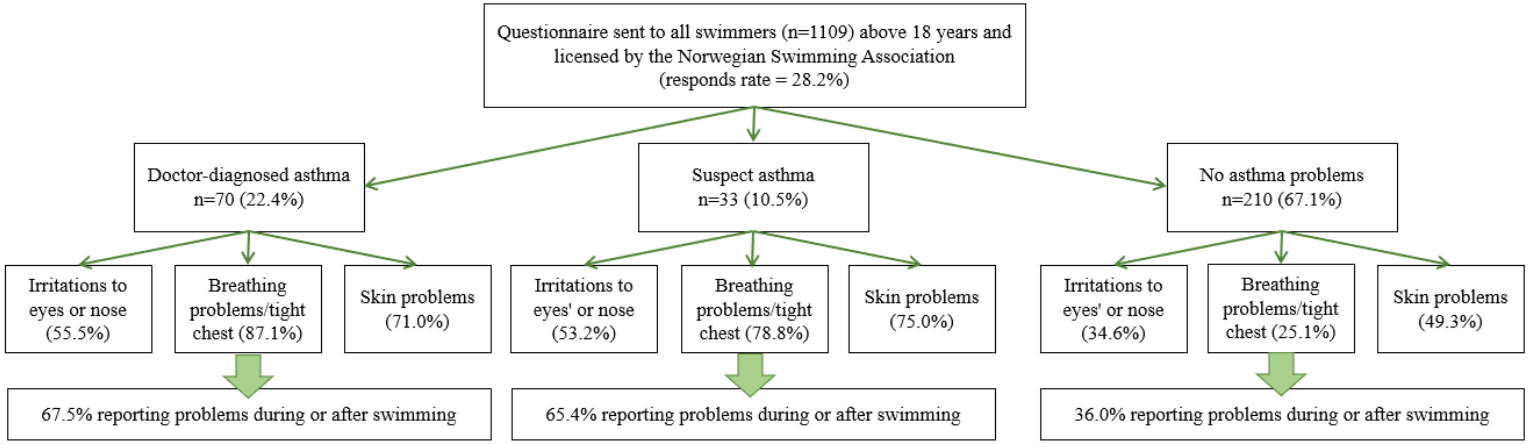

Figure 8:Reported prevalence of health problems during or after training amongst swimmers diagnosed with asthma, suspected of having asthma, and having no problems with asthma

In Table 1, the prevalence of reported symptoms during or after training is shown for different exposure groups. The increasingly dark shades of green indicate progressively increasing percentages of health problems. A significant difference ($p \leq 0.05$) was found between the swimmers spending less than 16 hours in the water per week and more than 16 hours in the water per week for all question categories in Table 1, excluding the question about red and itchy eyes (p=0.061). The difference between the two lowest exposure groups (less than 16 h) was statistically insignificant for all question categories listed in Table 1.

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

Survey Question	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 a red, itchy, or runny nose during or after training? (% yes)	29.1	37.4	46.9
Do you ever experience red or itchy eyes during or after training? (% yes)	42.3	40.1	62.5
Do you ever experience chest tightness during or after training? (% yes)	33.7	41.4	70.8
Do you ever experience skin irritations during or after training? (% yes)	46.2	54.6	78.5
Do your breathing problems increase as your activity level increases? (% yes)	34	32.9	61.5
Do your breathing problems affect your performance? (% yes)	27.9	26.4	52.5

Note: One swimmer did not report weekly exposure hours

Based on the responses from the swimmers, two facilities (referred to as Facilities 1 and 2a), were selected for further analysis, as the reported prevalence of asthma varied significantly between the two facilities (17.5% in Facility 1, and 36.4% in Facility 2a). In these facilities, an in-depth analysis of pool water management and air quality was also performed, and the results are shown in RQ 5 (Section 4.5). In Table 2, a comparison was made of the reported prevalence of health complaints at the two facilities.

The reported prevalence of chest or respiratory tightness during or after swimming differed significantly between the two facilities, and the age-adjusted OR for respiratory irritations and chest tightness was 8.7 (95% CI: 2.0 - 37.2, p=0.00) for Facility 2a compared to Facility 1. The age-adjusted OR for diagnosed and suspected asthma was 2.5 (95% CI: 0.7 - 8.5, p=0.145), which was not statistically significant.

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

Survey Question	Facility 1 (% yes)	Facility 2a (% 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

4.2 RQ 2- THE MOST IMPORTANT DETERMINANTS FOR ASSESSING tTHM IN THE AIR

This research question was investigated in paper I, which aimed to determine the size and magnitude of the variability in the concentrations of tTHM and analyse which determinants affected air exposure in three pool facilities. In each facility, air samples were collected above the surface of one sports pool (27-28°C) and one therapy pool (33-34°C), both 0.05 m and 0.60 m above the water's surface, repeatedly over different days of the week and different times during the day. These three pool facilities used different methods for hypochlorination: Facility 1 used calcium hypochlorite, Facility 2b used liquid sodium hypochlorite, and Facility 3 used electrolysis for the onsite production of sodium hypochlorite. The variables were analysed using the linear mixed effect model described in Section 3.3.

The results, which are summarized in Table 3, showed that all the water quality parameters were within the Norwegian regulations; however, the air concentrations of tTHM differed significantly between the three different pool facilities ($p < 0.05$). The mean air concentration of tTHM varied significantly within the same day and between different days. One example comes from Facility 2b, where the highest air concentrations were observed. Here, the mean day-to-day concentrations ranged from 341.7 µg/m^3 to 590.9 µg/m^3 and the air concentrations sampled during the same day ranged from 361.7 µg/m^3 to 781.7 µg/m^3.

Table 3: Means (AMs) for chemical parameters and bathers and the number of samples taken from each sampling location

Facility	Sampling location	tTHM (min-max) (µg/m^3)	Bathers	Cl_{Comb} (mg/l)	Cl_{Free} (mg/l)	T_{water} (° C)	pH	N
1	1	185.2 (99.7 – 316.4)	13	0.21	0.82	26.7	7.3	12
	2	132.6 (95.9 – 202.7)	8	0.21	1.22	33.1	7.5	17
2b	1	549.2 (366.5 – 781.7)	16	0.04	0.49	28.6	7.3	10
	2	362.6 (205.0 - 638.4)	31	0.19	1.02	34.1	7.2	20
3	1	234.1 (109.0 - 381.9)	8	0.24	1.01	28.1	7.3	24
	2	179.9 (87.2 - 306.3)	8	0.24	1.14	33.6	7.4	37

Despite the lower water temperatures in the sports pools, 32% higher concentrations, on average, were measured above the sports pools compared to the therapy pools. Between 34% (Facility 1) and 20% (Facility 3) higher concentrations were also measured 0.05 m above the water's surface compared to 0.60 m above the floor. The determinants (fixed effects) significantly affecting the air concentrations in the three pool facilities are shown in Table 4. These determinants explained 42% of the total variability in the tTHM air concentration and 98% of the between sampling location variability observed at each sampling location.

Table 4: Significant determinants of exposure

Fixed Effect	β	SE	e^{β}
Df	13		
Intercept	4.84*	0.17	126.47
Facility			
1	-0.18*	0.09	0.84
2b	0.91*	0.07	2.48
3	0	0	1
Height			
0.05 m	0.22*	0.05	1.25
0.60 m	0	0	1
Pool			
Therapy pool	-0.31*	0.06	0.73
Sports pool	0	0	1
Day			
Monday	0.24*	0.09	1.27
Wednesday	0.04	0.11	1.04
Friday	0	0	1
Time			
Morning	0.11*	0.05	1.12
Afternoon	0	0	1
Bathers			
0 - 6	0.25*	0.13	1.28
7 – 16	0.26*	0.13	1.30
17 – 34	0.35*	0.12	1.42
35 - 50	0	0	1

*Significant at $p< 0.1$

Using Table 4, the geometric mean (GM) (e^{β}) for the different exposure scenarios can be estimated using equation 3

$$\text{GM} = \text{Intercept} \times \text{Facility} \times \text{Height} \times \text{Pool} \times \text{Day} \times \text{Time} \times \text{Bathers} \qquad (3)$$

For example, if we assume 15 swimmers are present in the sports pool Friday evening, then the estimated air concentrations in Facilities 1 and 2b would be:

$$\text{Facility 1} = (126.47 \times 0.84 \times 1.25 \times 1.0 \times 1.0 \times 1.12 \times 1.30) = 193.3\ \mu\text{g/m}^3$$

$$\text{Facility 2b} = (126.47 \times 2.48 \times 1.25 \times 1.0 \times 1.0 \times 1.12 \times 1.30) = 570.8\ \mu\text{g/m}^3$$

This example demonstrates that the swimmers would be exposed to an air concentration in Facility 2b that is nearly three times higher than that in Facility 1.

4.3 RQ 3- ESTIMATING $CHCl_3$ CONCENTRATIONS BASED ON AIR AND WATER QUALITY

While the determinants contributing to the within and between variabilities of different facilities were investigated in paper I, the determinants in air and water causing the air concentration of $CHCl_3$ to vary within one swimming facility (RQ3) were investigated in paper II. The aim of this study was to see if the relationship between ventilation strategy and physical-chemical water quality could be used to estimate the exposure concentration of $CHCl_3$ in the air. Hence, information was collected on fresh air supply, air change rate, bather load, as well as other physical-chemical parameters in the air and water repeatedly three times a day and two days a week over a period of six weeks. Samples were collected from six different sampling locations in a leisure facility (Facility 3), which consisted of several swimming pools and aerosol-generating activities.

The results showed that all water quality parameters were in accordance with the Norwegian regulations. The ACH and $ACH_{freshair}$ for the different sampling days are listed in Table 5, along with information on the mean $CHCl_3$ concentrations measured in the morning and afternoon. As explained in Section 2.2, the ACH represents the number of 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. All variables, except the number of bathers and air and water temperatures, differed significantly according to the day sampling was conducted.

Table 5: ACH, $ACH_{freshair}$, and mean concentrations of $CHCl_3$ for both heights and sampling locations across sampling days

Day	**Time**	**ACH**	**$ACH_{freshair}$**	**n**	**Mean $CHCl_3$ (range) ($\mu g/m^3$)**
1 [A]	Morning	3.0	0.4*	8	274.9 (164.7–457.0)
	Afternoon	3.4	2.9	6	172.9 (87.2–358.9)
2 [B]	Morning	3.1	2.5	10	120.8 (80.7–159.8)
	Afternoon	3.6	3.6	6	150.9 (110.8–199.1)
3[A]	Morning	3.2	2.4	10	165.1 (124.0–285.8)
	Afternoon	3.7	3.7	6	196.7 (132.6–308.5)
4 [A]	Morning	2.9	2.2	10	216.3 (152.4 –362.6)
	Afternoon	3.4	3.4	6	218.0 (157.6–355.5)
5 [B]	Morning	3.1	2.5	10	169.9 (97.9–251.0)
	Afternoon	3.6	3.6	6	182.7 (110.8–267.0)
6 [A]	Morning	3.0	1.9	9	204.6 (147.7–308.4)
	Afternoon	3.0	2.1	6	241.0 (146.5–371.9)

[A] Monday, [B] Wednesday, *A fault with the fresh air dampers; n. d.= not detected or below the calculation limit

As shown in Table 2, the ACHs were all lower than the recommended 4-7. On the first day of sampling, 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) in the morning.

According to the linear mixed effect model, using $CHCl_3$ as an output variable showed that, of the collected air and water quality parameters, the variables significantly explaining the observed variability in $CHCl_3$ were RH, fresh air supply, and the water concentration of combined chlorine. For more details, see paper II.

4.4 RQ 4- UV LAMP AND THE AIR CONCENTRATIONS OF TTHM AND NCL3

In papers I and II, the determinants for assessing exposure to tTHM and the effects of determinants in the air and water on the air concentration of $CHCl_3$ were investigated. However, disinfection method is also an important determinant for the formation of DBPs, as some studies have showed that the concentrations of some DBPs in the water increase due to increased reactivity brought about by UV treatment (see Subsection 2.1.3). RQ4 was explored in paper III, where it was hypothesized that use of a UV treatment does not significantly affect the air concentrations of NCl_3 but rather will increase the overall exposure to tTHM. This hypothesis was investigated by collecting air concentrations of tTHM and NCl_3 simultaneously by the poolside (location 1) and in the inlet of the extract grill (location 2) in a poolroom consisting of only one therapy pool. This study was an experimental study in which samples were collected repeatedly with and without the use of a medium-pressure UV lamp in the water treatment system. More details are found in paper III.

The results show that slightly higher concentrations of tTHM (14%) and NCl_3 (10%) were observed by the poolside (location 1) compared to in the extract grill (location 2), and the air concentrations observed in the two sampling locations were statistically significant (p=0.02). By the poolside, air concentrations of tTHM were collected at both 0.05 m and 0.30 m above the water's surface, and, on average, a 2% difference in tTHM was observed between the two heights, a statistically insignificant result (p=0.66). When the UV treatment was used, the concentrations of tTHM $CHCl_3$, $CHClBr_2$, and $CHCl_2Br$ increased by 37%, 41%, 51% and 68%, respectively, compared to when the UV treatment was switched off. The concentrations of NCl_3 and $CHBr_3$, however, decreased by 15% and 12%, respectively.
Between 42% and 56% of the gases in the air are recirculated back into the poolroom along with the recycled air.

The correlation observed between NCl_3 and tTHM concentrations in the air when the UV treatment was on ($r^2 = 0.963$) (see Figure 9) was greater than when the UV treatment was off ($r^2 = 0.472$).

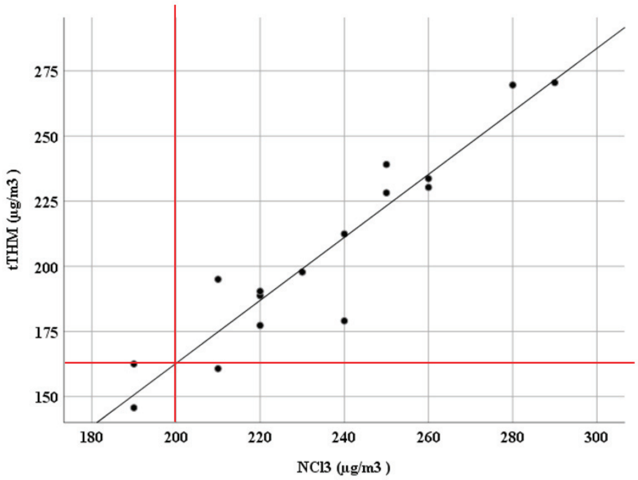

Figure 9: Correlation between NCl_3 and tTHM concentrations when the medium-pressure UV lamp was on

According to the linear mixed effect models built for NCl_3 and tTHM, most of the variability observed in the tTHM concentration was attributed to UV treatment, while most of the variability observed in the NCl_3 concentration was attributed to the number of bathers present in the pool.

4.5 RQ 5- COVARIATION AMONGST POOL WATER MANAGEMENT AND NCL3

In the two facilities selected for further investigation due to the reported prevalence of health effects (Section 4.1 (RQ1)), air samples of NCl_3 were collected, as well as information about strategies used for air and water treatment. In most previous studies, air samples of NCl_3 were investigated using cross-sectional study designs, and they largely neglected the determinants for the air concentrations of NCl_3.

In papers II and III, it was demonstrated that, for smaller pool rooms containing only one swimming pool with a ACH, the air in the room can be considered well mixed (paper III). However, in larger pool facilities, where multiple swimming pools are in the same room, the mean age of the air might not be the same for all sampling locations (paper III). 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 2a. As described in Subsection 2.1.3, the level of combined chlorine should never exceed 0.5mg/l. Furthermore, the combined chlorine should never be more than 50% of the measured concentration of free chlorine (6). The measured air concentrations in Facilities 1 and 2a are shown in Table 6. In Facility 1, the measured levels of free and combined chlorine never exceeded the Norwegian regulations. The concentration of NCl_3 ranged from 245µg/m^3 to 265µg/m^3, and the concentrations measured simultaneously from the two sampling locations varied by just 10µg/m^3, suggesting homogenous concentrations across this swimming pool, despite the low ACH.

Table 6: Technical data on ventilation and disinfection strategies, plus chemical-physical parameters for the two facilities

Facility	HRT (h)	m^3 water	ACH	%OA	Cl_{comb}	Cl_{Free}	pH	RH	T_{air} (ºC)	m^3/ swimmer	T_{water} (ºC)
1	4.6	2450	0.95	91%	0.17	0.64	7.12	71.3	27.1	28.3	28.0
2a	7.2	450	9.55	69%	0.52	0.78	7.02	45.1	28.4	7.7	26.5

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

In Facility 2a, the level of combined chlorine was always more than 50% of the measured concentration of free chlorine, and 50% of the measured values of combined chlorine exceeded the Norwegian limit of 0.5mg/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 58µg/m^3 to 327µg/m^3 in the morning and 92µg/m^3 to 461µg/m^3 in the evening. On Thursday during the week of measurement, low concentrations of NCl_3 were measured, with 58µg/m^3 in the morning and 92µg/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 were measured in the pool water. In general, the concentrations were always lower in the morning than in the evening, which is perhaps explained by increased swimmer load during the day.

In Facility 1a, almost no air was recirculated, and, on average, 91% of the air supply was fresh air from the outdoors. However, the ACH was low (0.95 h^{-1}). The average percentage of fresh air in Facility 2a was 69%, which was calculated based on the measured CO_2 concentrations. The ACH was also much higher (9.55 h^{-1}). In Facility 2a, the HRT was high and so was the swimmer load, showing that professional pool water management is crucial for achieving acceptable exposure levels.

4.6 RQ 6- Using CO_2 to predict tTHM and NCl_3 in the air?

In papers I, II and III, air exposure was investigated by measuring NCl_3 and tTHM concentrations. However, measuring these components is expensive and time-consuming and requires skilled personnel. In addition, no sensor exists which can monitor these components continuously. In papers IV and V, the air concentrations of CO_2 were measured to investigate if this substance could function as a predictor for tTHM (paper IV) and NCl_3 (paper V) concentrations in the air of swimming facilities.

The results in paper IV showed a statistically significant correlation between the measured level of CO_2 and number of occupants in the room ($\rho = 0.645$, $p = 0.01$) and between the tTHM and the CO_2 ($r = 0.38$, $p \leq 0.01$). Both the CO_2 and tTHM concentrations are significantly and positively correlated with RH, that is, when the RH increases, the air concentration rises. A significant negative correlation between tTHM concentration and ACH was also found. The random intercept model built for tTHM showed that 52% of the total variability observed could be explained by CO_2 concentration, occupancy load, and the water concentration of combined chlorine.

In paper V, the relationship between NCl_3 and CO_2 concentrations was investigated, and a significant correlation was also found between CO_2 in the extract channel and NCl_3 concentration ($r=0.80$, $p=0.01$). According to the random intercept model, 52% of the variability observed in the NCl_3 concentration could be explained by the CO_2 concentration measured in the extract grill.

In Figure 10, the relationship between the concentration of CO_2 measured in the extract channel, return air channel, supply air channel, and the number of occupants is shown. Note that the highest levels of CO_2 were observed during high occupancy. The concentration of CO_2 measured in the extract channel significantly correlated with occupancy level ($\rho = 0.82$, $p=0.01$). Hence, CO_2 can be used as a marker for NCl_3 exposure.

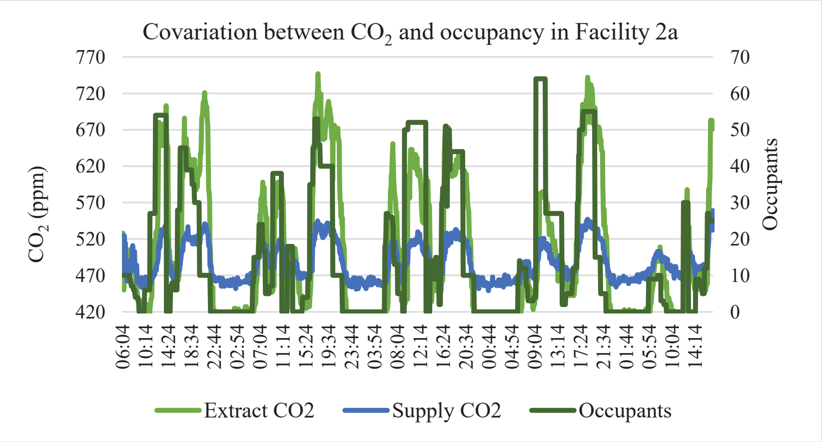

Figure 10: Number of occupants and measured concentrations of CO_2 in the extract and supply air channels of Facility 2a

5 DISCUSSION

In the following chapter, the results presented for each research question are discussed in two different sections according to the research objectives (RO): exposure assessment (Section 5.1) and exposure management (Section 5.2).

5.1 RO1- EXPOSURE ASSESSMENT

The prevalence of health effects amongst swimmers

Amongst all swimmers who responded to the questionnaire, the overall reported prevalence of doctor-diagnosed asthma was 22.4%. However, this estimate might be biased considering that only 313 out of 1109 swimmers responded to the survey. It is expected 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 spending >16 h in the water per week is assumed to be approximately 100%, these estimates are also considered to be representative. A similar 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 (97). In a Finish study including 200 competitive swimmers, a lower prevalence of doctor-diagnosed asthma (16%) was reported (98).

The difference in reported prevalence of doctor-diagnosed asthma might be caused by several factors, such as the concentrations of the air inhaled during training (80, 138) and selection bias. However, more severe cases of bronchial hyperreactivity and asthma have been found amongst swimmers compared to cross-country skiers (139) and healthy individuals (97). Considering that an increased prevalence of health effects has also been found among lifeguards, it is likely that the prevalence of health effects is caused not only by heavy exercise but also air exposure. In this study, a significant association was found between asthma diagnosis and pool facility. It also found 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. This finding highlights why it is important to establish a framework for assessing air exposure to make managing air concentrations less complex and reduce exposure to DBPs.

Towards a framework for exposure assessment

As described in Section 2.4, the unwanted health effects of exposure in the poolroom are primarily asthma and respiratory irritations. Such problems are caused by long-term exposure to unacceptably high air concentrations of irritants. Identifying determinants for assessing exposure should help future occupational hygienists and epidemiologist design effective sampling strategies as well as implement measures for effective hazard control. Thus, this aim was included in this Ph.D. work, that is, concentrations of tTHM and/or NCl_3 were measured repeatedly to identify the most important determinants for assessing exposure and understand the magnitude of the variability observed within and between pool facilities containing one or several swimming pools.

In a previous study carried out before the work of this thesis started, no difference was found between samples of tTHM collected 0.60 m and 1.5 m above the water's surface (140). Based on this result, to collect air concentrations representative of the breathing zones of the swimmers as well as people walking by the poolside, samples were collected simultaneously from 0.05 m and 0.60 m above the water's surface (papers I and II). Values of potentially important variables, such as the water concentrations of free and combined chlorine, water temperature, pH value, and number of bathers, were also collected.

In paper I, the within variabilities for heights, days, and sampling locations were always greater than the between variabilities, reflecting that time of day is of great importance when collecting representative air concentrations. As shown in Section 4.1 (RQ 1), the air concentrations measured over the course of the same day and the mean day-to-day concentrations vary significantly, highlighting that one single sample or one-day sampling may not be representative of the exposure of the users in the pool. Using a cross-sectional study design to collect information about the air quality and exposure, as done in several previous studies (24, 60, 141), is not considered suitable for collecting representative air samples in pool facilities. Rather, repeated measures over time are important in terms of understanding the exposure variability.

The results of the mixed effect model built in paper I show that swimming facility, height above the water's surface, swimming pool, day of the week, time of day, and number of bathers contribute to the mean exposure level. The mean overall air concentrations of tTHM differed significantly between the three swimming facilities, ranging from 154 μg/m^3 (Facility 1) to 425 μg/m^3 (Facility 2b). This finding suggest that, if swimmers are categorized in the same exposure category or when individual exposure is estimated based on air concentrations collected from a non-representative exposure scenario, the estimated risk related to exposure might be biased towards zero associations.

In paper III, samples of tTHM were collected simultaneously at 0.30 m and 0.05 m above the water's surface; however, only a 2 percentage point difference separated the two concentrations collected from the two different heights. This finding suggests that to collect air samples representative of the breathing zone of the swimmers, samples should be collected somewhere between 0.05 m and 0.30 m above the water. The results of paper III also show that when UV treatment is included in the water treatment, samples of tTHM may function as indicators for NCl_3 concentrations. For rooms containing only one swimming pool and in which the ACH is high (above 4), samples may be collected from one sampling location by the swimming pool to represent the air concentrations in the room. For larger pool facilities, however, with different ventilation systems and/or multiple swimming pools in the same room, samples should be collected from at least one location above each pool or from each long side of a pool if the ACH is low (below 4) (papers I and II).

Framework for assessing air concentrations

To assess the exposure amongst lifeguards, personal samples are considered more representative, as it is not possible to fully characterize personal exposure patterns using stationary test stands. In a previous study, it was suggested that stationary air samples collected in a swimming facility should be divided by two in order to represent personal samples (91). The sampling strategy used in this thesis is considered most relevant for assessing the exposure amongst the swimmers in the swimming pool or for source identification. All the studied swimming facilities used the same ventilation strategy. In facilities where this strategy is not applied, other sampling strategies should be tested.

To obtain representative air concentrations, samples should be collected by the poolside and below 30 cm above the water's surface in order to represent the breathing zone of the swimmers and when the swimmers are present in the pool. To estimate the long-term exposure and reduce the risk of misclassification amongst swimmers in epidemiological investigations, samples should be collected repeatedly, as the air concentration may vary significantly within and between days (paper I). If the ACH is low (below 4), the results presented in this thesis suggest that samples that should be collected from each long side of a pool. If the ACH is above 4, then one sampling location above each pool of interest might be considered representative (papers II and III).

During sampling of tTHM/NCl_3, information about RH, type of chlorine, type of water, combined chlorine, free chlorine, bather load, ACH, and fresh air supply should also be collected. In addition, information from the chlorine log should be studied to check for irregularities.

5.2 RO2- EXPOSURE MANAGEMENT

Techniques for managing indoor air pollution sources include source elimination, substitution, modification, or altering the amount, location, or time of exposure (142). Source elimination is not considered to be an option due to high residence time in the pools. Furthermore, some form of active disinfectant is necessary to provide hygienic conditions. Substituting bromine for chlorine has been tested in some studies. However, some studies suggest that brominated compounds are more toxic to human health, and chlorine is currently considered to be the most cost-effective option available on the market. Based on the results presented in chapter 4, modifying and limiting the amount, location, or time of exposure for exposure management is possible. In the following chapter, methods for exposure management in existing pool facilities will be discussed in relation to the results presented in chapter 4.

Air and water quality

Except for one of the swimming facilities investigated in paper V, the water quality in the investigated swimming facilities was always within the requirements for Norwegian pool water quality. However, the air exposure to tTHM and NCl_3 still varied extensively, and only 11% (6) of the collected samples of NCl_3 had concentrations below the 200 $\mu g/m^3$ proposed by the Nordic Expert Group.

As described in Section 2.2, no specific requirements for air quality in Norwegian swimming facilities exist. This lack of requirements is also considered to be the main reason why the average ACHs in in the investigated swimming facilities varied from 2.9 to 10. In a previous study, where the candidate with co-authors collected energy statistics from 45 facilities across Norway the reported ACHs ranged from 2.7 in leisure pools to 4.9 in conventional pool facilities (143), which might explain why higher air concentrations are measured in leisure pools compared to conventional swimming facilities. The recommendations concerning ventilation in Norwegian swimming facilities focus on how to reduce water evaporation and energy consumption rather than how to ensure proper air quality in the breathing zone of the pool users. The air and water quality in Norway are treated as two independent variables. However, the volatile components found in the air are formed in the water, and the correlation between the air concentration of NCl_3 and its water concentration is highly dependent on the ventilation (101). This finding was reinforced by paper II, in which fresh air supply, RH and combined chlorine were identified as important predictor variable for the variability observed in tTHM concentration.

Use of recirculating air has been found to be the most effective energy-saving measure (144); however, in paper III, where samples of tTHM were collected simultaneously in the air extract and air supply duct, it was found that between 40 and 60% of the tTHMs extracted from the pool room were recirculated back into the pool room, which corresponded to the percentage of recirculated air used in this pool room. In papers II and IV, the results also showed that fresh air supply significantly effects the exposure concentration of tTHM. To prevent the accumulation of volatile compounds in the air, it was concluded that a more dynamic strategy for air and water flow and treatment is needed, one which can reduce the variability in volatile compounds.

As explained in Section 2.1, different requirements for chlorine levels and fresh water supply exist and depend on the pool water temperature. For example, in a swimming pool containing water at 28 ºC, the minimum concentration of free chlorine is 0.4 mg/l and the recommended fresh water supply per bather is 30 l/day. In a therapy pool with a water temperature of 34 ºC, the required minimum concentration of free chlorine is 1.0 mg/l, and the recommended fresh water supply per bather is 60 l/day. Considering that different swimming pools have different requirements and bather loads, the emissions from the waters' surfaces will also be different, despite optimal ventilation effectiveness. After adjusting for the water concentration of combined chlorine, bather load, and RH, the between sampling location variability decreased (paper II), meaning that some of the heterogeneity observed within the poolroom can be attributed to use, the fresh air supply, and water management.

As found in papers I and II, the difference in pool water regulations (see Section 2.1) may be the main reason why the concentrations of tTHM were consequently lower above the therapy pools (34 ºC) compared to the sports pools (28 ºC), despite the increased formation potential for tTHM in higher water temperatures (46). The most active swimmers in Norway spend more than 16 hours in the water every week (paper V) and have high pulmonary ventilation. As presented in paper V, the estimated prevalence of doctor-diagnosed asthma amongst the most exposed swimmers in Norway is 36%. Amongst active swimmers, predictor variables, such as years of swimming, weekly exposure, and type of swimming facility, significantly affect the prevalence of asthma (papers I and V). While the air concentrations might not significantly affect the health of the general population spending a limited amount of time in swimming pools, the air concentrations above the sports pools affect the prevalence of health effects amongst swimmers. Based on this result, it is suggested that, in swimming facilities hosting active swimmers, stricter requirements for pool water management as well as air and water quality should be implemented. If possible, the most exposed swimmers should occupy the pools in the hours during which the exposure and bather load is at its lowest (paper V and paper I).

In papers II and IV, a significant positive relation between air concentrations of tTHM and combined chlorine was obtained, meaning that when the concentration of combined chlorine increases, the concentration of tTHM in the air also increases. In paper V, low concentrations of NCl_3 were also measured in the air of Facility 2a when the chlorine machine stopped working and the concentration of free chlorine was unacceptably low. As long as the microbiological water quality is maintained, these finding suggest that the concentration of free and combined chlorine should be kept as low as possible.

Currently, air supply is controlled using setpoints for RH and air temperature. However, findings from papers III and IV suggests that when the RH increases or when the fresh air supply decreases, the tTHM concentration will also increase. When adjusting the air supply to balance the RH and air temperature, air concentrations are adjusted as well. In general, the ventilation logs from the investigated swimming facilities shows that the ACH, including both fresh air and recirculated air, varies between 10% and 20% during opening hours, which does not correspond to the significant variations observed in bather load. As found in papers I and II, a more dynamic ventilation strategy is needed, and the fresh air ratio should be balance with respect to bather load and water quality, not just RH and air temperature.

Controlling air supply using CO_2 sensors

As summarized in Section 2.4, the exposure concentration of tTHM should not exceed between 140 $\mu g/m^3$ and 200 $\mu g/m^3$, and the air concentrations of NCl_3 should not exceed 200 $\mu g/m^3$ for stationary measurements in accordance with the limit value proposed by the Nordic Expert Group. These limits require not only an optimal ventilation strategy but also proper water quality. However, even if such limit values were to be implemented in Norway in the near future, monitoring NCl_3 and tTHM is expensive and requires skilled personnel. In addition, no senor technology for the continuous monitoring of these components exists. Since the air concentrations may vary significantly over time, there is no guarantee that the low air concentrations measured one day are representative of long-term exposure.

In paper V, CO_2 sensors were placed in the air supply and fresh and return air channels, and the correlation between CO_2 and NCl_3 concentrations was strong and significant ($r=0.80$). According to the random intercept model, the CO_2 concentration measured in the extract channel alone explained 52% of the observed variability in NCl_3 concentration. CO_2 concentration measured in the extract channel also correlated significantly with occupancy ($p= 0.82$). The precursors from the swimmers are the main sources of ammonium found in chlorinated swimming pool water which leads to the formation of the volatile NCl_3. However, the formation of tTHM depends also on the precursors in the filling water, contaminates in the chlorine, and precursors from bathers. Therefore, it is assumed that CO_2 will be a better predictor for NCl_3 compared to tTHM. A significant correlation was also found between CO_2 and tTHM ($r=0.38$, $p \leq 0.01$) (paper IV); however, the relationship is far from linear. The results from the linear mixed effect model show that the air supply should be balanced using CO_2 in combination with bather load and the water concentration of combined chlorine, suggesting that to create a more dynamic air supply and reduce the variability observed in tTHM and NCl_3, concentrations, CO_2 sensors can be used in the ventilation system. This placement could also reduce the overall energy used for ventilation, as the air supply would decrease during non-occupancy periods. Such a solution, however, might only be suitable for rooms with well-mixed air, which may not be the case for larger pool facilities. It also requires a relatively high ACH so that the sensors can detect representative concentrations of CO_2 in the breathing zone. For buildings with a low ACH ($0.2 – 0.5\ h^{-1}$), there might be a delay between the response from the ventilation system and the supply of fresh air, which, in some cases, might result in fresh air being supplied to the room after the occupants have left.

UV treatment

In Subsection 2.1.3, it was described that the results of laboratory studies have shown that NCl_3 is very photosensitive and can be effectively degraded in the water using a medium-pressure UV lamp (27). However, on-site measurements in real swimming pools have shown that UV treatment does not affect the concentration of NCl_3 considerably in water, especially not when the HRT of the water is several hours (33, 145), and, in paper III, it was hypothesized that UV treatment also has limited effect on NCl_3 concentrations in the air and increases the overall exposure concentration in the poolroom.

When the UV lamp was on, the concentration of combined chlorine in the water decreased 58%, the concentration of tTHM in the air increased 37%, and the concentration of NCl_3 in the air decreased 15%, thus the overall air exposure increased when the UV lamp was turned on. Using a linear mixed model, 30% of the variability in the tTHM concentration was attributed to UV treatment. For NCl_3, the number of bathers, explaining 30% of the variability, was the most important predictor variable. UV treatment has a limited effect on airborne NCl_3 but increases the air concentration of tTHM. To reduce the level of combined chlorine in the water, other methods, such as lowering the concentration of free chlorine or reducing the HRT is considered more effective than UV treatment, as long as the microbiological and hygienic water quality is maintained (146).

6 CONCLUSION

One main conclusion of this thesis is that the air concentrations vary extensively across times of day and days of the week. To collect representative samples, it is necessary to monitor different exposure scenarios; otherwise, exposure estimates may be no more valid than a random guess. In cases where repeated samples are collected, methods accounting for the dependency between the repeated observations should be used, as a correlation between the repeated samples collected of tTHM and NCl_3 was found. Even when the water quality is within the required limit values, the air concentrations of NCl_3 and tTHM may still vary extensively, with the overall concentration of NCl_3 higher than that proposed by the Nordic Expert Group (0.2 mg/m^3). The results also show that when the water concentration of combined chlorine increases, the air concentration of tTHM also increases. Furthermore, when the concentration of free chlorine decreases, the concentration of NCl_3 decreases. It is therefore recommended that the concentrations of free and combined chlorine be kept in the lower range of the acceptable limit values. The results suggest that the use of UV treatments should be carefully evaluated, as using such a treatment may increase the overall air exposure. It is recommended that other methods be used to reduce the concentration of combined chlorine. As the air quality is highly dependent on the water quality, the air and water quality should be treated as one system in which the air supply is controlled on the basis of bather load and water concentrations of combined chlorine. Both tTHM and NCl_3 should be monitored regularly in the air, and limit values for these components should be implemented. Considering that the concentration of CO_2 significantly correlates with occupancy and NCl_3 concentration, CO_2 sensors can be used to create a more dynamic air supply corresponding to the need of the users in the poolroom while reducing the variability observed in the air concentrations of NCl_3 and tTHM. The prevalence of health problems is greatest amongst the most exposed swimmers in the poolroom. Facilities hosting swimmers spending more than 16 hours in the water every week should have stricter requirements for pool water management and air quality.

Through this thesis work, six research questions have been answered and new knowledge was created.

7 FUTURE WORK

For future studies, the effects of lowering the water concentration of free and combined chlorine, without compromising microbiological water quality, on air quality should be elaborated. More studies on the dose-response to exposure amongst professional swimmers are needed so that limit values suitable for the protection of this class of swimmers in the poolroom can be implemented. The implementation of CO_2 sensors, and possibly the monitoring of the water concentration of combined chlorine, to control the air supply should be studied with respect to air exposure, user comfort, and energy use. Currently, no adsorbents are used in the return air channels of ventilation systems; however, filters able to adsorb the volatile gases observed in the hot-humid air of indoor swimming facilities might improve air quality as well as well as lower energy use.

For the optimal monitoring of air quality, sensors for the continuous air monitoring of NCl_3 and tTHM concentrations should be developed. As pool water management significantly effects the air concentrations in the poolroom, a proper training program for lifeguards is necessary.

BIBLIOGRAPHY

1. Det kongelige kulturdepartementet. Statusrapportering for svømmebasseng - 2012 2013.
2. Keuten MGA, Schets FM, Schijven JF, Verberk JQJC, van Dijk JC. Definition and quantification of initial anthropogenic pollutant release in swimming pools. *Water Research.* 2012;46(11):3682-92.
3. Richardson SD, DeMarini DM, Kogevinas M, Fernandez P, Marco E, Lourencetti C, et al. What's in the Pool? A Comprehensive Identification of Disinfection By-products and Assessment of Mutagenicity of Chlorinated and Brominated Swimming Pool Water. *Environmental Health Perspectives.* 2010;118(11):1523-30.
4. Wastensson G, Eriksson K. The Nordic Expert Group for Criteria Documentation of Health Risks from Chemicals. p 152. Inorganic chloramines. 2019. https://gupea.ub.gu.se/bitstream/2077/61724/4/gupea_2077_61724_4.pdf
5. World Health Organization. Guidelines for safe recreational water environments volume 2 swimming pools and similar environments. 2006 http://www.who.int/water_sanitation_health/bathing/srwe2full.pdf.
7. International Agency for Research on Cancer. Monographs on the Identification of Carcinogenic Hazards to Humans- List of Classifications. 2020. https://monographs.iarc.fr/list-of-classifications
8. Gouveia P, Felgueiras F, Mourao Z, Fernandes EO, Moreira A, Gabriel MF. Predicting health risk from exposure to trihalomethanes in an Olympic-size indoor swimming pool among elite swimmers and coaches. *Journal of Toxicology and Environmental Health.* 2019;82(9):577-90.
9. Marco E, Lourencetti C, Grimalt JO, Gari M, Fernández P, Font-Ribera L, et al. Influence of physical activity in the intake of trihalomethanes in indoor swimming pools. *Environmental Research.* 2015;140:292-9.
10. Erdinger L, Kühn KP, Kirsch F, Feldhues R, Fröbel T, Nohynek B, et al. Pathways of trihalomethane uptake in swimming pools. *International Journal of Hygiene and Environmental Health*. 2004;207(6):571-5.
11. Chowdhury S. Predicting human exposure and risk from chlorinated indoor swimming pool: a case study. *Environmental Monitoring and Assessment.* 2015;187(8):502.
12. Cao W-C, Zeng Q, Luo Y, Chen H-X, Miao D-Y, Li L, et al. Blood Biomarkers of Late Pregnancy Exposure to Trihalomethanes in Drinking Water and Fetal Growth Measures and Gestational Age in a Chinese Cohort. *Environmental health perspectives*. 2016;124(4):536-41.
13. Hwang B-F, Jaakkola JJK. Risk of stillbirth in the relation to water disinfection by-products: a population-based case-control study in Taiwan. *PloS one*. 2012;7(3):e33949-e.
14. Rivera-Núñez Z, Wright JM, Meyer A. Exposure to disinfectant by-products and the risk of stillbirth in Massachusetts. *Occupational and environmental medicine*. 2018;75(10):742-51.
15. Villanueva CM, Cantor KC, Cordier S, Jaakkola JJK, King WD, Lynch CF, Porru S, Kogevinas M. Disinfection byproducts and bladder cancer: a pooled analysis. *Epidemiology*. 2004:357-67.
16. The European Chemicals Agency. Guidance on the Biocidal Products Regulation. Volume V, Guidance on Disinfection By-Products. 2017. https://echa.europa.eu/documents/10162/15623299/bpr_guidance_vol_v_dbp_en.pdf/a57a2905-923a-5aa3-ead8-45f5c5503daf
17. Hery M, Hecht G, Gerber JM, Gendre JC, Hubert G, Rebuffaud J. Exposure to chloramines in the atmosphere of indoor swimming pools. *The Annals of Occupational Hygiene*. 1995;39(4):427-39.
18. Parrat J, Donzê G, Iseli C, Perret D, Tomicic, Schenk O. Assessment of Occupational and Public Exposure to Trichloramine in Swiss Indoor Swimming Pools: A Proposal for an Occupational Exposure Limit. *The Annals of Occupational Hygiene*. 2011:264-77.

19. Jacobs JH, Spaan S, van Rooy GBGJ, Meliefste C, Zaat VAC, Rooyackers JM, Heederik D. Exposure to trichloramine and respiratory symptoms in indoor swimming pool workers. *European Respiratory Journa*l. 2007;29(4):690.
20. Fornander L, Ghafouri B, Lindahl M, Graff P. Airway irritation among indoor swimming pool personnel: trichloramine exposure, exhaled NO and protein profiling of nasal lavage fluids. *International Archives of Occupational and Environmental Health*. 2013;86(5):571-80.
21. Fantuzzi G, Righi E, Predieri P, Giacobazzi P, Petra B, Aggazzotti G. Airborne trichloramine (NCl3) levels and self-reported health symptoms in indoor swimming pool workers: Dose-response relationships. *Journal of Exposure Science and Environmental Epidemiology*. 2012:1-6.
22. Westerlund J, Bryngelsson I-L, Löfstedt H, Eriksson K, Westberg H, Graff P. Occupational exposure to trichloramine and trihalomethanes: adverse health effects among personnel in habilitation and rehabilitation swimming pools. J*ournal of Occupational and Environmental Hygiene*. 2019;16(1):78-88.
23. Chu T-S, Cheng S-F, Wang G-S, Tsai S-W. Occupational exposures of airborne trichloramine at indoor swimming pools in Taipei. *Science of The Total Environment*. 2013;461-462:317-22.
24. Löfstedt H, Westerlund J, Graff P, Bryngelsson IL, Mölleby G, Olin AC, Eriksson K, Westberg H. Respiratory and Ocular Symptoms Among Employees at Swedish Indoor Swimming Pools. *Journal of Occupational and Environmental Medicine.* 2016;58(12):1190-5.
25. Rappaport SM. Assessment of long-term exposures to toxic substansces in the air *Annals of Occupational Hygien*e,. 1991;35(1):61-122.
26. Norwegian Institute for Water Research. Water quality and water treatment in swimming and leisure facilities; 2000 https://brage.bibsys.no/xmlui//bitstream/handle/11250/211098/-1/4318_72dpi.pdf.
27. Soltermann F. Trichloramine in swimming pool water: analysis methods, factors influencing its fate and effects of UV treatment. PhD thesis. 2015.
28. White GC. Handbook of chlorination and alternative disinfectants. Fourth Edition. John Wiley and sons, 1999.
29. De Laat J, Feng W, Freyfer DA, Dossier-Berne F. Concentration levels of urea in swimming pool water and reactivity of chlorine with urea. *Water Research*. 2011;45(3):1139-46.
30. Pickup J. Environmental safety of halogenated by-products from use of active chlorine. 2010. https://www.eurochlor.org/wp-content/uploads/2019/04/sd15-environmentalsafety-final.pdf
31. Holzwarth G, Balmer RG, Soni L. The fate of chlorine and chloramines in cooling towers Henry's law constants for flashoff. *Water Research.* 1984;18(11):1421-7.
32. Mr Peter Watts MGL, Ms M.E. Meek. Concise International Chemical Assessment Document 58 Chloroform. 2004.
33. Soltermann F, Widler T, Canonica S, von Gunten U. Photolysis of inorganic chloramines and efficiency of trichloramine abatement by UV treatment of swimming pool water. *Water Research*. 2014;56:280-91.
34. Cimetiere N, De Laat J. Effects of UV-dechloramination of swimming pool water on the formation of disinfection by-products: A lab-scale study. *Microchemical Journal*. 2014;112:34-41.
35. Cassan D, Mercier B, Castex F, A Rambaud. Effects of medium-pressure UV lamps radiation on water quality in a chlorinated indoor swimming pool. *Chemosphere.* 2006;62(9):1507-13.
36. Spiliotopoulou A, Hansen KMS, Andersen HR. Disinfection by-product formation of UV treated swimming pool water. *Proceedings of the 6th International Conference Swimming Pool & Spa* 2015.
37. Cheema WA, Andersen HR, Kaarsholm KMS. Improved DBP elimination from swimming pool water by continuous combined UV and ozone treatment. *Water Research*. 2018;147:214-22.
38. Etheridge E, Sandberg M. Building ventilation — theory and measurement: Wiley; 1996.

39. Heiselberg P, Bjørn E, Nielsen PV. Impact of Open Windows on Room Air Flow and Thermal Comfort. International Journal of Ventilation. 2002;1(2):91-100.
40. Kampel W, Aas B, Bruland A. Energy-use in Norwegian swimming halls. *Energy and Buildings*. 2013;59(0):181-6.
41. SINTEF Byggforsk. Ventilasjon og avfukting i svømmehaller og rom med svømmebasseng. 2003.
42. Nilsson PE. Achieving the desired indoor climate: The Commtech Group; 2003.
43. Seppänen OA, Fisk WJ, Mendell MJ. Association of ventilation rates and CO2 concentrations with health and other human responses in commercial and institutional buildings. *Indoor Air*. 1999;9(4):226-52.
44. Dougan DS, Damiano L. CO2-based demand control ventilation: Do risks outweight potential rewards? *ASHRAE Journal*. 2004;46(10):47-50, 2-4.
45. Norbäck D, Björnsson E, Janson C, Widström J, Boman G. Asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings. *Occupational and environmental medicine*. 1995;52(6):388-95.
46. Padhi RK, Sowmya M, Mohanty AK, Bramha SN, Satpathy KK. Formation and Speciation Characteristics of Brominated Trihalomethanes in Seawater Chlorination. *Water Environmental Research*. 2012;84:2003-9.
47. Ministry of Culture. Sport Facilities- Planning and Building. 2016. https://www.regjeringen.no/contentassets/dee978d794694506bba23a57d8a76ea8/v-0989b_idrettshaller_planleging_og_bygging_2016.pdf
48. Gabriel MF, Felgueiras F, Mourao Z, Fernandes EO. Assessment of the air quality in 20 public indoor swimming pools located in the Northern Region of Portugal. *Environment International.* 2019;133(Pt B):105274.
49. Li X-F, Mitch WA. Drinking Water Disinfection Byproducts (DBPs) and Human Health Effects: Multidisciplinary Challenges and Opportunities. *Environmental Science & Technology*. 2018;52(4):1681-9.
50. Rook J. Formation of haloforms during chlorination of naturals waters. J Water Treat Exam. 1974;23(2):234– 43.
51. Cotruvo JA, Amato H. National Trends of Bladder Cancer and Trihalomethanes in Drinking Water: A Review and Multicountry Ecological Study. *Dose-Response.* 2019;17(1):1559325818807781.
52. Freeman KS. Disinfection By-products and Bladder Cancer: Common Genetic Variants May Confer Increased Risk. *Environmental Health Perspectives.* 2010;118(11):A491-A.
53. Costet N, Villanueva CM, Jaakkola JJ, Kogevinas M, Cantor KP, King WD, et al. Water disinfection by-products and bladder cancer: is there a European specificity? A pooled and meta-analysis of European case-control studies. *Occupational and Environmental Medicine*. 2011;68(5):379-85.
54. World Health Organization. Guidelines for Drinking-water Quality. World Health Organization; 2017.
55. Kim H, Shim J, Lee S. Formation of disinfection by-products in chlorinated swimming pool water. *Chemosphere*. 2002;46(1):123-30.
56. Kanan A, Karanfil T. Formation of disinfection by-products in indoor swimming pool water: The contribution from filling water natural organic matter and swimmer body fluids. *Water Research*. 2011;45(2):926-32.
57. Lahl U, Bätjer K, Düszeln JV, Gabel B, Stachel B, Thiemann W. Distribution and balance of volatile halogenated hydrocarbons in the water and air of covered swimming pools using chlorine for water disinfection. *Water Research*. 1981;15(7):803-14.
58. Heller-Grossman L, Manka J, Limoni-Relis B, Rebhun M. Formation and distribution of haloacetic acids, THM and tox in chlorination of bromide-rich lake water. *Water Research*. 1993;27(8):1323-31.
59. Hansen KMS, Willach S, Antoniou MG, Mosbæk H, Albrechtsen H-J, Andersen HR. Effect of pH on the formation of disinfection byproducts in swimming pool water – Is less THM better? Water Research. 2012;46(19):6399-409.

60. Tardif R, Catto C, Haddad S, Simard S, Rodriguez M. Assessment of air and water contamination by disinfection by-products at 41 indoor swimming pools. *Environmental Research.* 2016;148:411-20.
61. Zwiener C, Richardson SD, De Marini DM, Grummt T, Glauner T, Frimmel FH. Drowning in Disinfection Byproducts? Assessing Swimming Pool Water. *Environmental Science & Technology.* 2007;41(2):363-72.
62. Xu X, Mariano TM, Laskin JD, Weisel CP. Percutaneous Absorption of Trihalomethanes, Haloacetic Acids, and Haloketones. *Toxicology and Applied Pharmacology*. 2002;184(1):19-26.
63. Aprea CM, Bruno B, Lunghini L, Pagliantini M, Peruzzi A, Sciarra G. Disinfection of swimming pools with chlorine and derivatives: formation of organochlorinated and organobrominated compounds and exposure of pool personnel and swimmers. *Natural Science*. 2010;2:68-78.
64. Aggazzotti G, Fantuzzi G, Righi E, Predieri G. Environmental and biological monitoring of chloroform in indoor swimming pools. *Journal of Chromatography A*. 1995;710(1):181-90.
65. Lévesque B, Ayotte P, LeBlanc A, Dewailly E, Prud'Homme D, Lavoie R, et al. Evaluation of dermal and respiratory chloroform exposure in humans. *Environmental Health Perspectives*. 1994;102(12):1082-7.
66. Nicholson B, Maguire BP, Bursill DB. Henry's law constants for the trihalomethanes: effects of water composition and temperature. *Environmental Science & Technology*. 1984;18(7):518-21.
67. Catto C, Sabrina S, Ginette C-T, Manuel R, Robert T. Occurrence and Spatial and Temporal Variations of Disinfection By-Products in the Water and Air of Two Indoor Swimming Pools. *International Journal of Environmental Research and Public Health*. 2012;9:2562-86.
68. Panyakapo M, Soontornchai S, Paopuree P. Cancer risk assessment from exposure to trihalomethanes in tap water and swimming pool water. *Journal of Environmental Sciences.* 2008;20(3):372-8.
69. Shi Y, Ma W, Han F, Geng Y, Yu X, Wang H, et al. Precise exposure assessment revealed the cancer risk and disease burden caused by trihalomethanes and haloacetic acids in Shanghai indoor swimming pool water. *Journal of Hazardous Materials.* 2019:121810.
70. Socialstyrelsen. Bassängbad Hälsorisker, regler och skötsel. 2006. https://www.folkhalsomyndigheten.se/contentassets/366079f0326e403d9082d597a3c06c09/bassangbad-halsorisker.pdf
71. Miljøministeriet Naturstyrelsen. Vejledning om kontrol med svømmebade, 2013. https://naturstyrelsen.dk/media/nst/66835/vejledning_kontro_svoemmebade_9-4-2013.pdf
72. Arbeidstilsynet Forskrift om Tiltaks- og grenseverdier, 704. 2016. https://www.arbeidstilsynet.no/globalassets/regelverkspdfer/forskrift-om-tiltaks--og-grenseverdier
73. Fantuzzi G, Righi E, Predieri G, Giacobazzi P, Mastroianni K, Aggazzotti G. Prevalence of Ocular, Respiratory and Cutaneous Symptoms in Indoor Swimming Pool Workers and Exposure to Disinfection By-Products (DBPs). *International Journal of Environmental Research and Public Health*. 2010;7(4):1379–91.
74. Verein Deutsher Ingenieure. Building Services in swimming baths Indoor pools VDI2089. 2010.
75. Thickett KM, McCoach JS, Gerber JM, Sadhra S, Burge PS. Occupational asthma caused by chloramines in indoor swimming-pool air. *European Respiratory Journal*. 2002;19(5):827.
76. Massin N, Bohadana AB, Wild P, Hery M, Toamain JP, Hubert G. Respiratory symptoms and bronchial responsiveness in lifeguards exposed to nitrogen trichloride in indoor swimming pools. *Journal of Occupational and Environmental Medicine.*1998:258-63.
77. Gagnaire F, Azim S, Bonnet P, Hecht G, Hery M. Comparison of the sensory irritation response in mice to chlorine and nitrogen trichloride. *Journal of Applied Toxicology*. 1994;14(6):405-9.
78. Chen WY, Horton DJ. Heat and Water Loss from the Airways and Exercise-Induced Asthma. *Respiration*. 1977;34(6):305-13.

79. Inbar O, Dotan R, Dlin RA, Neuman I, Bar-Or O. Breathing dry or humid air and exercise-induced asthma during swimming. *European Journal of Applied Physiology and Occupational Physiology*. 1980;44(1):43-50.

80. Kippelen P, Fitch KD, Anderson SD, Bougault V, Boulet L-P, Rundell KW, et al. Respiratory health of elite athletes – preventing airway injury: a critical review. *British Journal of Sports Medicine*. 2012;46(7):471.

81. The Norwegian Swimming Federation. Aktivitetstall IR 2016. https://svomming.no/wp-content/uploads/2016/05/Akt-tall06052016kl0800-red.pdf.

82. Andersson M, Backman H, Nordberg G, Hagenbjörk A, Hedman L, Eriksson E, et al. Early life swimming pool exposure and asthma onset in children – a case-control study. *Environmental Health*. 2018;17(1):34.

83. Bernard A, Carbonnelle S, Michel O, Higuet S, de Burbure C, Buchet JP, et al. Lung hyperpermeability and asthma prevalence in schoolchildren: unexpected associations with the attendance at indoor chlorinated swimming pools. *Occupational and Environmental Medicine.* 2003;60(6):385.

84. Andersson M, Hedman L, Nordberg G, Forsberg B, Eriksson K, Rönmark E. Swimming pool attendance is related to asthma among atopic school children: a population-based study. *Environmenal Health*. 2015.

85. Nickmilder M, Bernard A. Ecological association between childhood asthma and availability of indoor chlorinated swimming pools in Europe. *Occupational and Environmental Medicine.* 2007;64(1):37.

86. Valeriani F, Protano C, Vitali M, Romano Spica V. Swimming attendance during childhood and development of asthma: Meta-analysis. *Pediatrics International*. 2017;59(5):614-21.

87. Font-Ribera L, Villanueva CM, Nieuwenhuijsen MJ, Zock JP, Kogevinas M, Henderson J. Swimming pool attendance, asthma, allergies, and lung function in the Avon Longitudinal Study of Parents and Children cohort. *American Journal of Respiratory and Critical Care Medicine*. 2011;183(5):582-8.

88. Font-Ribera L, Kogevinas M, Zock JP, Nieuwenhuijsen MJ, Heederik D, Villanueva CM. Swimming pool attendance and risk of asthma and allergic symptoms in children. *European Respiratory Journal*. 2009;34(6):1304.

89. Beggs S, Foong YC, Le HCT, Noor D, Wood-Baker R, Walters JAE. Swimming training for asthma in children and adolescents aged 18 years and under. Evidence-Based Child Health: *A Cochrane Review Journal.* 2013;8(5):1514-81.

90. Rosenman KD, Millerick-May M, Reilly MJ, Flattery J, Weinberg J, Harrison R, et al. Swimming facilities and work-related asthma. *Journal of Asthma*. 2015;52(1):52-8.

91. Westerlund J, Graff P, Bryngelsson IL, Westberg H, Eriksson K, Löfstedt L. Occupational exposure to trichloramine and trihalomethanes- adverse respiratory and ocular effects among Swedish indoor swimming pool workers. *Annals of Occupational Hygiene.* 2016;59(8):1074-84.

92. Helenius IJ, Tikkanen HO, Sarna S, Haahtela T. Asthma and increased bronchial responsiveness in elite athletes: Atopy and sport event as risk factors. *Journal of Allergy and Clinical Immunology*. 1998;101(5):646-52.

93. Aggazzotti G, Fantuzzi G, Righi E, Predieri G. Blood and breath analyses as biological indicators of exposure to trihalomethanes in indoor swimming pools. *Science of The Total Environment*. 1998;217(1–2):155-63.

94. Bougault V, Turmel J, Levesque B, Boulet L-P. The Respiratory Health of Swimmers. *Sports Medicine*. 2009;39(4):295-312.

95. Bougault V, Turmel J, Boulet L-P. Bronchial Challenges and Respiratory Symptoms in Elite Swimmers and Winter Sport Athletes: Airway Hyperresponsiveness in Asthma: Its Measurement and Clinical Significance. *Chest.* 2010;138(2, Supplement):31S-7S.

96. Bougault V, Turmel J, St-Laurent J, Bertrand M, Boulet LP. Asthma, airway inflammation and epithelial damage in swimmers and cold-air athletes. E*uropean Respiratory Journal.* 2009;33(4):740.

97. Romberg K, Tufvesson E, Bjermer L. Asthma is more prevalent in elite swimming adolescents despite better mental and physical health. *Medicine & Science in Sports.* 2012;22(3):362-71.
98. Päivinen MK, Keskinen KL, Tikkanen HO. Swimming and asthma: factors underlying respiratory symptoms in competitive swimmers. *The Clinical Respiratory Journal.* 2009:97-103.
99. Stadelmann K, Stensrud T, Carlsen K-H. Respiratory Symptoms and Bronchial Responsiveness in Competitive Swimmers. *Medicine & science in sports & exercise.* 2010:43(3):375-81.
100. Stang J, Stensrud T, Mowinckel P, Carlsen K-H. Parasympathetic Activity and Bronchial Hyperresponsiveness in Athletes. *Medicine & Science in Sports & Exercise* 2016;48(11):2100-7.
101. Lévesque B, Duchesne J-F, Gingras S, Lavoie R, Prud'Homme D, Bernard E, et al. The determinants of prevalence of health complaints among young competitive swimmers. International *Archives of Occupational and Environmental Health*. 2006;80(1):32-9.
102. Rappaport SM. Assessment of long-term exposures to toxic substances in air. *Annals of Occupational Hygiene*,. 1991;35(1):61-122.
103. Rosenman KD, Millerick-May M, Reilly MJ FJ, Weinberg J, Harrison R, Lumia M, et al. Swimming facilities and work-related asthma. *J Asthma.* 2015;52(1):52-8.
104. Rappaport SM, Lawrence LK. Quantitative Exposure Assessment. 2008.
105. Lioy PJ. Assessing total human exposure to contaminants. A multidisciplinary approach. *Environmental Science & Technology.* 1990;24(7):938-45.
106. Zhang JJ, Lioy PJ. Human Exposure Assessment in Air Pollution Systems *TheScientificWorldJOURNAL.* 2002;2:497-513.
107. Kauppinen TP. Assessment of exposure in occupational epidemiology. *Scand J Work Environ Health*. 1994;20(special issue):19-29.
108. Burstyn I, Teschke K. Studying the Determinants of Exposure: A Review of Methods. American industrial hygiene association journal. 1999;60:57-72.
109. Burdorf A. Identification of determinants of exposure: consequences for measurement and control strategies. *Occupational and Environmental Medicine*. 2005;62(5):344.
110. Sedgwick P. Cross sectional studies: advantages and disadvantages. *British Medical Journal.* 2014;348:g2276.
111. Rappaport SM, Kupper LL. Variability of environmental exposures to volatile organic compounds. *Journal of Exposure Analysis and Environmental Epidemiology* 2004;14:92-107.
112. Symanski E, Chan W, Chang C-C. Mixed-effects models for the evaluation of long-term trends in exposure levels with an example from the nickel industry. *The Annals of Occupational Hygiene*. 2001;45(1):71-81.
113. Luoma M, Batterman SA. Autocorrelation and Variability of Indoor Air Quality Measurements. *AIHAJ - American Industrial Hygiene Association*. 2000;61(5):658-68.
114. Checkoway H, Pearce N, Kriebel D. Research Methods in Occupational Epidemiology: Oxford University Press; 2004.
115. Peretz C, Goren A, Smid T, Kromhout H. Application of Mixed-effects Models for Exposure Assessment. *The Annals of Occupational Hygiene.* 2002;46(1):69-77.
116. Boleij JSM, Buringh E, Heederik D, Kromhout H. Occupational Hygiene of Chemical and Biological Agents. Elsevier Science. 1995.
117. Rappaport SM, Kromhout H, Symanski E. Variation of Exposure Between Workers in Homogeneous Exposure Groups. *American Industrial Hygiene Association Journal.* 1993;54(11):654-62.
118. Statistisk Sentralbyrånd. Bruk av IKT i husholdningene 2019. https://www.ssb.no/ikthus.
119. Robson C. Real world research. third ed: John Wiley and Sons; 2011.
120. Rönmark EP, Ekerljung L, Lötvall J, Torén K, Rönmark E, Lundbäck B. Large scale questionnaire survey on respiratory health in Sweden: Effects of late- and non-response. *Respiratory Medicine.* 2009;103(12):1807-15.
121. Schouten B, Cobben F, Bethlehem J. Indicators for the representativeness of survey response *Survey Methodology*. 2009;35(1):101-13.

122. Tyrer S, Heyman B. Sampling in epidemiological research: issues, hazards and pitfalls *BJPsych Bulletin* 2016;40:57-60.
123. Szumilas M. Explaining Odds Ratios. *J Can Acad Child Adolesc Psychiatry*. 2010;19(3):227-9.
124. Sainani K. The importance of accounting for correlated observations. *PM R*. 2010;2(9):858-61.
125. Rabe-Hesketh S, Skrondal A. Multilevel and Longitudinal Modeling Using Stata- Volume 1: Continous Responses. Third ed: Stata Press; 2012.
126. Brady T. West KBW, Andrzei T. Gatecki. Linear mixed models: a practical guide using statistical software: CRC Press; 2006.
127. Baayen RH, Davidson DJ, Bates DM. Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*. 2008;59:390-412.
128. Park T, Park JK, Davis CS. Effects of covariance model assumptions on hypothesis testsfor repeated measurements: analysis of ovarian hormone dataand pituitary-pteryomaxillary distance data. *Statistics in Medicine*. 1994;20:2441-53.
129. Field A. Discovering statistics using SPSS. third edition ed: Sage; 2009.
130. Eyduran E, Akbas Y. Comparison of different covariance structure used for experimental design with repeated measurement. *The Journal of Animal & Plant Sciences*. 2010;20(1):44-51.
131. Field A. Discovering Statistics Using IBM SPSS Statistics. 5 ed: Sage; 2017.
132. Ras MR, Borrull F, Marcé RM. Sampling and preconcentration techniques for determination of volatile organic compounds in air samples. *Trends in Analytical Chemistry*. 2009;28(3):347-61.
133. United Stated Environmental Protection Agency. Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, (1999).
134. Lourencetti C, Grimalt JO, Marco E, Fernandez P, Font-Ribera L, Villanueva CM, et al. Trihalomethanes in chlorine and bromine disinfected swimming pools: Air-water distributions and human exposure. *Environment International.* 2012;45:59-67.
135. Bessonneau V, Derbez M, Clément M, Olivier T. Determinants of chlorination by-products in indoor swimming pools. *International Journal of Hygiene and Environmental Health.* 2011;215(1):76-85.
136. Cossec C, Laurent AM, Person A, Rouvié-Laurie I, Beaubestre C. Trichloramine and trihalomethanes concentrations in air or water of Paris indoor swimming pools and impact of different water treatment methods. *Pollution Atmospherique* 2016;228.
137. Scientific Instrument Services (SIS). Tenax® TA Breakthrough Volume Data 1996. https://www.sisweb.com/index/referenc/tenaxta.htm.
138. Langdeau J-B, Turcotte H, Thibault G, Boulet L-P. Comparative Prevalence of Asthma in Different Groups of Athletes: A Survey. *Canadian Respiratory Journal*. 2004;11(6):402-6.
139. Stang JS. Why do athletes develop asthma? Pathogenic mechanisms and asthma phenotypes2017.
140. Nitter TB, Kampel W, Svendsen, KvH., Aas B. Comparison of trihalomethanes in the air of two indoor swimming pool facilities using different type of chlorination and different types of water. *Water Science and Technology: Water Supply.* 2018;18(4):1350-1356.
141. Chen M-J, Lin C-H, Duh J-M, Chou W-S, Hsu H-T. Development of a multi-pathway probabilistic health risk assessment model for swimmers exposed to chloroform in indoor swimming pools. *Journal of Hazardous Materials.* 2011;185(2–3):1037-44.
142. Tichenor BA, Sparks LE. Managing Exposure to Indoor Air Pollutants in Residential and Office Environments. *Indoor Air*. 1996;6(4):259-70.
143. Nitter TB, Carlucci S, Olsen SN, Svendsen KvH. Energy use and perceived health in indoor swimming pool facilities. *IOP Conference Series: Materials Science and Engineering.* 2019;609:042051.
144. Nord N, Mathisen HM, Cao G. Energy cost models for air supported sports hall in cold climates considering energy efficiency. *Renewable Energy*. 2015;84:56-64.

145. Gerardin F, Hecht G, Hubert-Pelle G, Subra I. Traitement UV:suivi de l'évolution des concentrations en chloroforme et en trichlorure d'azote dans les eaux de baignade d'un centre aquatique. 2005. Contract No.: ND 2237.
146. Nitter TB, Svendsen KvH. UV treatment and air quality in a pool facility. Water Science and Technology. 2019;80(3): 499-506.

APPENDIX A: QUESTIONNAIRE

1. Age (in years)

2. Body weight (in kg)

3. Height (in cm)

4. Sex

☐ Male ☐ Female

5. Name of the facility where you usually swim.

6. For how many years have you been swimming?

☐ 1 - 5

☐ 6 - 10

☐ More than 10 years

7. Have you previously been/are you active in other sports besides swimming?

☐ No

☐ Yes

8. What type(s) of sport(s) have you been/are you active in?

9. How many days a week are you in the pool?

☐ 1 - 2

☐ 3 - 5

☐ 6 - 7

10. How long is one training session in the pool usually?

☐ Less than two hours

☐ 2 - 3 hours

☐ More than 3 hours

11. Have you been diagnosed with asthma by a licensed doctor?

☐ No ☐ Yes

12. Do you suspect that you are suffering from asthma even though you have not been diagnosed with this disease?

☐ No ☐ Yes

13. Have you been examined by a doctor because of breathing problems?

☐ No

☐ Yes, but without breathing tests

☐ Yes, with breathing tests

14. Have you previously been examined by a paediatrician, lung doctor, or any other hospital doctor because of breathing problems?

☐ No ☐ Yes

15. Have you had seizures with heavy breathing or wheezing in the past 12 months?

☐ No ☐ Yes

16. Do you cough during periods of the year?

☐ No

☐ Yes, but without expectoration

☐ Yes, with expectoration

☐ Yes, and I have had a cough which produced sputum consecutively for *three months* or more over the last two years

17. Have you of have you ever had a nose allergy?

☐ No

☐ Yes, but not for the last 12 months

☐ Yes, and I have struggled with this for the last 12 months

18. Have you struggled with any of the following continuously for at least 3 months during the last year?

	During training/competition	**After training/competition**	**Other times during the day**
Nasal congestion			
Mucus from the nose or back of the throat			
Pain or pressure in the face			
Reduced sense of smell			

19.

	No	**Yes**
Do you ever experience red, itchy, or runny eyes during or after training?		
Do you ever experience, during or after training, an itchy or runny nose?		
Have you ever experienced chest or respiratory density during or after swimming?		
Do your breathing problems increase with your activity level?		
Is the breathing problem affecting your sports performance?		

20. Do you smoke?

☐ No

☐ Yes, but less than 5 per day

☐ Yes, between 5 -20 per day

☐ Yes, more than 20 per day

21.Are you ever exposed to tobacco smoke during the day?

☐ No

☐ Yes, but less than 2 hours each day

☐ Yes, more than 2 hours per day

22. Do you snus?

☐ No ☐ Yes, sometimes ☐ Yes, every day

APPENDIX B: APPENDED PAPERS

Paper I:
T. B Nitter and K. v H. Svendsen. «Determinants of Exposure and Variability of Trihalomethanes in the Air of Three Indoor Swimming Pools.» *Annals of Work Exposures and Health.* 2019; 63(5):560-567. Doi: https://doi.org/10.1093/annweh/wxz024

Paper II:
T. B Nitter and K. v H. Svendsen. «Modelling the concentration of chloroform in the air of a Norwegian swimming pool facility- A repeated measures study.» *Science of the Total Environment.* 2019; 664:1039-1044.Doi: https://doi.org/10.1016/j.scitotenv.2019.02.113

Paper III:
T. B Nitter and K. v H. Svendsen. «UV treatment and air quality in a pool facility.» *Water Science and Technology*. 2019; 80(3):499-506. Doi: https://doi.org/10.2166/wst.2019.291

Paper IV:
T. B Nitter, M. S Grande, K. v H. Svendsen, S. Carlucci, R. Jørgensen, and G. Cao. «Can CO_2 sensors in the ventilation of a pool facility reduce the variability in the trihalomethane concentration in indoor air?» *Environment International*. 2020. Doi: https://doi.org/10.1016/j.envint.2020.105665

Paper V :
T. B Nitter and K. v H. Svendsen. « Covariation amongst pool management, air exposure and asthma for competitive swimmers in Norway.» *Science of the Total Environment.* 2020; 723. Doi: https://doi.org/10.1016/j.scitotenv.2020.138070

Paper I

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Original Article

Original Article

Determinants of Exposure and Variability of Trihalomethanes in the Air of Three Indoor Swimming Pools

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Abstract

Introduction: Negative health effects related to long-term exposure to volatile trihalomethanes (THMs) formed during the chlorination of pool water is recognized, but the determinants causing the concentrations to vary within and between sampling locations have not received much attention.
Methods: One hundred and twenty air samples of four THMs were examined in three Norwegian indoor pool facilities. In each facility, repeated samples were collected above a sports pool and a therapy pool, 0.05 and 0.60 m above the water's surface. A linear mixed model (LMM) was used to identify determinants of exposure and the variability in THM concentration within and between sampling locations, days, and heights in pool facilities.
Results: The within variability of days, sampling locations, and heights was greater than between days, sampling locations, and heights. Determinants contributing significantly to the exposure were pool facility, height, swimming pool, day of the week, time during the day, and number of bathers. These findings limits how exposure categories should be defined to be able to identify the real long-term exposure and to propose suitable exposure limit values.
Discussion: These determinants could help future research be designed with effective sampling strategies and to collect information about the real long-term exposure, which is important in terms of establishing a dose–response relationship and exposure limit values.
Conclusions: If unbiased exposure assessments are to be conducted among the different users of the pool facility, air samples should be collected over time and for different exposure scenarios.

Keywords: determinants of exposure, epidemiology, exposure assessment methodology, exposure assessment—mixed models, exposure variability, indoor environment, mixed effects models

Introduction

To prevent the growth of hazardous microorganisms in swimming pool waters, it is common to disinfect the pool water using chlorine. However, when chlorine reacts with organic and inorganic materials in the pool water, unwanted disinfection by-products (DBPs) are formed (World Health Organization, 2006). Increased prevalence of asthma and other respiratory irritations have been found among users who visit swimming pools on a regular basis (Bernard *et al.*, 2003; Bernard and Nickmilder, 2006). These health effects are most often linked to chronic exposure to chloramines in the air (Hery *et al.*, 1995; Jacobs *et al.*, 2007; Chu *et al.*, 2013). Another important group of DBPs is the trihalomethanes (THM), represented by the four components chloroform ($CHCl_3$), bromoform ($CHBr_3$), bromodichloromethane ($CHBrCl_2$), and dibromochloromethane ($CHBr_2Cl$). The sum of the four is referred to as total THM (tTHM). The tTHM is volatile and can penetrate the skin easily, making both inhalation and dermal absorption important pathways of exposure (Erdinger *et al.*, 2004; Chowdhury, 2015). Long-term health effects, such as adverse reproductive outcomes, cancer, and stillbirth, have been associated with exposure (World Health Organization, 2017; Rivera-Núñez *et al.*, 2018). In some studies, in which multi-pathway exposures have been estimated, the cancer risk of exposure to THMs in indoor swimming pool facilities is found to be unacceptably high compared with the upper limit of the acceptable cancer risk proposed by the European Commission (10^{-5}) (European Commission, 2009; Lee *et al.*, 2009; Chen *et al.*, 2011).

Some European countries have established exposure limit values for tTHM in swimming pool water, ranging from 20 to 100 $\mu g\ l^{-1}$ (ANSES, 2010; Ohlsson *et al.*, 2014; Rijksinstituut voor Volksgezondheid en Milieu, 2014). In Norway, no such limit for pool water exists. Although inhalation is recognized as the most important exposure pathway (Erdinger *et al.*, 2004; Aprea *et al.*, 2010), only one suggested limit value, proposed by the German Federal Environmental Agency (in VDI 2089) for $CHCl_3$ in indoor pool facilities exists (200 $\mu g\ m^{-3}$) (Verein Deutsher Ingenieure, 2010). It is important to understand the cause and magnitude of the variabilities in the contaminants to comprehend the dose–response relationship. This is essential before designing a sampling strategy or evaluating compliance with limit values and control measures (Burdorf, 2005). In pool facilities, the users are exposed to a mixture of components in the air and water (Catto *et al.*, 2012; Chowdhury, 2015; Tardif *et al.*, 2016), and the exposure concentrations of tTHM are relatively low. Studying the effect of chronic exposure to low-exposure concentrations is complicated (Goldberg and Hemon, 1993), especially since researchers often have limited time and resources available to conduct sufficient sampling for exposure characterization.

Identifying the determinants of exposure is essential in the control of exposure but also for a valid and precise assignment of exposure levels (Rappaport and Kupper, 2008). Although the occurrence and exposure to tTHMs in swimming pools have been investigated in several previous studies (Lee *et al.*, 2009; Westerlund *et al.*, 2016; Boudenne *et al.*, 2017), the determinants causing the concentration to vary within and between sampling locations have not received attention and no systematic sampling strategy to collect representative air samples has so far been proposed. The aim of this study is to determine the size and magnitude of the variability and to analyse which determinants affect the exposure within three pool facilities in order to be able to optimize a sampling strategy for tTHM.

Methods

The pool facilities

Three swimming pool facilities, each with several pools, located in the middle part of Norway were included in this study. The physical parameters and types of water and disinfectants used in these pools are given in Table 1. In Facilities 1 and 3, the swimming pools are located in the same room and ventilated using one ventilation system. In Pool Facility 2, the therapy pool and sports pool are located in two separate rooms, and these rooms have two different systems for both water circulation and ventilation.

Sampling and analytical method

In all, 120 stationary air samples were collected. In each pool facility, samples were collected above one therapy pool (Location 1) and one sports pool (Location 2), both 0.05 and 0.60 m simultaneously above the water's surface, during the morning and afternoon. Each day, two sampling sessions were conducted in the morning and one sampling session in the evening. Auxiliary data, such as bather load, water temperature, pH value, and free and combined chlorine were also recorded on each day of sampling. In one of the pool facilities (Facility 3), 61 air samples were collected on 6 days over a period of 6 weeks. In Facilities 1 and 2, 29 and 30 samples were collected, respectively, on ten different days over a period of 4 weeks.

Table 1. Physical parameters, disinfectants, and number of bathers for the three pool facilities

Facility	Pool	Size (m)	T_{water} (°C)[a]	Disinfectants	Bathers/year
1	Sports pool	25.0 × 12.5	27	$Ca(OCl)_2$	120 000
	Therapy pool	12.5 × 6.5	33	$Ca(OCl)_2$ + UV	
2	Sports pool	50.0 × 21.0	28	NaOCl+ UV	360 000
	Therapy pool	16.7 × 9.5	34	NaOCl+ UV	
3	Sports pool	25.0 × 12.5	28	Electrolysis[b] + UV	100 000
	Therapy pool	12.5 × 9.0	34	Electrolysis[b] + UV	

[a] T_{water}= water temperature.

[b] Soduim hypochlorite (NaOCl) produced on-site using electrolysis.

The sampling, quality assurance, and analytical methods are based on Method TO-17, published by the Unites States Environmental Protection Agency (US EPA) (United States Environmental Protection Agency, 1999). Samples were collected using the method of active air sampling, in which two low-flow pumps (Markes Int.) were calibrated to deliver between 40 and 50 ml min^{-1} for 20 min to collect ambient air into an automatic thermal desorption tube containing 200 mg Tenax TA (Markes Int.) simultaneously at both 0.05 and 0.60 m above the water surface. Analyses were performed using a Unity Thermal Desorber (Markes Int.) coupled with an Agilent Technologies 5975T Low Thermal Mass Gas Chromatography/Mass Selective Detector. The analysis setup is explained elsewhere (Nitter *et al.*, 2017).

Statistical analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences (IBM SPSS) 25. To verify that the three facilities and the sampling locations were statistically different from each other, the Bonferroni post hoc test and *t*-test were used. The linear mixed-effect model (LMM) was used to examine the relationship between the concentrations of tTHM and to identify the determinants of importance for the variability in measured concentrations. The concentration of tTHM was skewed and log-transformed before the statistical analysis and the Shapiro–Wilk test and Kolmogorov–Smirnov test showed no significant deviation form normality.

The LMM was fitted as follows:

$$B_{ij} = \beta_{0i} \times r_{0i} + \beta_{1i} \times F + \beta_{2i} \times h + \beta_{3i} \times P + \beta_{4i} \times \text{Day} + \beta_{5i} \times t + \beta_{6i} \times \text{Bathers} + e_{ij} \tag{1}$$

where B_{ij} is natural log transformed value of the tTHM concentration i for observation j; F is the facility; h is the height above water surface in metres; P is the type of swimming pool; Day is the day of the week; t is the time during the day; Bathers are the number of bathers in the pool; β_{0i} is the fixed intercept; r_{0i} is the random intercept, and e_{ij} is the random error.

All parameters were estimated using the method of restricted maximum likelihood (REML) (Symanski *et al.*, 2001; West *et al.*, 2006).

Analysing the variability and determinants of exposure

The dataset consisted of categorical variables, such as pool facility, swimming pool, and height above the water's surface, time during the day, day of the week, and the number of bathers, and continuous variables, such as free and combined chlorine, air temperature, relative humidity, pH value, and the log-transformed tTHM. First, the within and between subject variability was estimated using REML and without including additional factors and covariates. For this analysis, each pool facility was analysed separately. Each sampling location represents one swimming pool and both heights (0.05 and 0.60 m above water surface) and sampling location, day of the week and height above the water's surface were treated as the subject. The subject was included as random combination variable using the default variance components as a covariance structure. Models with different combinations of fixed effects were constructed by forward selection and the subsequent likelihood ratio test using maximum likelihood estimation. The final model was estimated by REML. Sampling location was the subject of the analysis and was included as random variable using the default variance components as a covariance structure.

Results

The characteristics for the three different pool facilities with sampling location, tTHM, bathers, free and combined chlorine, water temperature, pH value, and number of samples are given in Table 2. All water quality parameters were in accordance with Norwegian regulations (Norwegian Ministry of Health, 1996).

Table 2. Mean (AM) descriptive statistics for chemical parameters, bathers, and number of samples from each sampling location

Facility	Sampling location	tTHM (min–max) (μg m^{-3})	Bathers	Cl_{Comb} (mg l^{-1})	Cl_{Free} (mg l^{-1})	T_{water} (°C)	pH	*N*
1	1[a]	185.2 (99.7–316.4)	13	0.21	0.82	26.7	7.3	12
	2[b]	132.6 (95.9–202.7)	8	0.21	1.22	33.1	7.5	17
2	1	549.2 (366.5–781.7)	16	0.04	0.49	28.6	7.3	10
	2	362.6 (205.0–638.4)	31	0.19	1.02	34.1	7.2	20
3	1	234.1 (109.0–381.9)	8	0.24	1.01	28.1	7.3	24
	2	179.9 (87.2–306.3)	8	0.24	1.14	33.6	7.4	37

AM, arithmetic mean; Cl_{comb}, combined chlorine; Cl_{free}, free chlorine; T_{water}, water temperature; *N*, number of repetitions.

[a] Sports pool.

[b] Therapy pool.

Table 3. Within and between variability of the logtransformed tTHM at different sampling locations, days, and heights for each pool facility

	N	μ (SD)	σ_b^2 (SD)	σ_w^2 (SD)
Pool Facility 1				
Sampling locations	29	4.99 (0.32)	0.04 (0.06)	0.09 (0.02)
Day			0.04 (0.04)	0.08 (0.02)
Height			0.03 (0.04)	0.09 (0.02)
Pool Facility 2				
Sampling locations	30	6.06 (0.22)	0.09 (0.14)	0.09 (0.03)
Day			0.03 (0.03)	0.11 (0.03)
Height			0.01 (0.02)	0.13 (0.03)
Pool Facility 3				
Sampling locations	61	5.25 (0.34)	0.03 (0.04)	0.11 (0.02)
Day			0.03 (0.02)	0.09 (0.02)
Height			0.03 (0.05)	0.10 (0.02)

N, number of samples; μ, the log transformed concentration of tTHM; SD, standard deviation; σ_b^2, between variability (sampling location, day, height); σ_w^2, within variability (sampling location, day, height).

As given in Table 2, the highest level of tTHM was observed above the sports pools in each pool facility, and the highest concentrations were observed in Pool Facility 2. The tTHM levels for all pool facilities and sampling locations were statistically significantly different from each other ($P < 0.05$).

Variability within each facility

In Table 3, the estimates of the within and between variability for sampling locations, days, and heights for each of the three pool facilities are given.

As given in Table 3, the within sampling location variability was greater than or equal to the between sampling location variability. The variability between days was less than that within days, and the variability within heights was greater than that between heights, reflecting the importance of the time of the day for sampling.

Determinants of exposure

The determinants shown to affect significantly the exposure contamination level of the different sampling locations are given in Table 4. The fixed factors height, pool, day, time, and bathers explain 42% of the total variability for each sampling location, of which these fixed factors reduced the within sampling location variability by 36% and the between sampling location variability by 98%.

The geometric mean (GM) (e^{β}) for different exposure scenarios can be estimated using the values obtained in Table 4. To determine the worst case (Monday morning) and best case (Friday afternoon) for exposure among a

Table 4. Significant determinants of exposure

Fixed effect	β	SE	e^{β}
df	13		
Intercept	4.84*	0.17	126.47
Facility			
1	−0.18*	0.09	0.84
2	0.91*	0.07	2.48
3	0	0	1
Height			
0.05 m	0.22*	0.05	1.25
0.60 m	0	0	1
Pool			
Therapy pool	−0.31*	0.06	0.73
Sports pool	0	0	1
Day			
Monday	0.24*	0.09	1.27
Wednesday	0.04	0.11	1.04
Friday	0	0	1
Time			
Morning	0.11*	0.05	1.12
Afternoon	0	0	1
Bathers			
0–6	0.25*	0.13	1.28
7–16	0.26*	0.13	1.30
17–34	0.35*	0.12	1.42
35–50	0	0	1
Random effects for sampling locations	Variance		
σ_w^2	0.062		
σ_b^2	0.001		
−2LL	*39.5*		

df, degrees of freedom; β, regression coefficient of the different determinants; SE, standard error; e, determinants for estimating the geometric mean (GM) of different exposure scenarios.
*$P < 0.10$.

team of 15 swimmers training in the sports pool in the morning in Pool Facility 2, the following calculation can be done:

$$\begin{aligned}\mathrm{GM} = {} & \mathrm{Intercept} \times \mathrm{Facility} \times \mathrm{Height} \times \\ & \mathrm{Pool} \times \mathrm{Day} \times \mathrm{Time} \times \mathrm{Bathers}\end{aligned} \tag{2}$$

$$\text{Worst case}_{\text{Facility 2}}\mathrm{GM} = (126.47 \times 2.48 \times 1.25 \times 1.0 \times 1.27 \times 1.12 \times 1.30) = 725.0\,\mu\,\mathrm{g\,m^{-3}}$$

$$\text{Best case}_{\text{Facility 2}}\mathrm{GM} = (126.47 \times 2.48 \times 1.25 \times 1.0 \times 1.27 \times 1.12 \times 1.30) = 530.1\,\mu\,\mathrm{g\,m^{-3}}$$

Swimmers training Monday morning are, on average, exposed to 37% higher concentrations compared to swimmers training on Friday afternoon. Using the same scenario to calculate the worst case in Facility 1, the mean exposure is estimated to 292.3 µg $\mathrm{m^{-3}}$, meaning that the swimmers in Facility 2 are exposed to 2.48 times higher concentrations compared with the swimmers in Facility 1.

Discussion

In our study, the within days and within heights variability was greater than the between days and between heights variability in all pool facilities. The within and between sampling location variabilities obtained from Facility 2 were equal (0.09), while, in the other two facilities, the within swimming pool (sampling locations) variabilities were 2.3 (Facility 1) and 3.7 (Facility 3) times greater compared with the between sampling location variabilities. The equality in the variabilities within and between pools for Facility 2 is probably explained by the swimming pools being located in two different rooms and being ventilated by two different ventilation systems. Greater variability within pools than between pools was also found in the water of eight swimming pools in London (Chu and Nieuwenhuijsen, 2002). In a cross-sectional study, in which air and water samples were collected once from 41 pool facilities, the results showed great variability between the different swimming pools (Tardif *et al.*, 2016). However, in this study, the variabilities between days and times of day were not considered.

For components such as THMs, the long-term average exposure is relevant, as the health effects are caused by long-term chronic exposure (Boleij *et al.*, 1995). To understand the long-term average exposure, our findings highlight the importance of collecting repeated samples during different scenarios over time. Samples should also be collected from each room in the facility or from each zone in which different ventilation systems are used.

In Facility 2, the highest measured concentration during a 20-min sampling time within the same day ranged from 361.7 to 781.7 µg m^{-3}, and the mean day-to-day concentration in this facility ranged from 341.7 to 590.9 µg m^{-3}. This highlights that one single sample or 1-day sample is not representative of the exposure of a user who spends only a few hours in the pool. Using a cross-sectional study design to collect information about the air quality and exposure, which was done in several previous studies (Chen *et al.*, 2011; Löfstedt *et al.*, 2016; Tardif *et al.*, 2016), is not considered suitable for collecting representative air samples in pool facilities. Rather, repeated measures over time are important in terms of understanding the total variability and the change in exposure over time.

Our study shows that the swimming facility, height above the water's surface, swimming pool, day of the week, time during the day, and number of bathers contribute to the mean exposure level. These fixed factors also reduced the magnitude of the between sampling location variability within the facilities and suggested that some of the heterogeneity observed in each facility was due to these determinants. From the literature, the level of THM is reported to increase rapidly within the first few hours after the precursors are introduced to the chlorinated water (Urano *et al.*, 1983), and, in a previous study, it was suggested that an equilibrium period of 72 h is the optimal time for THM formation in water (D Eichelsdörfer and Jandik, 1983). As given in Table 4, the concentration of THM was consequently higher on Mondays compared with Wednesdays and Fridays, which could be explained by the high bather load in the weekends. We also measured higher concentrations in the morning compared with in the afternoon, which might be explained with the ventilation being reduced by ~30% during the night. The fresh air supply is also reduced during night mode ventilation. As given in Table 4, the exposure levels were smallest for the highest number of bathers. When the bathers are present in the pool this increases the water turbulence and the evaporation rate from the water to the air, thereby leading to increased contamination level. However, at some point, the degassing from the water might be higher than the formation rate of tTHMs in the water, which might also explain why the lowest contamination level was observed when the bather load in the pool was at its highest. This hypothesis however, should be investigated further.

Although increased water temperatures are related to increased formation of THMs (Padhi *et al.*, 2012), there are several reasons why higher concentrations were measured above the sports pools compared with above the therapy pools, despite the fact that the therapy pools had higher bather loads as well as higher water temperatures. In Norway, it is a requirement that 60 l of fresh water per bather be supplied in therapy pools, while, for pools with lower water temperatures, the requirement for fresh water is only 30 l $bather^{-1}$ (Norwegian Ministry of Health, 1996; Norwegian Institute for Water Research, 2000). In addition, it might be reasonable to assume that the swimmers in the sports pool have a higher activity level and release more precursors into the water.

As given in Tables 2 and 4, the choice of pool facility significantly affects the exposure level. In a recent study, we documented that the chlorination method and type of water significantly affects the types and formation of THMs (Nitter *et al.*, 2017). This is explained partly by contaminates of bromide in the brine solution used to produce NaOCl (World Health Organization, 2017) since previous studies have documented that the presence of bromine has been found to increase the formation of THMs (Amy *et al.*, 1987).

A swimming club training Monday morning in the sports pool will be exposed to higher concentrations compared to swimmers training Friday afternoon. However, if these swimmers are categorized in the same exposure category during an epidemiological investigation, doing so might bias the estimated risk of exposure towards association considering that the afternoon swimmers are less exposed compared to swimmers swimming in the morning.

Taking into account the determinants of exposure identified in Table 3, a more dynamic strategy for both the water exchange and the ventilation system is necessary. As of today, the fresh air and water supply are approximately constant regardless of the day of the week, time of day, or number of bathers in the pool. A balanced system, accounting for these determinants, may more appropriate considering the great within day, within height, and within sampling location variability. Considering that the average exposure level above the sports pool, which is 32% higher than that above the therapy pool, despite the lower water temperatures, it would make sense to increase the fresh water supply per bather for waters with lower temperatures.

Conclusions

The determinants of exposure represented in Table 4 indicate which factors are important to consider in effective sampling strategies, as these determinates explained most of the heterogeneity within each pool facility. Our findings highlight the need for a more dynamic water and air circulation system, one which is able to identify the variations within each sampling location in terms of times, days, and bather loads.

Considering that the exposure concentration is very time-dependent, varying with days of the week and times during the day, this time dependency should be considered before exposure categories among the different users of the pool facilitates in epidemiological investigations are created. Putting every swimmer in the same exposure category might prevent the investigator from understanding the dose–response relationship.

Declaration

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References

Amy GL, Chadik PA, Chowdhury ZK. (1987) Developing models for predicting trihalomethane formation potential and kinetics. *Int Water Supply*; **79**: 89–97.

Aprea M-C, Banchi B, Lunghini L *et al.* (2010) Disinfection of swimming pools with chlorine and derivatives: formation of organochlorinated and organobrominated compounds and exposure of pool personnel and swimmers. *Nat Sci*; **2**: 68–78.

Bernard A, Carbonnelle S, Michel O *et al.* (2003) Lung hyperpermeability and asthma prevalence in schoolchildren: unexpected associations with the attendance at indoor chlorinated swimming pools. *Occup Environ Med*; **60**: 385–94.

Bernard A, Nickmilder M. (2006) Respiratory health and baby swimming. *Arch Dis Child*; **91**: 620–1.

Boleij JSM, Buringh E, Heederik D *et al.* (1995) *Occupational Hygiene of Chemical and Biological Agents*. Elsevier Science and Technology, Imprint: Elsevier Science Ltd. ISBN10: 0444819975. ISBN13: 9780444819970.

Boudenne JL, Parinet J, Demelas C *et al.* (2017) Monitoring and factors affecting levels of airborne and water bromoform in chlorinated seawater swimming pools. *J Environ Sci (China)*; **58**: 262–70.

Burdorf A. (2005) Identification of determinants of exposure: consequences for measurement and control strategies. *Occup Environ Med*; **62**: 344–50.

Catto C, Sabrina S, Ginette CT *et al.* (2012) Occurrence and spatial and temporal variations of disinfection by-products in the water and air of two indoor swimming pools. *Int J Environ Res Public Health*; **9**: 2562–86.

Chen MJ, Lin CH, Duh JM *et al.* (2011) Development of a multi-pathway probabilistic health risk assessment model for swimmers exposed to chloroform in indoor swimming pools. *J Hazard Mater*; **185**: 1037–44.

Chowdhury S. (2015) Predicting human exposure and risk from chlorinated indoor swimming pool: a case study. *Environ Monit Assess*; **187**: 502.

Chu TS, Cheng SF, Wang GS *et al.* (2013) Occupational exposures of airborne trichloramine at indoor swimming pools in Taipei. *Sci Total Environ*; **461–462**: 317–22.

Chu H, Nieuwenhuijsen MJ. (2002) Distribution and determinants of trihalomethane concentrations in indoor swimming pools. *Occup Environ Med*; **59**: 243–7.

Eichelsdörfer D, Jandik J. (1983) Organic halogen compounds in the circulation cycle of swimming pool water. *Arch Badewesens*; **36**: 142–47.

Erdinger L, Kühn KP, Kirsch F *et al.* (2004) Pathways of trihalomethane uptake in swimming pools. *Int J Hyg Environ Health*; **207**: 571–5.

European Commission. (2009) *Risk assessment methodologies and approaches for genotoxic and carcinogenic substances*. SCHER/SCCP/SCENIHR scientific opinion on the risk assessment methodologies and approaches for genotoxic and carcinogenic substances, January 2009. Available at http://ec.europa.eu/health/ph_risk/committees/04_scher/docs/scher_o_113.pdf

French Agency for Food, Environmental and Occupational Health and Safety (ANSES). (2010) *Évaluation des risques sanitaires liés aux piscines Partie I : piscines réglementées Avis de l'Afsset Rapport d'expertise collective*. Available at https://www.anses.fr/fr/system/files/EAUX2007sa0409Ra.pdf

Goldberg M, Hémon D. (1993) Occupational epidemiology and assessment of exposure. *Int J Epidemiol*; **22**(Suppl 2): S5–9.

Hery M, Hecht G, Gerber JM *et al.* (1995) Exposure to chloramines in the atmosphere of indoor swimming pools. *Ann Occup Hyg*; **39**: 427–39.

Jacobs JH, Spaan S, van Rooy GB *et al.* (2007) Exposure to trichloramine and respiratory symptoms in indoor swimming pool workers. *Eur Respir J*; **29**: 690–8.

Lee J, Ha KT, Zoh KD. (2009) Characteristics of trihalomethane (THM) production and associated health risk assessment in swimming pool waters treated with different disinfection methods. *Sci Total Environ*; **407**: 1990–7.

Löfstedt H, Westerlund J, Graff P *et al.* (2016) Respiratory and ocular symptoms among employees at Swedish indoor swimming pools. *J Occup Environ Med*; **58**: 1190–5.

Nitter TB, Kampel W, Svendsen KVH *et al.* (2017) Comparison of trihalomethanes in the air of two indoor swimming pool facilities using different type of chlorination and different types of water. *Water Sci Technol Water Supply*; **18**: 1350–56.

Norwegian Institute for Water Research. (2000) *Water quality and water treatment in swimming pool facilities (original title: Vannkvalitet og vannbehandling i bade- og svømmeanlegg)*. Report NIVA 4318-2000. Available at https://brage.bibsys.no/xmlui/bitstream/handle/11250/211098/4318_72dpi.pdf?sequence=1&isAllowed=y

Norwegian Ministry of Health. (1996) *Regulations for swimming facilities, swimming pools and sauna (Original title: Forskrift for badeanlegg, bassengbad og badstu m.v)*. Available at https://lovdata.no/dokument/SF/forskrift/1996-06-13-592

Ohlsson M, Norén R, Winberg L *et al.* (2014) *Badhus. Strategiska frågor och ställningstagaden*. City: Sveriges Kommuner och Landsting. Swedens municipalities and county councils (*Original Name: Sveriges kommuner och landsting*). ISBN: 978-91-7585-197-6.

Padhi RK, Sowmya M, Mohanty AK *et al.* (2012) Formation and speciation characteristics of brominated trihalomethanes in seawater chlorination. *Water Environ Res*; **84**: 2003–9.

Rappaport SM, Kupper LL. (2008) *Quantitative exposure assessment*. ISBN 9780980242805. LULU PRESS, p 183.

Rijksinstituut voor Volksgezondheid en Milieu. (2014) *Normen en methoden voor kwaliteitsparameters in het te wijzigen Besluit hygiëne badinrichtingen en zwemgelegenheden. Standards and methods for quality parameters in the decision to amend hygiene and safety at bathing establishments and swimming areas (original title: Normen en methoden voor kwaliteitsparameters in het te wijzigen besluit hygiene en veiligheid badinrichtingen en zwemgelegenhenden)*. RIVM report 2014-0121. National Institute for Health and Environment (original name: Rijksinstituut voor volksgezondheid en milieu (RIVM)). Available at https://www.rivm.nl/bibliotheek/rapporten/2014-0121.pdf.

Rivera-Núñez Z, Wright JM, Meyer A. (2018) Exposure to disinfectant by-products and the risk of stillbirth in Massachusetts. *Occup Environ Med*; **75**: 1–10. doi:10.1136/oemed-2017-104861

Symanski E, Chan W, Chang CC. (2001) Mixed-effects models for the evaluation of long-term trends in exposure levels with an example from the nickel industry. *Ann Occup Hyg*; **45**: 71–81.

Tardif R, Catto C, Haddad S *et al.* (2016) Assessment of air and water contamination by disinfection by-products at 41 indoor swimming pools. *Environ Res*; **148**: 411–20.

United States Environmental Protection Agency. (1999). *Compendium of methods for the determination of toxic organic compounds in ambient air.* Report number: EPA/625/R-96/010b. Cincinnati, OH: U. S. Environmental Protection Agency Office of Research and Development National Risk Management Research Laboratory Center for Environmental Research Information. Available at https://www3.epa.gov/ttnamti1/files/ambient/airtox/tocomp99.pdf

Urano K, Wada H, Takemasa T. (1983) Empirical rate equation for trihalomethane formation with chlorination of humic substances in water. *Water Res*; **17**: 1797–802.

Verein Deutsher Ingenieure. (2010) *Building services in swimming baths—indoor pools*. Germany: Deutsches Institut fur Normung E.V. (DIN), VDI 2089 BLATT 1.

West BT, Welch KB, Gatecki AT. (2006) *Linear mixed models: a practical guide using statistical software*: USA: Chapman and Hall/CRC, Taylor and Francis group. ISBN 9781466560994.

Westerlund J, Bryngelsson IL, Löfstedt H *et al.* (2016) Occupational exposure to trichloramine and trihalomethanes—adverse respiratory and ocular effects among Swedish indoor swimming pool workers. *Ann Occup Hyg*; **59**: 1074–84.

World Health Organization. (2006) *Guidelines for safe recreational water environments. Volume 2. Swimming pools and similar environments*. Report. Geneva: World Health Organization. ISBN: 9241546808.

World Health Organization. (2017) *Guidelines for drinking—water quality*. Geneva: World Health Organization. ISBN: 9789241549950.

Paper II

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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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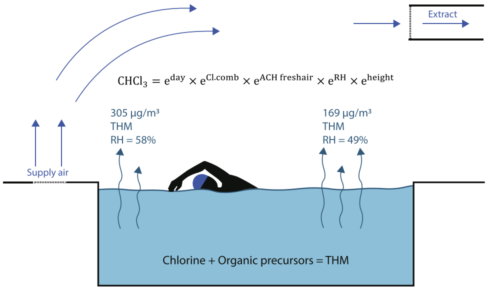
HIGHLIGHTS

- 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



$$CHCl_3 = e^{day} \times e^{Cl.comb} \times e^{ACH\ freshair} \times e^{RH} \times e^{height}$$

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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 ($p \leq 0.05$). 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 ($p \leq 0.05$). 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:

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

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 ≤ 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) (μg/m^3)	Mean $CHCl_2Br$ (range) (μg/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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References

Al-Omari, A., Fayyad, M., Qader, A.A., 2005. Modeling trihalomethane formation for Jabal Amman water supply in Jordan. Environ. Model. Assess. 9 (4), 245. https://doi.org/10.1007/s10666-005-3334-4.

Asdrubali, F., 2009. A scale model to evaluate water evaporation from indoor swimming pools. Energ. Buildings 41 (3), 311–319. https://doi.org/10.1016/j.enbuild.2008.10.001.

Baayen, R.H., Davidson, J.D., Bates, D.M., 2008. Mixed-effects modeling with crossed random effects for subjects and items. J. Mem. Lang. 59, 390–412. https://doi.org/10.1016/j..jml.2007.12.005.

Baroja, O., Rodríguez, E., Gomez de Balugera, Z., Goicolea, A., Unceta, N., Sampedro, C., Alonso, A., Barrio, R.J., 2005. Speciation of volatile aromatic and chlorinated hydrocarbons in an urban atmosphere using TCT-GC/MS. J. Environ. Sci. Health A 40 (2), 343–367. https://doi.org/10.1081/ESE-200045548.

Bernard, A., Carbonnelle, S., Michel, O., Higuet, S., de Burbure, C., Buchet, Buchet, J.-P., Hermans, X., Doyle, I., 2003. Lung hyperpermeability and asthma prevalence in schoolchildren: unexpected associations with the attendance at indoor chlorinated swimming pools. Occup. Environ. Med. 60 (6), 385–394. https://doi.org/10.1136/oem.60.6.385.

Bernard, A., Nickmilder, M., Voisin, C., Sardella, A., 2009. Impact of chlorinated swimming pool attendance on the respiratory health of adolescents. Pediatrics 124 (4), 1110–1118. https://doi.org/10.1542/peds.2009-0032.

Bessonneau, V., Derbez, M., Clément, M., Thomas, O., 2011. Determinants of chlorination by-products in indoor swimming pools. Int. J. Hyg. Environ. Health 215 (1), 76–85. https://doi.org/10.1016/j.ijheh.2011.07.009.

Chowdhury, S., 2015. Predicting human exposure and risk from chlorinated indoor swimming pool: a case study. Environ. Monit. Assess. 187 (8), 502. https://doi.org/10.1007/s10661-015-4719-8.

Chu, T.-S., Cheng, S.-F., Wang, G.-S., Tsai, S.-W., 2013. Occupational exposures of airborne trichloramine at indoor swimming pools in Taipei. Sci. Total Environ. 461-462, 317–322. https://doi.org/10.1016/j.scitotenv.2013.05.012.

Compendium of methods for the determination of toxic organic compounds in ambient air, 1999. second edition. https://www3.epa.gov/ttnamti1/files/ambient/airtox/to-17r.pdf.

Erdinger, L., Kühn, K.P., Kirsch, F., Feldhues, R., Fröbel, T., Nohynek, B., Gabrio, T., 2004. Pathways of trihalomethane uptake in swimming pools. Int. J. Hyg. Environ. Health 207 (6), 571–575. https://doi.org/10.1078/1438-4639-00329.

Guglielmina Fantuzzi, E.R., Predieri, G., Giacobazzi, P., Petra, B., Aggazzotti, G., 2012. Airborne trichloramine (NCl3) levels and self-reported health symptoms in indoor swimming pool workers: dose-response relationships. J. Expo. Sci. Environ. Epidemiol., 1–6 https://doi.org/10.1038/jes.2012.56.

Hery, M., Hecht, G., Gerber, J.M., Gendre, J.C., Hubert, G., Rebuffaud, J., 1995. Exposure to chloramines in the atmosphere of indoor swimming pools. Ann. Occup. Hyg. 39 (4), 427–439. https://doi.org/10.1016/0003-4878(95)00013-5.

International Organization for Standardization, 2000. ISO 16017-1:2000(E). Indoor, ambient and workplace air — sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography. Vol. ISO 16017-1:2000 (E).

Jacobs, J.H., Spaan, S., van Rooy, G.B.G.J., Meliefste, C., Zaat, V.A.C., Rooyackers, J.M., Heederik, D., 2007. Exposure to trichloramine and respiratory symptoms in indoor swimming pool workers. Eur. Respir. J. 29 (4), 690–698. https://doi.org/10.1183/09031936.00024706.

Lebon, M., Fellouah, H., Galanis, N., Limane, A., Guerfala, N., 2017. Numerical analysis and field measurements of the airflow patterns and thermal comfort in an indoor swimming pool: a case study. Energ. Effic. 10 (3), 527–548. https://doi.org/10.1007/s12053-016-9469-0.

Leech, N.L., Barrett, K.C., Morgan, A.G., 2015. IBM SPSS for Intermediate Statistics: Use and Interpretation. fifth edition.

Levesque, B., Vezina, L., Gauvin, D., Leroux, P., 2015. Investigation of air quality problems in an indoor swimming pool: a case study. Ann. Occup. Hyg. 59 (8), 1085–1089. https://doi.org/10.1093/annhyg/mev038.

Löfstedt, H., Westerlund, J., Graff, P., Bryngelsson, I.-L., Mölleby, G., Olin, A.-C., Eriksson, K., Westberg, H., 2016. Respiratory and ocular symptoms among employees at Swedish indoor swimming pools. J. Occup. Environ. Med. 58 (12), 1190–1195. https://doi.org/10.1097/JOM.0000000000000883.

Nitter, T.B., Kampel, W., Svendsen, K.v.H., Aas, B., 2017. Comparison of trihalomethanes in the air of two indoor swimming pool facilities using different type of chlorination and different types of water. Water Sci. Technol. 18 (4), 1350–1356. https://doi.org/10.2166/ws.2017.201.

Norwegian Ministry of Health, 1996. Regulations for Swimming Facilities, Swimming Pools and Sauna.

Shah, M.M., 2014. Methods for calculation of evaporation from swimming pools and other water surfaces. January 2014 ASHRAE Transactions 120 pp. 3–17.

SINTEF Byggforsk, 2003. Ventilasjon og Avfukting i Svømmehaller og Rom Med Svømmebasseng.

The European Chemicals Agency, 2017. Guidance on the Biocidal Products Regulation Volume V, Guidance on Disinfection By-Products.

Varraso, R., Massin, N., Hery, M., Fradier-Dusch, M., Michaely, J.-P., Fournier, M., Hubert, G., Biette, P., Rieger, B., Berthelin, A., Hecht, G., Nadif, R., 2002. Not only training but also exposure to chlorinated compounds generates a response to oxidative stimuli in swimmers. Toxicol. Ind. Health 18 (6), 269–278. https://doi.org/10.1191/0748233702th150oa.

VDI 2089, 2010. Technische Gebâudeausrûstung von Schwimmbâdern Hallenbâder Builing Services in Swimming Bath Indoor Pools.

Westerlund, J., Graff, P., Bryngelsson, I.-L., Westberg, H., Eriksson, K., Löfstedt, H., 2016. Occupational exposure to trichloramine and trihalomethanes- adverse respiratory and ocular effects among Swedish indoor swimming pool workers. Ann. Occup. Hyg. 59, 1074–1084. https://doi.org/10.1093/annhyg/mev045.

World Health Organization, 2006. Guidelines for safe recreational water environments volume 2, swimming pools and similar environments. http://www.who.int/water_sanitation_health/bathing/srwe2full.pdf.

World Health Organization, 2017. Guidelines for drinking-water quality. http://apps.who.int/iris/bitstream/10665/254637/1/9789241549950-eng.pdf?ua=1.

Paper III

Paper IV

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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.

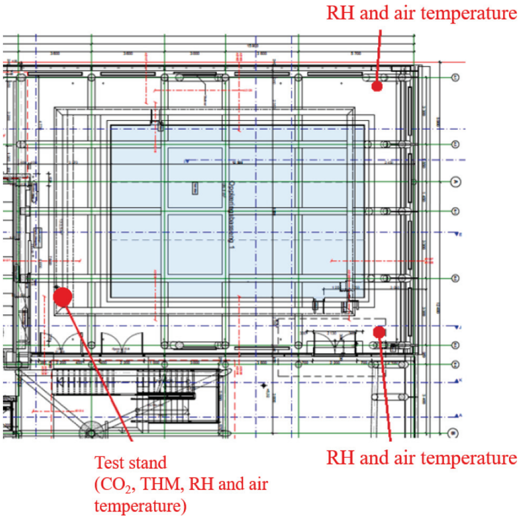

Fig. 1. Sketch of the pool facility with its sampling locations.

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:

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

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 $\mu g/m^3$ and the number of occupants is 20, results in an estimated geometric mean CO_2 concentration of:

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

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 $\mu g/m^3$, was measured the final day of sampling and is close to the threshold value of 200 $\mu g/m^3$ 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 $\mu g/m^3$, the cancer risk among elite swimmers was found to be unacceptably high (Gouveia et al., 2019), and therefore keeping the concentrations below 200 $\mu g/m^3$ 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 $\mu g/m^3$. 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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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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References

Afifi, M.Z., Blatchley, E.R., 2015. Seasonal dynamics of water and air chemistry in an indoor chlorinated swimming pool. Water Res. 68, 771–783. https://doi.org/10.1016/j.watres.2014.10.037.

ASHRAE, 2016. I Interactions Affecting the Achievement of Acceptable Indoor Environments. Guideline 10.

Bessonneau, V., Derbez, M., Clément, M., Olivier, T., 2011. Determinants of chlorination by-products in indoor swimming pools. Int. J. Hyg. Environ. Health 215 (1), 76–85. https://doi.org/10.1016/j.ijheh.2011.07.009.

Peretz, C., Goren, A., Smid, T., Kromhout, H., 2002. Application of mixed-effects models for exposure assessment. Ann. Work Expo Health 46 (1), 69–77. https://doi.org/10.1093/annhyg/mef009.

Cossec, C.L., Laurent, A.-M., Person, A., Rouvié-Laurie, I., Beaubestre, C., 2016. Trichloramine and trihalomethanes concentrations in air or water of Paris indoor swimming pools and impact of different water treatment methods. Pollut. Atmos. 228, 1–14.

Chu, T.-S., Cheng, S.-F., Wang, G.-S., Tsai, S.-W., 2013. Occupational exposures of airborne trichloramine at indoor swimming pools in Taipei. Sci. Total Environ. 461–462, 317–322. https://doi.org/10.1016/j.scitotenv.2013.05.012.

Ciuman, P., Lipska, B., 2018. Experimental validation of the numerical model of air, heat and moisture flow in an indoor swimming pool. Build. Environ. 145, 1–13. https://doi.org/10.1016/j.buildenv.2018.09.009.

Daiber, E.J., DeMarini, D.M., Ravuri, S.A., et al., 2016. Progressive increase in disinfection byproducts and mutagenicity from source to tap to swimming pool and spa water: impact of human inputs. Environ. Sci. Technol. 50 (13), 6652–6662. https://doi.org/10.1021/acs.est.6b00808.

Deutsches Institut für Normung (DIN), 2012. Treatment of water of swimming pools and baths – Part 1: General requirements. DIN 19643.

Dougan, D.S., Damiano, L., 2004. CO_2-based demand control ventilation: Do risks outweight potential rewards? ASHRAE J. 46 (10) 47–50, 52–54.

Font-Ribera, L., Gràcia-Lavedan, E., Aragonés, N., et al., 2018. Long-term exposure to trihalomethanes in drinking water and breast cancer in the Spanish multicase-control study on cancer (MCC-SPAIN). Environ. Int. 112, 227–234. https://doi.org/10.1016/j.envint.2017.12.031.

Gabriel, M.F., Felgueiras, F., Mourao, Z., Fernandes, E.O., 2019. Assessment of the air quality in 20 public indoor swimming pools located in the Northern Region of Portugal. Environ. Int. 133 (Pt B), 105274. https://doi.org/10.1016/j.envint.2019.105274.

Gouveia, P., Felgueiras, F., Mourao, Z., Fernandes, E.O., Moreira, A., Gabriel, M.F., 2019. Predicting health risk from exposure to trihalomethanes in an Olympic-size indoor swimming pool among elite swimmers and coaches. J. Toxicol. Environ. Health A 82 (9), 577–590. https://doi.org/10.1080/15287394.2019.1634383.

Fantuzzi, G., Righi, E., Predieri, G., Giacobazzi, P., Mastroianni, K., Aggazzotti, G., 2010. Prevalence of ocular, respiratory and cutaneous symptoms in indoor swimming pool workers and exposure to Disinfection By-Products (DBPs). Int. J. Environ. Res. Public Health 7 (4), 1379–1391. https://doi.org/10.3390/ijerph7041379.

Hery, M., Hecht, G., Gerber, J.M., Gendre, J.C., Hubert, G., Rebuffaud, J., 1995. Exposure to chloramines in the atmosphere of indoor swimming pools. Ann. Occup. Hyg. 39 (4), 427–439. https://doi.org/10.1016/0003-4878(95)00013-5.

Hsu, H.T., Chen, M.J., Lin, C.H., Chou, W.S., Chen, J.H., 2009. Chloroform in indoor swimming-pool air: Monitoring and modeling coupled with the effects of environmental conditions and occupant activities. Water Res. 43 (15), 3693–3704. https://doi.org/10.1016/j.watres.2009.05.032.

International Organization for Standardization, 2000. ISO 16017-1:2000(E). Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography.

Jacobs, J.H., Spaan, S., van Rooy, G.B.G.J., et al., 2007. Exposure to trichloramine and respiratory symptoms in indoor swimming pool workers. Eur. Respir. J. 29 (4), 690. http://erj.ersjournals.com/content/29/4/690.abstract.

Kampel, W., Carlucci, S., Aas, B., Bruland, A., 2016. A proposal of energy performance indicators for a reliable benchmark of swimming facilities. Energy Build. 129, 186–198. https://doi.org/10.1016/j.enbuild.2016.07.033.

Lévesque, B., Duchesne, J.-F., Gingras, S., et al., 2006. The determinants of prevalence of health complaints among young competitive swimmers. Int. Arch. Occup. Environ. Health 80 (1), 32–39. https://doi.org/10.1007/s00420-006-0100-0.

Liu, Z., Ma, S., Cao, G., Meng, C., He, B.-J., 2018. Distribution characteristics, growth, reproduction and transmission modes and control strategies for microbial contamination in HVAC systems: a literature review. Energy Build. 177, 77–95. https://doi.org/10.1016/j.enbuild.2018.07.050.

Lu, C.Y., Lin, J.M., Chen, Y.Y., Chen, Y.C., 2015. Building-related symptoms among office employees associated with indoor carbon dioxide and total volatile organic compounds. Int. J. Environ. Res. Public Health 12 (6), 5833–5845. https://doi.org/10.3390/ijerph120605833.

Luoma, M., Batterman, S.A., 2000. Autocorrelation and variability of indoor air quality measurements. AIHAJ – Am. Ind. Hyg. Assoc. J. 61 (5), 658–668. https://doi.org/10.1080/15298660008984575.

Markes Int, 2019a. ACTI-VOC low-flow sampling pump. https://www.markes.com/Products/Sampling-accessories/Sampling/ACTI-VOC-low-flow-pump.aspx.

Markes Int, 2019b. Stainless steel thermal desorption sorbent tubes. https://www.markes.com/Products/Sampling-accessories/Sorbent-tubes/Stainless-steel.aspx.

Andersson, M., Backman, H., Nordberg, G., et al., 2018. Early life swimming pool exposure and asthma onset in children – a case-control study. Environ. Health 17 (1), 34. https://doi.org/10.1186/s12940-018-0383-0.

Lebon, M., Fellouah, H., Galanis, N., Limane, A., Guerfala, N., 2017. Numerical analysis and field measurements of the airflow patterns and thermal comfort in an indoor swimming pool: a case study. Energy Effic. 10 (3), 527–548. https://doi.org/10.1007/s12053-016-9469-0.

Ministry of Culture, 2016. Idrettshaller Planlegging og bygging (Sport Facilities – Planning and Building). https://www.regjeringen.no/contentassets/dee978d794694506bba23a57d8a76ea8/v-0989b_idrettshaller_planleging_og_bygging_2016.pdf.

Nitter, T.B., Carlucci, S., Olsen, S.N., Svendsen, K.V.H., 2019. Energy use and perceived health in indoor swimming pool facilities. IOP Conf. Ser. 609, 042051. https://doi.org/10.1088/1757-899x/609/4/042051.

Nitter, T.B., Wolfgang, K., Svendsen Kv, H., Aas, B., 2018. Comparison of trihalomethanes in the air of two indoor swimming pool facilities using different type of chlorination and different types of water. Water Sci. Technol.-W Sup. 18 (4), 1350–1356. http://ws.iwaponline.com/content/early/2017/10/09/ws.2017.201.abstract.

Nitter, T.B., Svendsen, K.V.H., 2019b. Modelling the concentration of chloroform in the air of a Norwegian swimming pool facility-a repeated measures study. Sci. Total Environ. 664, 1039–1044. https://doi.org/10.1016/j.scitotenv.2019.02.113.

Nitter, T.B., Svendsen, K.V.H., 2019a. UV treatment and air quality in a pool facility. Water Sci. Technol. 80 (3), 499–506. https://doi.org/10.2166/wst.2019.291.

Norbäck, D., Björnsson, E., Janson, C., Widström, J., Boman, G., 1995. Asthmatic symptoms and volatile organic compounds, formaldehyde, and carbon dioxide in dwellings. Occup. Environ. Med. 52 (6), 388–395. https://doi.org/10.1136/oem.52.6.388.

Norwegian Ministry of Health, 1996. Regulations for swimming facilities, swimming pools and sauna. https://lovdata.no/dokument/SF/forskrift/1996-06-13-592.

Padhi, R.K., Sowmya, M., Mohanty, A.K., Bramha, S.N., Satpathy, K.K., 2012. Formation and speciation characteristics of brominated trihalomethanes in seawater chlorination. Water Environ. Res. 84, 2003–2009. https://doi.org/10.2175/106143012X13415215906735.

Rodríguez, A., Tajuelo, M., Rodríguez, D., Seseña, S., Ruiz, P., Palop, M.L., 2018. Assessment of chemical and microbiological parameters of indoor swimming pool atmosphere using multiple comparisons. Indoor Air 28 (5), 676–688. https://doi.org/10.1111/ina.12477.

Seppänen, O.A., Fisk, W.J., Mendell, M.J., 1999. Association of ventilation rates and CO2 concentrations with health and other human responses in commercial and institutional buildings. Indoor Air 9 (4), 226–252. https://doi.org/10.1111/j.1600-0668.1999.00003.x.

Qiao, S., Qu, Y., Ma, Y., et al., 2019. A Sensitive carbon dioxide sensor based on photoacoustic spectroscopy with a fixed wavelength quantum cascade laser. Sensors 19 (9). https://doi.org/10.3390/s19194187.

SINTEF Byggforsk, 2003. Ventilasjon og avfukting i svømmehaller og rom med svømmebasseng. https://bks.byggforsk.no/DocumentView.aspx?documentId=534&sectionId=2.

United States Environmental Protection Agency, 1999. Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, second ed. United States Environmental Protection Agency.

Verein Deutsher Ingenieure, 2010. Building Services in swimming baths Indoor pools (VDI 2089).

World Health Organization, 2006. Guidelines for safe recreational water environments volume 2 swimming pools and similar environments. http://www.who.int/water_sanitation_health/bathing/srwe2full.pdf.

World Health Organization, 2017. Guidelines for Drinking-water Quality, fourth ed. World Health Organization, Geneva, Switzerland.

Paper V

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

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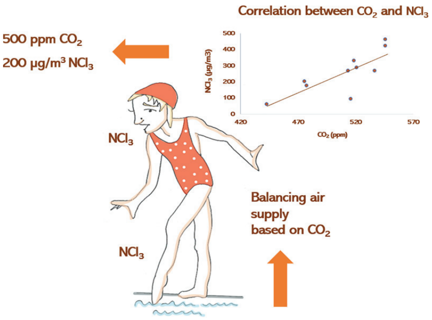
HIGHLIGHTS

- 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 µg/m^3 to 461 µg/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.

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 $\mu g/m^3$ 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 × 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 × 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 though 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 censors (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:

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

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 logic 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

$$\gamma_{ij} = \beta_0 + \beta_1 x_{ij1} + \zeta_j + \in_{ij}, \tag{2}$$

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 (Tyrer 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 responds 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 ($p \le 0.05$) 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 where 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

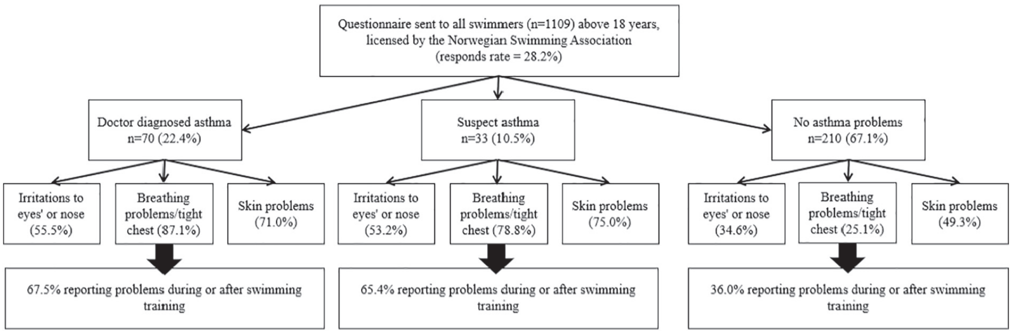

Fig. 1. Reported prevalence of health problems during or after training amongst swimmers diagnosed with asthma, suspecting asthma and having no problems with asthma.

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 (28.1percentage 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 Heathcare, 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 μg/m^3 to 265 μg/m^3, and the concentration measured simultaneously from the two sampling locations only varied by 10 μg/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 μg/m^3 to 327 μg/m^3 in the morning and 92 μg/m^3 to 461 μg/m^3 in the evening. On Thursday during the week of measurement, low concentrations of NCl_3 were measured, with 58 μg/m^3 in the morning and 92 μg/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^{-}). 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 CO_2 sensors to predict the concentrations of NCl_3 in the air

A significant Pearson's correlation was found between the NCl_3 concentration in the air and the concentration of CO_2 (average over 3 h) measured in the extract channel ($r = 0.80$, $p = 001$). A significant Spearman's correlation was also found between the CO_2 concentration and occupancy load ($\rho = 0.82$, $p = 0.01$). The covariations between the number of occupants and the measured concentration of CO_2 in the extract, supply and fresh air channels are shown in Fig. 2.

As shown in Fig. 2, during the night, the CO_2 concentrations measured in the extract channel are below the CO_2 concentration measured in the fresh air channel, suggesting that some of the CO_2 in the room is absorbed by the pool water during the night. In Table 5, the random intercept model for ln NCl_3 with the CO_2 concentration as a fixed effect is shown.

The CO_2 concentration was a significant predictor variable ($p = 0.004$), and, after this component was included into the random intercept mode, the total variability ($\sigma_w^2 + \sigma_b^2$) 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 NCl_3 and CO_2 concentrations is significant. In Fig. 3, a scatterplot between CO_2 and NCl_3 concentrations is shown. The star represents the predicted concentration of CO_2 necessary to keep the concentration of NCl_3 below 200 μg/m^3, based on the estimates in Table 5. According to the plot and the random intercept model, the CO_2 concentrations should be below 500 ppm in order to keep the concentration of NCl_3 below 200 μg/m^3. 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 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 Finish study, which included 200 competitive swimmers, a lower prevalence of doctor-diagnosed asthma (16%) was reported (Päivinen et al., 2009).

Table 4
Exposure concentrations of NCl_3 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 NCl_3 during morning and evening.

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 NCl_3 measured in the evening in Facility 1 and Facility 2 were 250 μg/m^3 and 305 μg/m^3, respectively. While the concentrations of NCl_3 in Facility 1 varied from 245 μg/m^3 to 265 μg/m^3, the concentrations of NCl_3 measured in Facility 2 varied from 92 μg/

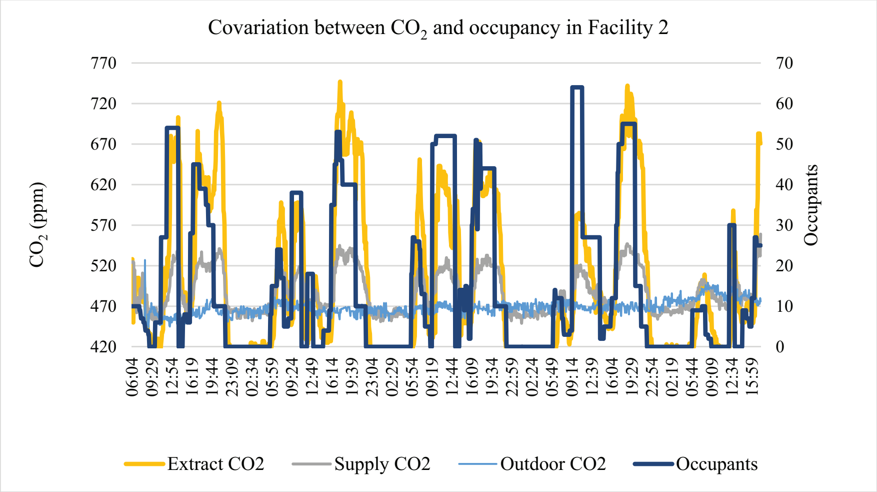

Fig. 2. Number of occupants and measured concentrations of CO2 in the extract, supply and fresh air channels of Facility 2.

m^3 to 461 $\mu g/m^3$. Although higher concentrations of NCl_3 where 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 NCl_3 was above 500 $\mu g/m^3$. However, these results are based on only one sample of NCl_3 collected from each of 20 swimming facilities included in the study (Fantuzzi et al., 2013). The highest concentrations of NCl_3 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 NCl_3 (58 $\mu g/m^3$ in the morning, and 92 $\mu g/m^3$ in the evening) observed on this day.

Table 5
Random intercept model for ln NCl_3 using the CO_2 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 CO_2 sensors to predict the concentration of NCl_3 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 NCl_3 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 NCl_3 observed in Facility 1 are associated with better pool management, despite varying swimmer load. According to the Nordic Expert Group, however, the concentrations of NCl_3 should not exceed 200 $\mu g/m^3$ in stationary air samples. Of the 20 NCl_3 samples collected in this study, 16 exceeded this value. In Facility 1,

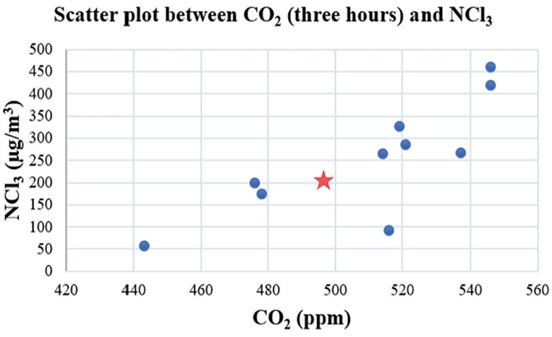

Fig. 3. Scatterplot of the CO2 measured in the extract and NCl3.

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 μg/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 μg/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 where 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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References

Andersson, M., Backman, H., Nordberg, G., Hagenbjörk, A., Hedman, L., Eriksson, K., Rönmark, E., 2018. Early life swimming pool exposure and asthma onset in children – a case-control study. Environ. Health 17, 34. https://doi.org/10.1186/s12940-018-0383-0.

Bougault, V., Turmel, J., St-Laurent, J., Bertrand, M., Boulet, L.P., 2009. Asthma, airway inflammation and epithelial damage in swimmers and cold-air athletes. Eur. Respir. J. 33 (4), 740. https://doi.org/10.1183/09031936.00117708.

Bougault, V., Turmel, J., Boulet, L.-P., 2010. Bronchial challenges and respiratory symptoms in elite swimmers and winter sport athletes: airway hyperresponsiveness in asthma: its measurement and clinical significance. Chest 138 (2, Supplement), 31S–37S. https://doi.org/10.1378/chest.09-1689.

Bougault, V., Loubaki, L., Joubert, P., Turmel, J., Couture, C., Laviolette, M., Chakir, J., Boulet, L.-P., 2012. Airway remodeling and inflammation in competitive swimmers training in indoor chlorinated swimming pools. J. Allergy Clin. Immunol. 129 (2), 351–358. https://doi.org/10.1016/j.jaci.2011.11.010.

Chen, W.Y., Horton, D.J., 1977. Heat and water loss from the airways and exercise-induced asthma. Respiration 34 (6), 305–313. https://doi.org/10.1159/000193842.

Cohen, D.E., Wolff, E., 2000. In: Kanerva, L., Wahlberg, J.E., Elsner, P., Maibach, H.I. (Eds.), Handbook of Occupational Dermatology. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-07677-4_177.

Det kongelige kulturdepartementet, 2013. Statusrapportering for svømmebasseng - 2012. https://www.regjeringen.no/globalassets/upload/kud/idrett/rapporter_utredninger/statusrapportering_svommebasseng_2012.pdf.

Fantuzzi, G., Righi, E., Predieri, G., Giacobazzi, P., Petra, B., Aggazzotti, G., 2013. Airborne trichloramine (NCl_3) levels and self-reported health symptoms in indoor swimming pool workers: dose-response relationships. J Expo Sci Environ Epidemiol 23, 88–93. https://doi.org/10.1038/jes.2012.56.

Folkehelseinstituttet, 2018. Reseptregisteret. http://www.reseptregisteret.no/Prevalens.aspx.

Hery, M., Hecht, G., Gerber, J.M., Gendre, J.C., Hubert, G., Rebuffaud, J., 1995. Exposure to chloramines in the atmosphere of indoor swimming pools. The Annals of Occupational Hygiene 39 (4), 427–439. https://doi.org/10.1016/0003-4878(95)00013-5.

Inbar, O., Dotan, R., Dlin, R.A., Neuman, I., Bar-Or, O., 1980. Breathing dry or humid air and exercise-induced asthma during swimming. Eur. J. Appl. Physiol. Occup. Physiol. 44 (1), 43–50. https://doi.org/10.1007/BF00421762.

Keuten, M.G.A., Schets, F.M., Schijven, J.F., Verberk, J.Q., van Dijk, J.C., 2012. Definition and quantification of initial anthropogenic pollutant release in swimming pools. Water Res. 46 (11), 3682–3692. https://doi.org/10.1016/j.watres.2012.04.012.

Kippelen, P., Fitch, K.D., Anderson, S.D., Bougault, V., Boulet, L.-P., Rundell, K.W., Sue-Chu, M., McKenzie, D.C., 2012. Respiratory health of elite athletes – preventing airway injury: a critical review. Br. J. Sports Med. 46 (7), 471–476. https://doi.org/10.1136/bjsports-2012-091056.

Langdeau, J.B., Turcotte, H., Bowie, D.M., Jobin, J., Desgagne, P., Boulet, L.P., 2000. Airway hyperresponsiveness in elite athletes. Am. J. Respir. Crit. Care Med. 161 (5), 1479–1484. https://doi.org/10.1164/ajrccm.161.5.9909008.

Langdeau, J.-B., Turcotte, H., Thibault, G., Boulet, L.-P., 2004. Comparative prevalence of asthma in different groups of athletes: a survey. Can. Respir. J. 11 (6), 402–406. https://doi.org/10.1155/2004/251453.

Langhammer, A., Brumpton, B.M., 2014. Fedme, metabolsk syndrom og astma. Allergi i praksis (1), 17–20. https://www.naaf.no/globalassets/x-gamle-bilder/documents/1.-allergi-i-praksis/1—2014/sider-fra-aip_1_2014_femde_og_astma_-langhammer_brumpton.pdf.

Lévesque, B., Duchesne, J.-F., Gingras, S., Lavoie, R., Prud'Homme, D., Bernard, E., Boulet, L.P., Ernst, P., 2006. The determinants of prevalence of health complaints among young competitive swimmers. Int. Arch. Occup. Environ. Health 80 (1), 32–39. https://doi.org/10.1007/s00420-006-0100-0.

Löfstedt, H., Westerlund, J., Graff, P., Bryngelsson, I.L., Mölleby, G., Olin, A.C., Eriksson, K., Westberg, H., 2016. Respiratory and ocular symptoms among employees at Swedish indoor swimming pools. J. Occup. Environ. Med. 58 (12), 1190–1195. https://doi.org/10.1097/JOM.0000000000000883.

Nitter, T.B., Svendsen, K.V.H., 2019a. Determinants of exposure and variability of trihalomethanes in the air of three indoor swimming pools. Annals of Work Exposures and Health 63 (5), 560–567. https://doi.org/10.1093/annweh/wxz024.

Nitter, T.B., Svendsen, K.V.H., 2019b. UV treatment and air quality in a pool facility. Water Sci. Technol. 80 (3), 499–506. https://doi.org/10.2166/wst.2019.291.

Nitter, T.B., Svendsen, K.V.H., 2019c. Modelling the concentration of chloroform in the air of a Norwegian swimming pool facility-A repeated measures study. Sci. Total Environ. 664, 1039–1044. https://doi.org/10.1016/j.scitotenv.2019.02.113.

Nitter, T.B., Wolfgang, K., Svendsen, K.V.H., Aas, B., 2018. Comparison of trihalomethanes in the air of two indoor swimming pool facilities using different type of chlorination and different types of water. Water Sci. Technol. Water Supply 18 (4), 1350–1356. http://ws.iwaponline.com/content/early/2017/10/09/ws.2017.201.abstract.

Päivinen, M.K., Keskinen, K.L., Tikkanen, H.O., 2009. Swimming and asthma: factors underlying respiratory symptoms in competitive swimmers. Clin. Respir. J. 47 (2), 97–103. https://doi.org/10.1111/j.1752-699X.2009.00155.x.

Parrat, J., Donzé, G., Iseli, C., Perret, D., Tomicic, C., Schenk, O., 2011. Assessment of Occupational and Public Exposure to Trichloramine in Swiss Indoor Swimming Pools: A Proposal for an Occupational Exposure Limit. 56(3), pp. 264–277. http://annhyg.oxfordjournals.org/content/56/3/264.long.

Peretz, C., Goren, A., Smid, T., Kromhout, H., 2002. Application of mixed-effects models for exposure assessment. Annals of Work Exposures and Health 46 (1), 69–77. https://doi.org/10.1093/annhyg/mef009.

Richardson, S.D., DeMarini, D.M., Kogevinas, M., Fernandez, P., Marco, E., Lourencetti, C., Ballesté, C., Heederik, D., Meliefste, K., McKaque, A.B., Marcos, R., Font-Ribera, L., Grimalt, J.O., Villanueva, C.M., 2010. What's in the pool? A comprehensive identification of disinfection by-products and assessment of mutagenicity of chlorinated and brominated swimming pool water. Environ. Health Perspect. 118 (11), 1523–1530. https://doi.org/10.1289/ehp.1001965.

Romberg, K., Tufvesson, E., Bjermer, L., 2012. Asthma is more prevalent in elite swimming adolescents despite better mental and physical health. Medicine & Science in Sports 22 (3), 362–371. https://doi.org/10.1111/j.1600-0838.2010.01177.x.

Rönmark, E.P., Ekerljung, L., Lötvall, J., Torén, K., Rönmark, E., Lundbäck, B., 2009. Large scale questionnaire survey on respiratory health in Sweden: effects of late- and non-response. Respir. Med. 103 (12), 1807–1815. https://doi.org/10.1016/j.rmed.2009.07.014.

Schouten, B., Cobben, F., Bethlehem, J., 2009. Indicators for the representativeness of survey response. Surv. Methodol. 35 (1), 101–113. https://www150.statcan.gc.ca/n1/en/pub/12-001-x/2009001/article/10887-eng.pdf?st=NQEEoFZp.

Sedgwick, P., 2014. Cross sectional studies: advantages and disadvantages. BMJ : British Medical Journal 348, g2276. https://doi.org/10.1136/bmj.g2276.

Stang, J.S., 2017. Why do athletes develop asthma? Pathogenic mechanisms and asthma phenotypes. http://hdl.handle.net/11250/2490794.

Szumilas, M., 2010. Explaining odds ratios. J. Can. Acad. Child Adolesc. Psychiatry 19 (3), 227–229. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2938757/pdf/ccap19_3p227.pdf.

The Norwegian Ministry of Heathcare, 1996. Regulations for water parks, swimming pools and saunas, etc. https://lovdata.no/dokument/SF/forskrift/1996-06-13-592.

Thickett, K.M., McCoach, J.S., Gerber, J.M., Sadhra, S., Burge, P.S., 2002. Occupational asthma caused by chloramines in indoor swimming-pool air. Eur. Respir. J. 19 (5), 827–832. https://doi.org/10.1183/09031936.02.00232802.

Torèn, K., Brisman, J., Järvholm, B., 1993. Asthma and asthma-like symptoms in adults assessed by questionnaires: a literature review. Chest 104 (2), 600–608. https://doi.org/10.1378/chest.104.2.600.

Tyrer, S., Heyman, B., 2016. Sampling in epidemiological research: issues, hazards and pitfalls. BJPsych Bulletin 40 (2), 57–60. https://doi.org/10.1192/pb.bp.114.050203.

Wastensson, G., Eriksson, K., 2019. The Nordic expert group for criteria documentation of health risks from chemicals. Inorganic chloramines, 152. https://gupea.ub.gu.se/bitstream/2077/61724/4/gupea_2077_61724_4.pdf.

Williams, A.E., 2011. Immunology Mucosal and Body Surface Defences. Wiley-Blackwell 978-0-470-09003-9.