Science of the Total Environment 651 (2019) 775–786

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Investigating the effects of design and management factors on DBPs levels in indoor aquatic centres

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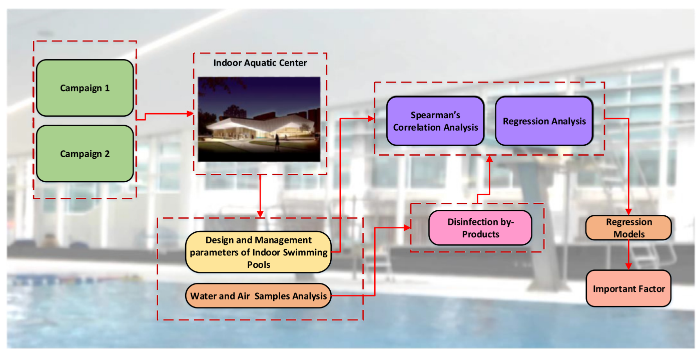
HIGHLIGHTS

- Disinfection by-products in air and water were analyzed at five aquatic centers.
- Effects of water treatment processes on trihalomethanes and trichloramine were compared.
- Correlation of design and management factors with disinfection by-products was evaluated.
- Regression models were developed for trihalomethanes and trichloramine.
- First time to quantify the effect of number of spray features on air and water quality

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 June 2018
Received in revised form 11 September 2018
Accepted 13 September 2018
Available online 17 September 2018

Editor: G. Ashantha Goonetilleke

Keywords:
Disinfection by-product
Indoor swimming pool
Trihalomethane
Trichloramine
Regression model

ABSTRACT

Disinfection by-products (DBPs) in indoor swimming pool water and air have long been a critical human health risk concern. This study investigated the effects of several indoor swimming pool design and management factors (e.g. ventilation, water treatment, pool operations, pool type) on the concentrations of DBPs, such as trihalomethanes (THMs) and chloramines, in pool water and air. Two sampling campaigns, A and B, were carried out to measure the concentrations of DBPs under different conditions. In both campaigns, 46 pool water samples, seven tap water samples, and 28 ambient air samples were collected and analyzed. Regression models were also developed and validated for investigating the combined effects of design and management factors on total trihalomethanes (TTHM) and trichloramine. The model results show that pool water characteristics (e.g., total organic content, temperature, conductivity, pH and alkalinity) and management factors (e.g., the number of bathers and sprayers) have direct effects on DBP concentrations. Pool water characteristics such as UV absorbance, hardness, and oxidation-reduction potential and a management factor UV intensity have inverse effects on DBPs levels. Based on the correlation analysis, other factors such as fan speed, fresh air, pool age, and basin area were found to be correlated with the concentrations of individual THMs and trichloramine in both water and air. It was also observed that the concentration of THMs varies with pool type. It is note worthy that the effects of the number of sprayers was quantified for the first time. This study comprehensively assessed pool design and management factors and identified their effects on DBPs, providing indoor swimming pool facilities with useful information to control DBPs in the indoor swimming environment.

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https://doi.org/10.1016/j.scitotenv.2018.09.172
0048-9697/

1. Introduction

Swimming is highly recommended for health and well-being through increased social interaction, relaxation, and exercise (WHO, 2006). However, swimming pool water can be host to various pathogens, which must be controlled to protect the health of bathers. Since the early 1900s, municipalities have attempted to make swimming safer through the disinfection of water in swimming pools (Olsen, 2007). However, disinfection by-products (DBPs) are generated in swimming pools when chlorine reacts with natural organic matter present in the source water and bather inputs such as urine, sweat, dead skin, hair, saliva, and personal care products (Chowdhury et al., 2014; Kim et al., 2002). Hitherto, almost 700 different species of DBPs have been detected in drinking water (Richardson and Postigo, 2016), and over 100 have been found in swimming pools (Richardson et al., 2010).

In spite of the protection to public health provided by chlorination of swimming pool water, some DBPs have been linked to potential adverse health effects such as cancer, respiratory symptoms, and skin and eye irritations. Exposure to these DBPs could pose health risks to bathers and pool facility staff (Villanueva et al., 2007; Cantor et al., 2010; Nieuwenhuijsen et al., 2009; Rahman et al., 2010; Bernard et al., 2009; Jacobs et al., 2007; Thickett et al., 2002; Voisin et al., 2014; Weisel et al., 2009; Fantuzzi et al., 2010). Additionally, several studies have demonstrated the potential mutagenicity and genotoxicity of DBPs (Cantor et al., 2010; Kogevinas et al., 2010; Liviac et al., 2010).

Trihalomethanes (THMs) and chloramines are the two of the most commonly reported species of DBPs in swimming pools (Villanueva and Font-Ribera, 2012; Simard et al., 2013). Trihalomethanes comprise four different compounds: chloroform, bromodichloromethane (BDCM), dibromochloromethane (DBCM), and bromoform. The total concentration of the four THMs, namely total trihalomethanes (TTHM), is often used in drinking water and pool water guidelines. Chloramines include monochloramine, dichloramine, and trichloramine. These compounds are responsible for the unpleasant "pool smell", which are formed in the presence of nitrogenous precursors introduced by bathers (Villanueva and Font-Ribera, 2012; Weaver et al., 2009). Due to its volatility, trichloramine is present in aquatic facilities predominantly in air rather than in water (Jacobs et al., 2007). As a result, inhalation is the dominant pathway for exposure, which potentially leads to the health effects previously reported, such as respiratory irritation and asthma. Monochloramine and dichloramine are less volatile and therefore more likely to be present in water than air. Previous studies did not identify similar health effects due to exposure to these species (Soltermann et al., 2014). Haloacetic acids (HAAs) are another type of DBP that has been found in swimming pools (Simard et al., 2013); however, HAAs are not as volatile as THMs and are therefore not likely to be detected in air (Font-Ribera et al., 2016; Kim and Weisel, 1998). As the DBP management options presented in this study are predominantly air-related (fresh air, air handling unit fan speed, and operation of source capture/exhaust system), our focus has been on reducing inhalation exposure to THMs and trichloramine.

Although pool water has been found to be significantly more toxic than tap water (Plewa et al., 2011; Daiber et al., 2016), most jurisdictions do not have regulations for DBPs in pool water. For instance, Canada only has a guideline for TTHM (100 μg/L) in drinking water (Health Canada, 2017). Very few countries have reference values or guidelines for THMs in pool water, such as Germany (20 μg/L TTHM; DIN, 2012), Switzerland (30 μg/L TTHM; ANSES, 2012), Netherlands (50 μg/L TTHM; RIVM, 2014), China (100 μg/L THMs; MHURD, 2016), and Denmark (25–50 μg/L TTHM; Denmark, 2012). The UK and Finland both recommended a maximum concentration of 100 μg/L TTHM, and a threshold limit of 20 μg/L was suggested in France (PWTAG, 2009; ANSES, 2012).

Previous studies have demonstrated many pool design and management factors that influence water and air quality in pool facilities. Some of the most important factors affecting DBP concentrations in swimming pool water includes: source water quality (often municipal drinking water), chlorine dose, type of organic or inorganic precursors present (Kim et al., 2002; Lahl et al., 1981; LaKind et al., 2010), pH (Hansen et al., 2012), temperature (Chu and Nieuwenhuijsen, 2002; Simard et al., 2013; Kanan and Karanfil, 2011), disinfectant type (Lee et al., 2009; Richardson et al., 2010; Weng et al., 2012), number of bathers (Aggazzotti et al., 1990, 1995; Chu and Nieuwenhuijsen, 2002), turbulence caused by bather activity, the presence of water features such as sprayers, fountains, water slides, wave pools, and water/air jets (Aggazzotti et al., 1998; Hery et al., 1995; Daiber et al., 2016; Kristensen et al., 2010), and pool type (spas vs pools, Daiber et al., 2016; leisure vs recreational pools, Hery et al., 1995).

The concentration of DBPs detected can also depend on the time and location of sampling (Catto et al., 2012; Hsu et al., 2009; Kristensen et al., 2010). The intensity of swimming activity has been shown to affect the DBPs exposure (Aggazzotti et al., 1990; Erdinger et al., 2004; Marco et al., 2015), likely due to increased respiration and blood circulation during exercise.

Ventilation is one operating condition that has been studied extensively for DBPs in the indoor swimming pool environment. Changes in DBP concentrations or exposure during different ventilation conditions were observed in the field studies by Parrat et al. (2012), Jacobs et al. (2007), and Bessonneau et al. (2011). Chiu et al. (2017) and Bowen et al. (2007) also examined ventilation systems following reported ocular and respiratory symptoms among pool patrons and employees. Models predicting the potential variation of DBPs related to changes in ventilation systems were presented by Catto et al. (2012), Schmalz et al. (2011), and Hsu et al. (2009). Only two studies made "real-time, full-scale" changes to ventilation systems at pool facilities and subsequently measured the resulting DBP concentrations. Tardif et al. (2017) reported the effects of changing buffer tank stripping and ventilation on the DBPs in pool water and air. Weng et al. (2011) evaluated the effects of changing heating, ventilation and air conditioning (HVAC) on the DBP concentrations in the air of pool facilities. Chowdhury et al. (2014) have suggested that more studies are required to understand the variability and circulation of swimming pool facility air for DBPs exposure risk mitigation.

The effects of UV treatment on pool water and air quality remain a source of debate (Hansen et al., 2013; Weng et al., 2012). Some studies reported that increasing UV treatment intensity could increase DBPs in water, while other studies showed the opposite results (Cassan et al., 2006; Cheema et al., 2017; Beyer et al., 2004; Afifi and Blatchley, 2016). Although UV treatment has been used specifically to reduce chloramine levels in pool waters, Tardif et al. (2017) noted a related increase in THMs in air and water. Plewa et al. (2011) observed a reduction in cytotoxicity of pool water when UV treatment is combined with chlorination. Soltermann et al. (2013) tested pool water before and after UV treatment and found that UV treatment can cause the generation of carcinogenic DBPs. To our best knowledge, only two "real-time, full-scale" field studies implementing changes in UV treatment have been published (Tardif et al., 2017; Cassan et al., 2006).

In addition to ventilation and UV treatment, other pool water treatments, including flocculation, chlorine injection, water refresh volume, and filter type (Tardif et al., 2017; Cassan et al., 2006; Glauner et al., 2005; Kanan, 2010), have also been reported to affect DBP concentrations in swimming pool water. The aforementioned studies, considering various management options for reducing DBP exposure, were predominantly based on lab experiments, observational study, and modelling. To our best knowledge, only three "real-time, full-scale" field studies have been reported, in which the operating factors of swimming pool systems were changed first and then the DBPs in water and air were measured to evaluate the potential for reducing exposure to DBPs (Tardif et al., 2017; Weng et al., 2011; Cassan et al., 2006). More direct study in operating pools is required to increase understanding of the design and management factors that impact air and water quality in indoor swimming pools.