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Review

Occurrence, origin, and toxicity of disinfection byproducts in chlorinated swimming pools: An overview

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ABSTRACT

Disinfection treatments are critical to conserve the microbiological quality of swimming pool water and to prevent water-borne infections. The formation of disinfection byproducts (DBPs) in swimming pools is an undesirable consequence resulting from reactions of disinfectants (e.g. chlorine) with organic and inorganic matter present in pool water, mainly brought by bathers. A considerable body of occurrence studies has identified several classes of DBPs in swimming pools with more than 100 compounds detected, mainly in chlorinated freshwater pools. Trihalomethanes (THMs), haloacetic acids (HAAs), haloacetaldehydes (HALs) are among the major DBPs in swimming pools. Other DBPs such as haloacetonitriles (HAN), haloamines, nitrosamines, and halobenzoquinones have also been detected. Researchers have been interested in identifying the precursors responsible for the formation of DBPs. In swimming pools, anthropogenic organic loads brought by swimmers increase the complexity of pool water chemistry. When human inputs (e.g. sweat, urine, hair, skin and personal care products) containing very diverse organic compounds are introduced to pools by swimmers, they react with chlorine resulting in the formation of complex mixtures of DBPs. The overwhelming majority of the total organic halide (TOX) content is still unknown in swimming pools. Exposure of swimmers to DBPs can take place through multiple routes, depending on the chemical properties of each DBP. Toxicological studies have shown that swimming pool water can be mutagenic with different potencies reported in different studies. Many DBPs have been shown to be genotoxic and carcinogenic. DBPs were also shown to induce reproductive and neurotoxic adverse effects in animal studies. Epidemiologic studies in humans have shown that exposure to DBPs increases the risk of respiratory adverse effects and bladder cancer. Association between DBPs and other health effects are still inconclusive. Data gathered in the present review (occurrence, toxicity, and toxicological reference values) could be used in conducting chemical risk assessment studies in swimming pools.

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1. Introduction

Disinfection of drinking water was one of the major public health advances of the twentieth century. The adoption of water chlorination as a standard treatment technique caused a large drop in mortality from infectious disease around the world (Boorman et al., 1999). The efficiency of chlorination in conserving the quality of drinking water from microbiological deterioration has contributed to the extrapolation of its application to include swimming pools and recreational water venues (WHO, 2006). Disinfection of swimming pool water is essential to kill pathogenic microorganisms and prevent outbreaks of infectious diseases (ANSES, 2011). Chlorination represents the most commonly used disinfection treatment in swimming pools (Lakind et al., 2010). Chlorine can be added in the form of compressed chlorine gas, sodium hypochlorite solution (NaOCl), or solid calcium hypochlorite ($Ca(OCl)_2$). Alternative disinfectants include other chlorine-based disinfectants (e.g. chlorine dioxide, stabilized chlorine), chloramines, and ozone. As in drinking water, disinfection of swimming pool water leads to the undesirable formation of disinfection byproducts (DBPs). Evidence from toxicological and epidemiological studies about adverse health effects for DBPs have raised concerns about the chemical safety of swimming pool waters. The first studies investigating the occurrence of DBPs in swimming pools date back to 1980 (Beech et al., 1980; Weil et al., 1980). Since then, many studies have been performed to examine the occurrence of DBPs in pools in different countries (Aggazzotti and Predieri, 1986; Chu and Nieuwenhuijsen, 2002; Judd and Jeffrey, 1995; Kim et al., 2002). Today, after more than 35 years of research, more than 100 DBP have been detected in swimming pools (Chowdhury et al., 2014; Daiber et al., 2016; Richardson et al., 2010; Teo et al., 2015). The formation of DBPs in swimming pool waters is attributed to precursors that can be derived from the filling water as well as from pool users. Human inputs into swimming pools are diverse and include constituents of urine, sweat, rhino-pharyngeal secretions, skin particles, skin lipids (sebum), hair, cosmetics, sunscreens and other personal care products (Keuten et al., 2012, 2014; Kim et al., 2002; Lakind et al., 2010; Richardson et al., 2010; Weisel et al., 2009). Chlorine, mainly in the form of hypochlorous acid and hypochlorite ions, reacts with these organic compounds resulting in the formation of complex mixtures of DBPs. Many classes of DBPs including haloamines, trihalomethanes (THMs), haloacetic acids (HAAs), haloacetonitriles (HANs), halodiacids, haloacetaldehydes (HALs), haloketones (HKs), haloaldehydes, haloamides, halophenols, halobenzoquinones and *N*-nitrosamines, have been identified in swimming pools (Chowdhury et al., 2014; Richardson et al., 2010; Teo et al., 2015; Wang et al., 2013a; Zwiener et al., 2007). However, the continuous inputs of organic loads by swimmers results in the formation of complex mixture of DBPs that have not been identified yet. In drinking water, more than 50% of the halogenated DBP material formed during chlorination are still not accounted for (Krasner et al., 2006; Richardson and Postigo, 2011; Weinberg et al., 2002). Taking into consideration the complexity of anthropogenic inputs, the fraction of unidentified DBPs in swimming pools is even higher (Kim et al., 2002; Lakind et al., 2010; Manasfi et al., 2017b). The following sections present an overview of occurrence data for DBPs in swimming pools, the precursors that have been demonstrated to generate DBPs, and finally the toxicological and human health effects related to the exposure to DBPs.

2. Occurrence of DBPs in swimming pools

In the recent years, many studies have investigated the occurrence of DBPs in swimming pools. The levels and nature of DBPs in swimming pools depend on several factors including the type of disinfectant, characteristics of the pool, pool users' hygiene (Zwiener et al., 2007), use of pools (competition, relaxation, recreational activities) (Weng and Blatchley, 2011; Keuten et al., 2014), and nature of water used to fill the pools whether it is tap water, seawater or even thermal water (ANSES, 2013). Most of the studies analyzing the occurrence of DBPs investigated pools that were filled with municipal (tap) water and treated with chlorine (Teo et al., 2015). Very few studies dealt with pools fed with seawater or with bromide-rich water (Huang et al., 2008; Parinet et al., 2012; Manasfi et al., 2016; Font-Ribera et al., 2016) or with pools treated with bromine for disinfection (Lee et al., 2010; Hoffmann, 2015; Chowdhury et al., 2016). Two recent papers have reviewed the major disinfection by-products that have been commonly reported in chlorinated and brominated swimming pools (Chowdhury et al., 2014; Teo et al., 2015). The detected DBPs included haloamines, THMs, HAAs, haloaldehydes, halonitriles, haloketones (HKs), halonitromethanes, haloamides, haloalcohols, haloacids and other halogenated and non-halogenated DBPs (Chowdhury et al., 2014).

2.1. Haloamines

In terms of occurrence levels, chloramines (or bromamines in bromide-rich waters) are the disinfection by-products detected at the highest levels amongst DBPs, with monochloramine (NH_2Cl) mainly found in water (up to 1180 $\mu g\,L^{-1}$), followed by trichloramine (NCl_3) (up to 800 $\mu g\,L^{-1}$) and dichloramine ($NHCl_2$) (up to 650 $\mu g\,L^{-1}$) (Table 1). Trichloramine, which is four hundred fold more volatile than its two congeners (Chu et al., 2013), is also found in air with levels strongly inversely correlated to ventilation applied in indoor swimming pools (Lévesque et al., 2015; Gérardin et al., 2015). Chloramines are often determined as a global parameter (combined chlorine or total inorganic chloramines) by