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1 Occurrence and formation of disinfection by-products in the 2 swimming pool environment: A critical review

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A B S T R A C T

Disinfection of water for human use is essential to protect against microbial disease; 14
 however, disinfection also leads to formation of disinfection by-products (DBPs), some of 15
 which are of health concern. From a chemical perspective, swimming pools are a complex 16
 matrix, with continual addition of a wide range of natural and anthropogenic chemicals via 17
 filling waters, disinfectant addition, pharmaceuticals and personal care products and 18
 human body excretions. Natural organic matter, trace amounts of DBPs and chlorine or 19
 chloramines may be introduced by the filling water, which is commonly disinfected 20
 distributed drinking water. Chlorine and/or bromine is continually introduced via the 21
 addition of chemical disinfectants to the pool. Human body excretions (sweat, urine and 22
 saliva) and pharmaceuticals and personal care products (sunscreens, cosmetics, hair 23
 products and lotions) are introduced by swimmers. High addition of disinfectant leads to a 24
 high formation of DBPs from reaction of some of the chemicals with the disinfectant. 25
 Swimming pool air is also of concern as volatile DBPs partition into the air above the pool. 26
 The presence of bromine leads to the formation of a wide range of bromo- and bromo/ 27
 chloro-DBPs, and Br-DBPs are more toxic than their chlorinated analogues. This is 28
 particularly important for seawater-filled pools or pools using a bromine-based disinfec- 29
 tant. This review summarises chemical contaminants and DBPs in swimming pool waters, 30
 as well as in the air above pools. Factors that have been found to affect DBP formation in 31
 pools are discussed. The impact of the swimming pool environment on human health is 32
 reviewed. 33

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90 Introduction

92 Swimming pool chemical water quality is currently a topic of
 93 interest, with many studies occurring in both the United
 94 States and Europe. Swimming pool chemical water quality is
 95 of possible public health concern due to the formation of
 96 disinfection by-products (DBPs), where total DBP concentra-
 97 tions have been shown to progressively increase in pools and
 98 spas (up to 610% and 900%, respectively) compared to their
 99 respective filling waters (Daiber et al., 2016). Swimming pool
 100 DBPs are unwanted consequences from the reactions of
 101 components of the swimming pool water and the disinfect-
 102 ant, during the swimming pool disinfection process. There is
 103 an increased potential risk to babies and small children where
 104 the health effects of DBPs may be more pronounced. Uptake of
 105 DBPs are likely increased in children compared to adults due
 106 to higher breathing rates of children (up to twice those of
 107 adults) and their lesser developed gastrointestinal tracts and
 108 blood brain barriers possibly leading to higher absorption of
 109 DBPs (Thompson, 2004). Additionally, children's organs are
 110 not fully developed, particularly the liver and kidneys, which
 111 have been shown to be two to nine times slower in the
 112 breakdown of chemical compounds compared to adults, and,
 113 in combination with immature metabolite breakdown mech-
 114 anisms, may not be able to metabolise and remove DBPs
 115 sufficiently (Thompson, 2004). DBPs in swimming pools have

been potentially linked to several health issues, including
 116 asthma, bladder cancer, liver and kidney issues (Villanueva et
 117 al., 2007; Villanueva and Font-Ribera, 2012). Swimming pool
 118 waters have shown increased genomic DNA damage effects
 119 on Chinese hamster ovary cells than the corresponding filling
 120 water (Liviak et al., 2010b), which is likely due to more than
 121 one mutagen (Honer et al., 1980). Respiratory issues, such as
 122 asthma, wheeze, cough and lower respiratory tract infections,
 123 have been correlated with swimming pool attendance, which
 124 is likely due to chlorinated volatile DBPs, such as chloramines
 125 (Bernard et al., 2006; Ferrari et al., 2011; Jacobs et al., 2007;
 126 Kaydos-Daniels et al., 2008; Rosenman et al., 2015; Uyan et al.,
 127 2009). However, these studies are not conclusive and
 128 Goodman and Hays (2008) suggested that "it is premature to
 129 draw conclusions about the causal link between swimming
 130 and asthma", warranting further investigation of the health
 131 effects of the swimming pool environment. 132

Indoor swimming pools are of particular concern since they
 133 may be more regularly used all year round, and volatile DBPs
 134 can become trapped within the environmental air of indoor
 135 swimming pool complexes. The higher the concentration of
 136 these volatile DBPs in the swimming pool water, the higher
 137 their concentration in the air above the pool. Volatile com-
 138 pounds of potential health concern in the air pose a risk not
 139 only to regular swimmers, but also to regular non-swimmers,
 140 such as swimming pool workers and non-swimming visitors. 141

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