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# The Good, the Bad, and the Volatile: Can We Have Both Healthy Pools and Healthy People?

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Swimming is a healthful activity that comes with increased risk of exposure to pathogenic microorganisms and disinfection agents/byproducts.

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Given the popularity of swimming for recreation and sport, it is remarkable that we are only in the early stages of understanding swimming pool chemistry, human exposure(s), and potential health risks. This is partly due to the complexity of swimming pool water chemistry, which increases with transformations that water undergoes as it moves from its source to pools filled with swimmers (Figure 1). Source waters are variable mixtures containing low levels of hundreds to thousands of chemicals originating from natural and anthropogenic inputs. Source water is then modified by disinfection processes at the water treatment plant. This chemically diverse and continually changing mixture reaches the swimming pool facility where it undergoes major changes due to additional disinfection and swimmer activity. Each pool has a unique set of characteristics that, combined with varying chemistry of source waters, makes characterization of chemistry, toxicity, and exposure an extraordinarily difficult undertaking.

Swimmers themselves complicate pool water chemistry and toxicity by introducing undesirable substances (e.g., skin, bodily excretions such as sweat, urine, and fecal matter; pathogens; and personal care products, such as lotions and sunscreens). This was highlighted recently by a study demonstrating that even with secure swim diapers and swim pants, a large fraction (from about half to almost all) of *Cryptosporidium*-sized particles are released from humans to pool water quickly (within a few minutes); a single "fecal accident" can release 100 million or more parasites (*1*). Because swimming pools are virtual communal baths, disinfection (typically by chlorination) to prevent disease outbreaks is essential. However, the disinfection process itself can introduce hazards by reacting with pool water substances to form disinfection byproducts (DBPs), some of which have been associated with adverse health effects (*2*). Thus swimming can expose people to potential biological and chemical health risks. On the other hand, swimming is an enjoyable, healthful physical activity. We examine three key aspects related to swimming pools and public health: exposure, health effects, and alternative disinfectants.

**Exposure.** Disinfection is critical to protect public health from pathogens in pool water, but can also result in the formation of DBPs.

**Health Effects.** Swimming has many documented health benefits, but some studies have reported adverse health effects from swimming-related DBP exposure.

**Alternative Disinfectants.** Most research on pool disinfection—including disinfectant efficacy, DBP formation, and health risks—has focused on Cl-based disinfectants. (Editor's Note: "Cl-based" here refers to molecules containing chlorine atom[s]; see Box for clarification of chlorine disinfection chemistry.) Other disinfectants are used, but less is known about both their ability to inactivate pathogens and the chemistry and toxicities of the suites of DBPs formed.

In this article, we give an overview of these three topics and describe the long- and short-term measures needed to ensure that we can have both healthy pools and healthy people.

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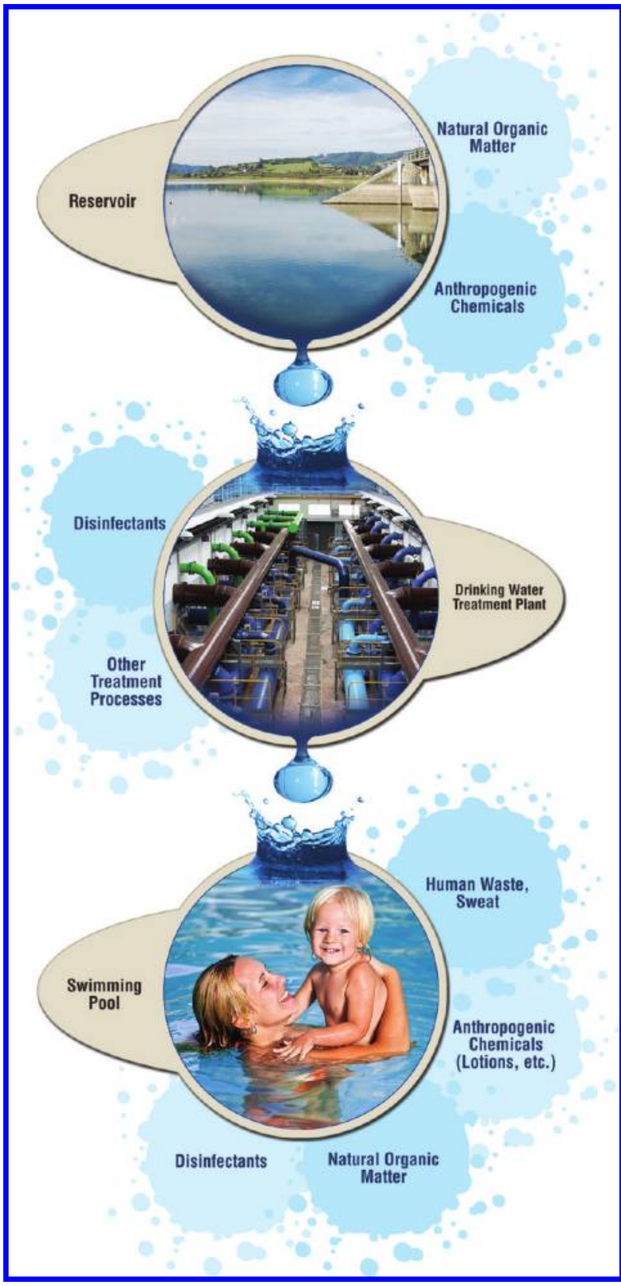


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**FIGURE 1. Water composition changes as it moves from its source to the water treatment plant and then to the swimming pool.**

## Exposure to Pathogens and DBPs

**Pathogens in Pools, or Why We Disinfect in the First Place.** Some of the pathogens identified in pool water include bacteria (*Pseudomonas*, *Shigella*, *E. coli*), viruses (adenovirus, hepatitis A, echovirus), and protozoa (*Cryptosporidium*, *Giardia*) (*3*−*5*). Exposures to these pathogens can result in illnesses, such as dermatitis, conjunctivitis, respiratory infection, nausea, cramps, fever, body aches, fatigue, vomiting, and/or diarrhea. In rare instances, exposure to pathogens in swimming pools can even result in death (*3, 5*). Between 1971 and 2000, >11,000 cases of illness associated with swimming in pools were reported in the U.S. alone (*3*) and these numbers are likely an underestimate of the true number of cases due to unrecognized and unreported outbreaks (*3*).

Inadequate disinfection is a major contributor to disease outbreaks (*3, 4*); most pools (54%) have code violations for water quality, recirculation systems, or pool management (*5*). Given the prevalence of outbreaks and the severity of the illnesses (*6*), it is clear that pool disinfection is a crucial component of public health and safety.

**DBPs in Pools—What We Know (And Don't Know) About Exposures.** The interaction between disinfectants and pool water substances yields a complicated and variable mixture of DBPs that is still only partially understood for chlorine disinfection and less well-understood for other disinfectants. DBPs can be inhaled or ingested during swimming, or absorbed dermally (*7*) and volatile DBPs have been the focus of most swimming pool research to date. Specifically, exposure assessments have focused on two classes of DBPs from Cl-based disinfection (see Box): chloramines and trihalomethanes (THMs).

**Chlorine-based disinfectants frequently used in municipal pools ("chlorine disinfectants" refer to these compounds)** (*8*)

- Chlorine gas ($Cl_2$)
- Sodium or calcium hypochlorite (NaOCl or Ca[OCl]$_2$)
- Chlorinated isocyanurates (e.g., sodium dichloro-s-triazinetrione dihydrate)
- Bromochlorodimethylhydantoin ($C_5H_6BrClN_2O_2$)
- Chlorine dioxide ($ClO_2$) (not used in the U.S.)

Researchers have observed average trichloramine ($NCl_3$) levels in indoor pool air of approximately 0.1−0.7 mg/m$^3$ (*9, 10*). Unfortunately, the common technique for measuring $NCl_3$ (*11*) is not specific (*12*) and both inorganic chloramines (e.g., monochloramine [$NH_2Cl$] and dichloramine [$NHCl_2$]) and some organic chloramines can also contribute to this measurement (*13*). For THMs, research has focused on chloroform ($CHCl_3$) (the most commonly detected THM) in air and water at pools. Indoor pool air mean $CHCl_3$ levels can range from 100 to 200 $\mu$g/m$^3$, with peaks above 300 $\mu$g/m$^3$ (*14*). Mean $CHCl_3$ water levels in indoor pools typically range from 10 to 80 $\mu$g/L (*14*), with occasional higher levels reported. Accurate exposure assessments to THMs (and most likely other DBPs as well) in pool environments are difficult, because DBP formation is impacted by many factors, including total organic content, number of people in the water, and water temperature. Furthermore, DBP levels can vary considerably within a pool. Future exposure assessments will also need to consider changes in DBP formation from alternative disinfectant use. For example, pools treated with a combination of chlorine and ozone ($O_3$) or by electrochemically generated mixed oxidants may produce less $CHCl_3$ (*15*).

In addition to measures of volatiles in water and air, biomonitoring of exhaled air and blood have been used to estimate total exposures (the sum of uptake from oral, dermal, and inhalation routes) associated with swimming. $CHCl_3$ levels in exhaled air have been reported, but exposure interpretation is difficult because of the short physiological half-life of $CHCl_3$ (making it essential that measures be taken at similar times postexposure across studies). Plasma $CHCl_3$ levels have also been measured in swimmers, with one study using this biomonitoring approach to describe changes in blood levels before and after swimming (*16*). To put perspective on exposure to $CHCl_3$ at pools, we can compare blood $CHCl_3$ levels in swimmers to individuals just after showering or bathing. This exercise is useful because studies that have explored health effects associated with THMs in tap water may shed light on health effects and pool exposures. One showering/bathing study (*17*) and a pool study (*16*) reported similar levels of $CHCl_3$ in water and gave water and blood (or plasma) $CHCl_3$ levels for comparison. For swimmers exiting the pool, the water/plasma $CHCl_3$ ratio was approximately 30:1; for showering/bathing 10 min postshower, the water/blood ratio was approximately 600:1. While $CHCl_3$ uptake from swimming appears greater than showering, several limitations and caveats must be recognized: (i) there are limited data on simultaneous water and blood $CHCl_3$ measures; (ii) uptake is dependent on air/water $CHCl_3$ concentrations, exercise intensity and duration, water temperature, physiologic characteristics of individuals (*18*), and number of swimmers in the pool (*16*); (iii) measurement of THMs in blood/plasma can be biased from analytical issues, such as contamination from collection materials and loss from sample handling; (iv) use of blood vs plasma may yield different results, due to loss of volatiles during plasma preparation; and (v) timing of postactivity collection affects blood concentrations and must be consistent for interstudy comparison.

In summary, swimming pool exposure to pathogens is well-documented and varies depending upon swimmer health (i.e., swimmer introduction of infectious agents into the pool water) and hygiene and pool operation and maintenance. In contrast, the published DBP exposure literature includes information on only a few chemicals from a mixture likely comprised of hundreds or thousands of chemicals in swimming pool water and air. While recent studies have sought to expand the database on DBPs in swimming pool air and water, it is clear that a comprehensive exposure assessment for swimming pool DBPs is many years away.

## Swimming Exercise Benefits and DBP Exposure Risks

Health benefits associated with swimming include improvement of asthma symptoms and cardiorespiratory fitness. Health risks studied for their association with swimming in chlorinated pools include asthma, irritation, allergy, and bladder/liver cancer. We provide here a qualitative overview of the reported benefits and risks, as there are insufficient consistent data to conduct a quantitative risk/benefit comparison across these health outcomes.

**Health Benefits with Pool Swimming.** Pediatricians have long recommended swimming exercise for children, particularly for asthmatic children, because of its lower asthmogenicity compared to other forms of exercise (*19*). Possible bases for lower asthmogenicity include lower pollen count over water, higher hydrostatic pressure on the chest, controlled breathing, peripheral vasoconstriction (*19*), and humidity of the air above the pool water (*20*). Research on the effects of swim exercise on asthma symptoms and exercise-induced asthma (EIA) shows mixed results. Some studies report reduction in EIA severity, decrease in emergency room visits/hospitalizations, number of asthma attacks, wheezing days per person, and decrease in asthma medication use, while others report no improvements (*20*–*22*). These discrepancies are likely due to factors such as how well a pool is operated and maintained, type of pool or disinfectant used, asthma medication use, and duration, frequency, and vigor of swim effort (*20*).

The literature on the effects of swimming exercise on aerobic fitness of asthmatics was reviewed by Welsh et al. (*22*), who noted that most, but not all, studies found positive effects of swim training on fitness as measured by improved aerobic efficiency, physical working performance, and recovery heart rates.

**Potential Health Risks from Swimming Pool Disinfection.** Two classes of DBPs have been studied for their association with potential health effects: chloramines (irritation, allergy, asthma) and THMs (bladder/liver cancer). We give an overview of some of the more recent literature to illustrate the complexities and seeming contradictions in these studies.

**Respiratory Effects, Infection, Allergy, Atopic Dermatitis.** Previous studies report an increased incidence of asthma in elite and Olympic swimmers (*23*). Studies on associations between infant and childhood exposure to DBPs in pools and allergic illness, pulmonary integrity, and asthma were conducted by a research group in Belgium (*9, 24, 25*). This culminated in a hypothesis linking human exposure to chlorination DBPs and development/exacerbation of allergic diseases (*9*). These findings, while not always consistent, brought attention to the issue of childhood exposure to DBPs at pools and the potential for adverse respiratory and allergy-related effects, spurring additional research. However, others (e.g., *26*–*28*) have reported mixed results on the relationship between childhood swimming pool attendance and respiratory tract effects, allergies, infection, and atopic dermatitis. These mixed results are possibly due to study design issues (*12, 23*). For example, physical activity may be a confounder in studies of swimming and respiratory effects, as it has been associated with reduced hay fever, bronchial hyperresponsiveness, and asthma development (*27, 29*). Further complicating swimming pool studies is the presence of other variables with the pool environment that can influence respiratory health and infection rates (bacteria, viruses, dampness and molds, and interactions with groups) (*26, 28*).

**Cancer.** A retrospective cancer study (*30*) estimated past THM concentrations using annual average THM levels in treated water. Participants who reported ever swimming in a pool showed an increased risk of bladder cancer. When broken out by lifetime swimming hours and compared to never swimming, the odds ratios were no longer statistically significant. In another study, swimmers' exposure to $CHCl_3$ was determined by measuring air and water $CHCl_3$ concentrations at indoor pools and in exhaled air samples before and after swimming (*31*). Cancer risk was estimated using a physiologically based pharmacokinetic model and laboratory animal cancer tests. The estimated $CHCl_3$ levels in swimmers were approximately 4 orders of magnitude lower than the lowest no-observed-effect-levels for liver tumors in laboratory animals.

In summary, many studies of the effect of swim training with asthmatics and healthy individuals have found various health benefits, including improved aerobic fitness, improved asthma symptoms, and respiratory function. However, most studies did not provide information on pool characteristics, including method of disinfection or pool type (indoor or outdoor pools). In many cases, there is insufficient information in the published literature to distinguish possible effects associated with DBP exposure from other variables, such as swim exercise itself or exposure to irritants and allergens. Cancer and swimming studies are difficult to interpret at this time due to the difficulty in characterizing long-term exposures to DBPs and the lack of information on carcinogenicity of the mixtures in swimming pools, as well as disentangling exposures from swimming and those from showering, bathing, and other activities involving chlorinated tap water.

## Cl-Based Disinfectants Versus Other Types of Disinfectants—the DBPs We Know Versus the DBPs We Don't Know

**Formation of DBPs.** Despite the public health relevance and long history of chemical disinfection for pools, surprisingly little data exist on DBPs in swimming pools. Chlorine is the most popular disinfectant for swimming pools and is the most thoroughly studied. Several researchers have measured THMs and chloramines in chlorinated swimming pools and swimming pool air; a new study reports levels of THMs in chlorinated and ozonated–chlorinated pools (*15*). However, until very recently, there were no comprehensive assessments of DBPs in swimming pool waters beyond these few targeted

DBPs. Zwiener et al. (*32*) and Richardson et al. (*33*) provide a more complete picture of DBP composition of chlorinated outdoor public pools and chlorinated or brominated indoor pools, respectively. A greater number (>100) of DBPs were identified in the indoor pools, including most classes of DBPs found in chlorinated drinking water, but also nitrogen-containing DBPs ("N-DBPs") such as haloamides, halonitriles, haloanilines, haloamines, haloanisoles, and halonitro-compounds. N-DBPs are likely present in pool waters due to nitrogen-containing precursors from swimmers (urine, sweat, etc.).

Other N-DBPs reported in chlorinated swimming pool waters include organic chloramines (*13*), nitrosamines (*34*), and cyanogen chloride and cyanogen bromide (*35*). Chlorate ($ClO_3^-$) (*36*), chlorite ($ClO_2^-$), and bromate ($BrO_3^-$) (*37*) have also been found in chlorinated or ozonated pools. DBPs formed by the reaction of chlorine or bromine with sunscreen ingredients have also been reported (*32*).

Compared with Cl-based disinfectants, almost nothing is known about pool water DBPs from other disinfectants, including bromine-based disinfectants, $O_3$, copper/silver (Cu/Ag), and UV disinfection. UV disinfection, when used prior to chlorination for drinking water, can increase halogenated DBP levels, presumably through changes to the natural organic matter making it more reactive with chlorine (*38*).

**Toxicity of DBPs.** Very limited toxicological data exist for pool DBPs. Most DBPs studied for toxicity are formed by chlorination of drinking water; less is known about DBPs from other disinfectants and for pool water. Chlorinated swimming pool extracts can be mutagenic in *Salmonella* (*39*) and can induce DNA damage in Hep-G2 cells (comet assay) (*40*). DBPs found in pool water that have some or all of the toxicological characteristics of human carcinogens include bromodichloromethane ($CHBrCl_2$), dichloroacetic acid ($CHCl_2COOH$), dibromoacetic acid ($CHBr_2COOH$), $BrO_3^-$, and nitrosodimethylamine ($[CH_3]_2NNO$, NDMA) (*2*). Chloral hydrate ($CCl_3CH[OH]_2$) also causes cancer (liver) in rodents (*2*).

Other DBPs found in pool waters are highly genotoxic or cytotoxic in in vitro assays. In general, N-DBPs are more genotoxic or cytotoxic than those without nitrogen (*2*). Similarly, DBPs containing Br or iodine (I) are more genotoxic than those containing Cl only (*2*). Brominated DBPs can be activated to mutagens in the body by the enzyme glutathione S-transferase-theta-1 (GSTT1-1), and a recent study found higher bladder cancer risks for people expressing GSTT1-1, suggesting that genetic susceptibility may play a role in DBP toxicity (*41*).

**Efficacy — What Do We Know About Inactivation of Important Pathogens by Pool Disinfectants?** In selecting a pool disinfectant, we must consider not only the types of DBPs formed, but whether the disinfectant can inactivate — quickly and completely — pathogens associated with illness. As with other aspects of swimming pools and health, research on disinfectant efficacy appears to be in its infancy. For example, minimal information is available for pool disinfection of pathogens of public concern, e.g., HIV, H1N1 (swine flu) (*42*). Disinfectant times for fecal contaminants in chlorinated pools range from <1 min for *E. coli* O157:H7 to 10.6 days for *Cryptosporidium* (*43*). Some efficacy data are available for other disinfectants in drinking water, but it is not clear whether these apply to pool situations.

## What We Need To Do in the Long-Term to Improve the Swimming Pool Environment

**Pathogens and Adverse Health Effects.** The U.S. does not have uniform standards for design, construction, operation, and maintenance of pools, and requirements for preventing and responding to recreational water illnesses vary across localities. The U.S. Centers for Disease Control and Prevention (CDC) is in the process of developing a Model Aquatic Health Code (*44*) to address this issue and to promote healthy pools and healthy people.

**DBPs and Adverse Health Effects.** Most studies exploring relationships between swimming and adverse health effects are cross-sectional and have raised as many questions as they have answered. Large-scale prospective studies are needed to fill data gaps spanning the areas of diagnosis, chemical/biologic measurements, human exposure patterns, and pool operation/maintenance (*12*). Detailed recommendations for evaluating potential health hazards from swimming pools were given by Weisel et al. (*12*). This type of research is essential, but may take years to definitively answer questions about DBPs, exposure, and health.

## What We Can Do Now to Have Both Healthy Pools and Healthy People

Given the multifactorial nature of health effects that may be associated with swimming in disinfected pools, the diverse mixtures of chemicals formed in pool environments, and the time and resources that will be required to fully elucidate associations between pool environments and potential health effects, it would seem at first blush that in the near future we will not have the knowledge base with which to understand how to simultaneously have healthy pools and healthy people (i.e., by reducing exposure to both pathogens *and* DBPs). However, this is not the case. While we may not have complete understanding of the chemistry, exposures, and toxicities associated with swimming pool disinfection and DBPs, we do understand some of the underlying causes of unwanted DBP formation and unnecessarily high exposures, and these can be mitigated before all of the scientific explorations are completed. The near-term solutions will require the cooperation of both aquatic facilities staff and the swimming public.

**Pool Operators.** Pool disinfection is essential to preventing exposure to pathogens; proper disinfectant use along with known engineering solutions can reduce DBP formation. Shortcomings related to pool operation and maintenance include lack of standardized training for pool staff, lack of national certification of aquatic staff, poor record keeping on pool maintenance, poor monitoring of pool quality, and lack of knowledge on how to respond to maintenance lapses (*5*). Inadequate disinfection and nonuniform water quality standards also contribute to disease outbreaks (*4*). Training should also include how to address pools contaminated with diarrheal fecal matter, vomit, or blood (resources and recommendations available at ref *45*).

**The Swimming Public.** The public must get past its acceptance of poor pool hygiene. For example, in the U.S., with limited hygiene requirements before and during swimming, there is a culture that seems to humorously "celebrate" using the pool as a urinal. There is ample anecdotal evidence that children and young adults on swim teams are discouraged from taking bathroom breaks while training. A YMCA in New Jersey notes: "When possible please use the restroom before class. *Bathroom breaks disrupt the flow of the class* [emphasis added]" (*46*).

Fecal contamination from diarrheal illness and diaper leakage contribute to the fecal load in pools and the need for higher levels of disinfectants. Public education is needed regarding the immediate reporting of fecal incidents to pool operators and refraining from swimming while ill or while recovering from diarrheal illness. Showering before swimming should be required to reduce organic loading to pools (*3*); a 17 s shower can reduce a bather's contamination of a pool by 35–60% (*47*), thereby reducing the amount of disinfectant needed and the levels of DBPs.

The public mindset must be changed; swimmers may be open to modifying their behaviors once they become aware of the health risks associated with unhygienic practices (*6*). Substantial investments into education and outreach will be necessary to effect these changes. By improving disinfection practices and reducing the input of contaminants—both chemical and biological—we can achieve our goal of healthier pools and healthier people.

*Judy S. LaKind, Ph.D., president of LaKind Associates, LLC, associate professor, University of Maryland School of Medicine, and adjunct associate professor, Penn State College of Medicine, is a health and environmental scientist with expertise in strategic risk management and assessment of human health risks. Dr. LaKind's recent research has addressed the uses and interpretation of biomonitoring information and children's environmental health issues. Susan D. Richardson, Ph.D., is a research chemist at the U.S. EPA's National Exposure Research Laboratory in Athens, GA. Her research has focused on the identification, characterization, and quantification of new disinfection byproduct (DBPs), with an emphasis on alternative disinfectants. She is particularly interested in promoting new health effects research so that the risks of DBPs can be determined and minimized. Benjamin C. Blount, Ph.D., Chief of the Perchlorate and Volatile Chemical Biomonitoring Laboratory at the CDC, is an analytical biochemist with expertise in measuring biomarkers of human exposure to environmental toxicants. Dr. Blount has published extensively on environmental exposure issues, including water-related chemical exposures. Please address correspondence regarding this manuscript to lakindassoc@comcast.net.*

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