Evaluation of the Effectiveness and Issues of Different Swimming Pool Disinfection Processes

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Produced by Dr Simon Toze, Urban Water Futures for Enviroswim.

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Introduction

Swimming pools provide a favourite recreational activity in Australia with many homes having private pools and/or spas as well as most councils and many accommodation facilities providing swimming pool facilities.

Roy Morgan estimated that in 2018 that there were 920,000 domestic pools in Australia. This does not include the many commercial and public pools and spas run by local councils, hotels and resorts, and gymnasiums (Roy Morgan, 2018).

All pools and spas need to be properly maintained to ensure the water quality is an appropriate high standard to protect human health and water aesthetics. This is particularly important for pools with broader community access due to the number of different people of varying ages and health conditions potentially using these pools.

The water in pools and spas is commonly treated by a combination of filtration and disinfection. Disinfection processes can vary depending on the size and use of the pools, however, by far the most common disinfectant used are chlorine-based compounds.

This paper provides information from the scientific literature on the history of swimming pool disinfection, the health risks posed by microbial pathogens and chemical contaminants and investigates the benefits and issues relating to the different disinfection options available to swimming pool owners and operators.

Pool and spa treatment and disinfection requirements

While pools for bathing have been in exisiting since the antiquities, the use of swimming pools for exercise and recreation gained broad popularity in the 20th century. Pre the 1920's, swimming pools were not disinfected and primarily relied on filtration to maintain water quality (Olsen 2007). In the decades preceding, technological and scientific advances was showing that untreated water was a high risk for diseases caused by pathogens in the water. This led to investigations into the mechanisms that would efficiently remove these pathogens from water, in particular drinking water.

The disinfection of water was shown to be a major need to achieve reductions in the rocks from waterborne diseases. A range of disinfection processes including different chemicals that could act on the pathogens, ozonation and UV light were investigated in these early years, however, the abundant supply of chlorine, which was recognised for it's strong oxidative potential in water, made chlorine-based chemicals become the preferred disinfectant for many water treatment processes (Olsen 2007). More recently, however, due to increasing concerns about the health impacts of chlorine and disinfection by-products produced by the disinfection process, several alternative disinfection mechanisms have become more widely tested and used.

Compared to drinking water, swimming pools are much more dynamic environments, and the quality of the water can be impacted by a range of factor including location, climate and temperature, bather load and bather hygiene (Carter and Joll, 2017). This means that there needs to be care and attention to maintaining appropriate pool water quality including the use and maintenance of adequate disinfection. In Australia, all States have guidelines pertaining to the maintenance and operation of swimming pools and spas (ACT, 1999; Northern Territory, 2006; NSW 2013; Queensland, 2019; South Australia, 2013; Victoria, 2020; Western Australia, 2015). Much of detail in these regulations focus on commercial level swimming pools as these have much higher bathing loads than personal swimming pools, however the information provided is pertinent to private pools as well. These regulations focus on water quality requirements as well as demonstration of the removal of microbial pathogens and other contaminants. There is reference to chlorine-based disinfectant as these are the most commonly used disinfectants, but all the regulations note that there are possible alternative disinfection processes available either to chlorine or as a supplement to chlorine.

The Australian Pesticides and Veterinary Medicines Association (2014) regulates the chemicals used for pool and spa disinfection systems and lists the disinfection capability required for different microbial pathogens. For approval, any disinfection system must demonstrate the capacity to able to reduce a pre-determined number of recommended test organisms within a specific duration of time (the time varies depending on the type of microorganism). The disinfection system also must be able to maintain a constant, measurable residual in the water that is effective against harmful microorganisms introduced into the water.

Microbial Pathogen Risks for Swimming Pools and Spas.

The most common microorganisms of concern are the enteric microorganisms that can be excreted by infected individuals bathing in the pool. This can either be in the form of small numbers shed from the skin of carriers of these microorganisms through to accidental faecal releases by infected bathers. Thus, the numbers of microbial pathogens in a swimming pool can vary from very low from diffuse shedding through to high numbers from accidental releases. Other possible sources of harmful microorganisms are animals that can gain access to pools, in particular birds such as waterfowl. This is more likely to be a problem for outdoor pools than indoor pools. Birds and animals are mostly likely to add zoonotic pathogens (those pathogens which can infect both animals and humans), predominantly pathogenic bacteria and protozoa via defecation to the water.

The other sources of pathogenic microorganisms are those that are commonly exist in water sources as part of the natural microbial population but have the capacity to cause infection and disease if they come in contact with a susceptible individual, usually young children, elderly and those with weakened immune systems. Opportunistic pathogens are bacteria such as Legionella and Pseudomonas as well as Protozoa such as Acanthamoeba. While a much less risk for healthy individuals, maintaining good pool water quality and appropriate disinfection levels is important to keep these opportunistic pathogens under control as they are more adapt at thriving and increasing in number in poor quality water than introduced pathogens shed by infected individuals.

Enteric microorganisms of concern can be bacteria, viruses, or protozoa. Examples of the most common pathogens are given in Table 1.

- Treatment resistance;
- Numbers in pool water after contamination event or reductions in pool quality;
- Infection risk.

The larger microbial pathogens, in particular protozoa such as *Cryptosporidium* and *Giardia* can be removed from the water by filtration. Filtration, however, is not a guaranteed process for complete removal of protozoa and is very inefficient in removing smaller pathogens, in particular viruses from the water column. In addition, filtration can only remove pathogens from water and is not an active process in killing or inactivating pathogens. This means that even large pathogens such as protozoa could potentially break through the filtration process and renter the pool water. Thus, disinfection remains an important process for maintaining the quality of the pool water and protecting the health of bathers.

Table 1. Examples of microbial pathogens that can be present in pool water.

Pathogen Type	Example pathogens[1]	Numbers (/g faeces[2] or /L of water[3])	Infection risk[2]	Treatment resistance[2]
Bacteria	*E. coli* O157	10^8	Low	Low
	Salmonella	10^6	Low	Low
	Campylobacter	10^6	Moderate	Low
	Legionella[2]	$10\text{-}10^3$	Low	Moderate
Virus	Adenovirus	10^{10}	High	Moderate
	Norovirus	10^{11}	High	Moderate
	Enterovirus	10^6	High	Moderate
Protozoa	*Cryptosporidium*	10^6 - 10^7	High	Very High
	Giardia	10^6	High	High

[1] The pathogens listed below are not an exhaustive list of the pathogens that could be present in pool water.

[2] It has been calculated that an accidental release of faeces from an individual has been estimated to be a mean of 0.14/g per shedding event (Gerba, 2000)

[3] Legionella is an opportunistic pathogen commonly found in fresh water and is capable of replicating in water sources. It is not excreted in the faeces of infected individuals. Numbers are usually low but can increase in poorly maintained water.

[3] The risk of infection is the likelihood to become infective after contact with pathogens. A high infection risk means a high probability of becoming infected after contact with low numbers of the pathogen. A low infection risk where, in general, infection is more likely to occur only after contact with high numbers of a pathogen. Infection risk can also vary between strains of the same pathogen.

[4] The resistance of different pathogens to treatment can vary between different forms of disinfection.

Bacteria in pools

The presence and risks of bacteria in swimming pools were the first to be recognised as a problem for swimming pool water. This is due to the fact that bacteria are living, metabolically active microorganisms and therefore were already well known and studied long before viruses and protozoa were known to be sources of health risks. Additionally, culture and detection methodologies for non-bacterial pathogens were much more difficult making detecting viruses and protozoa in environmental samples such as pool water much more problematic.

Journal reports of the concerns regarding bacteria in swimming pools date back to the early 20th century (Stokes, 1927; France and Fuller, 1940; Mood, 1950). Bacteria commonly detected in these early studies included *E. coli*, *Streptococcus* species, *Staphylococcus aureus* and several species of *Pseudomonas* (France and Fuller, 1940). Some of these bacteria are often enteric in origin, however, others such as *Staphylococcus* and *Pseudomonas* can come from the skin and mucosal membranes of bathers (Bartram, 2006).

Much of the initial studies on bacteria in swimming pool water focused on determining if there was a specific group of bacteria that could be used as an efficient indicator of pool water quality. As the coliforms were the most common used from drinking water at that time there was consideration that they may be useful for swimming pools as well. However, the different dynamics of pools being enclosed systems with frequent different people bathing in the pool meant that pools were found to be different environments to drinking water systems. For example, France and Fuller (1940) found that streptococci were able to be routinely detected in pool water in the absence of coliforms when the chlorine residual was between 0.3 and 0.6 mg/L, leading them to suggest that streptococci could be a better indicator of pool water quality than coliforms.

More recent studies have continued to show that indicator and of-concern bacteria can be detected in swimming pools despite disinfection measures. The majority of studies have focused on the detection of indicator bacteria, notably *E. coli*, *Pseudomonas aeruginosa* and streptococci (Reyes-Batlle et al., 2020; Millis et al., 1981; Lerman et al., 1993; Wei et al., 2018). While *E. coli* is commonly a commensal, non-pathogenic bacteria used as an indicator organism, with the possession of appropriate additional genetic virulence factors, this bacterium can become pathogenic. A common pathogenic strain of *E. coli* (O157:H7) has been implicated in 7 outbreaks in swimming pools in the USA between 1982 and 2002 (Rangel et al., 2005). Recorded incidences of disease caused by other pathogenic bacteria in swimming pools are less common but have included *Campylobacter jejuni* and Shigella sonnei (Barna and Kádár, 2012).

As well as pathogenic bacteria coming from bathers, either from faecal contamination or from skin and mucosal excretions, swimming pools can harbour bacteria that can be opportunistic pathogens under appropriate conditions. The most common opportunistic pathogens detected are *Pseudomonas aeruginosa*, *Legionella* spp. and non-tubercular mycobacteria (MAC) (Leoni et al., 1999; Leoni et al., 2001; Firuzi et al., 2020). Such opportunistic pathogens can be commonly detected in water and soil sources (i.e., they may not be of human or animal origin) and are normally present a very low health risk to health bathers. Under conditions that can enable these bacteria to flourish, however, for example less than optimal disinfection processes, they can present a high health risk hazard, especially for people with weakened immune systems (Roser et al., 2014; Gamage et al., 2021). Even in pools that have active disinfection, such opportunistic pathogens can be more resistant to disinfection than bacteria that originate from bathers (Snelling et al., 2006; Donohue et al., 2019). While the vegetative cells of such opportunistic pathogens present in the water may still be effectively removed by disinfectants such as chlorine, even if slower than bacteria shed by bathers, these opportunistic pathogenic bacteria can be difficult to completely remove due to their ability to integrate into biofilms or within free living protozoa. Such actions (integration into biofilms or residing within host protozoa) can protect these bacteria from biocidal action of most disinfectants (Snelling et al., 2006; Nisar et al., 2020; Grobe et al., 2001; Goeres et al., 2004).

Viruses in pools

Viruses are very small pathogens shed by infected bathers into pool water. Most viruses of concern that could be present in swimming pool water are faecal in origin and released into the pool water via accidental dedication events (even if very small amounts released) by infected individuals. Viruses are obligate intercellular pathogens which means that they require a host to replicate and thus, cannot multiply in the environment. In addition, most viruses are species specific, which means that viruses that pose a health risk in pools originate from bathers. Due to their extremely small size (<100 nm in diameter), viruses are not effectively removed via mechanical treatment processes such as filtration and thus disinfection processes are the only effective means of controlling the risks from viruses in pools.

Apart from those viruses that are enteric in origin there are also a smaller number of viruses that may also be shed via skin infections (e.g., the papillomaviruses that can cause warts). Sinclair et al. (2009) examined the incidences of worldwide viral outbreaks in recreational waters with 49% of cases being linked to swimming pools. They also found that all of the reviewed cases were from enteric viruses with noroviruses being the leading cause of outbreaks followed by adenoviruses, and then enteroviruses and hepatitis A virus. Bonadonna and La Rosa (2019) also undertook a literature review of viral outbreaks associated with swimming pools. They found that there were cases of viral infections from swimming pools reported from numerous countries across the globe with the causative agents all being enteric in origin. They also reported that detection of viruses in chlorinated pool water often occurred in the absence of detection of indicator bacteria such as faecal coliforms. This demonstrated the higher resistance to disinfection (all chlorine based in this report) of these viruses than bacteria.

La Rosa et al. (2015) tested outdoor and indoor pools in Italy for the presence of a range of enteric and non-enteric viruses. In this study they were unable to detect any enteric viruses but detected human papillomaviruses (HPV) and polyomaviruses in 64% of the samples tested, indicating that these non-enteric viruses are being frequently discharged into pool water from non-faecal excretions. All but one of the pool samples had free chlorine levels above 1mg/L at the time of sampling. No indicator bacteria or *Staphylococcus aureus* were detected in any of these tested samples, again suggesting that such viruses have higher potential resistance to swimming pool disinfection processes. All the viral detections in this study were via molecular methods however, therefore, the infectivity of the viruses detected remains unknown. More HPV and polyomavirus detections occurred from samples collected from indoor swimming pools than outdoor pools.

A comparison of the relative resistance of adenovirus, norovirus, and human polyomavirus to 2.5 mg/L chlorine in seawater found that polyomavirus was the most resistant with between 1-1.5 log reductions after 30 minutes contact with chlorine (de Abreu Corrêa et al., 2012). In comparison, they found that adenovirus had 2.6-2.7 log reduction and norovirus 2.5-3.5 log reduction under the same conditions. Kahler et al. (2010) investigated chlorine inactivation of a number of enteric viruses in lake and river waters. They found that at pH 7, 15 °C and 0.2 mg/L free chlorine, norovirus had the overall highest susceptibility across all the water types with a 3-log reduction of 6 seconds or less. The next most suspectable was human adenovirus (18 seconds or less) followed by the two enteroviruses (coxsackievirus and echovirus) with coxsackievirus the most resistant of the viruses tested with a requirement of up to 10 minutes for a 3-log reduction at pH 7, 15 °C and 0.2 mg/L free chlorine. It was also noted that water quality could influence the times for a 3 log reduction times and characteristics (i.e., first or second order decay). These studies all show that different viruses can vary in their resistance to chlorine-based disinfection methods but generally are sensitive to ozone and UV disinfection. The exception is adenovirus which is recognised to have a higher resistance to UV irradiation than other viruses and most non-viral pathogens.

Protozoa in pools

The two protozoan pathogens most frequently detected in swimming pools are *Giardia lamblia* and *Cryptosporidium pavum*. Both Protozoa are excreted in the faeces of infected individuals in the form of cysts (*Giardia*) or oocysts (*Cryptosporidium*). These (oo)cysts contain dormant trophozoites and are known to be resistant to many environmental conditions. The trophozoites within the (oo)cysts remain dormant until ingested by a new host where they then exist the (oo)cyst and infect the new host. As such, like viruses, they are incapable of replicating in environmental sources and need a host in which to reproduce.

Cryptosporidium is of particular concern due to the high resistance of the oocyst to environmental conditions and is particularly noted for its resistance to disinfectants such as chlorine. Carpenter et al. (1999) found that *C. parvum* oocysts remained infective after exposure to 2 ppm chlorine for at least 24 hours and for at least 3 hours with exposure to 10 ppm chlorine at 20 °C under simulated pool conditions. They also showed that under these simulated conditions, the addition of faecal material to the model pool caused the oocysts to remained infectious even after exposure 10 ppm chlorine for 72 hours (3 days).

A review by Lu et al. (2013) listed numerous reported incidences of cryptosporidiosis across multiple countries with reported incidences of cryptosporidiosis being most common in the warmer summer months. In Australia alone, 41 of 42 cases of gastroenteritis linked to swimming pools were caused by *Cryptosporidium* (Dale et al., 2010). An in-depth analysis of cryptosporidiosis cases in Western Australia found that there were several species of *Cryptosporidium* linked to cases of cryptosporidiosis from swimming pools apart from the most common cause, *C. parvum*, with pool linked gastroenteritis cases also linked to *C. hominis*, *C. meleagridis* and *C. fayeri* (Braima et al., 2021).

It was also observed that while drinking water systems are often well designed to remove the risk from *Cryptosporidium*, similar control and removal performances were not as likely due to the materials from bathers being in constant circulation in the pool reducing effective removal (Lu et al., 2013). Because of the chlorine resistance of *Cryptosporidium* many swimming pools rely on filtration for primary defence against this protozoan pathogen. Due to the small size of the oocysts, however, common sand filters may be less suitable for removal of such small particles (Wood et al., 2019).

Ozone and UV are disinfectant mechanisms that are more effective against *Cryptosporidium* (Lu et al., 2013; Wood et al., 2019), however neither leave long term residuals that would inactivate oocysts in the pool environment prior to the filtration and disinfection system. Using chlorine to create a residual will not be effective for any *Cryptosporidium* oocysts in the main pool environment.

Giardia is the other predominant protozoa that can cause of gastroenteritis from swimming pools. For example, in 2003-2004, *Giardia* was the identified responsible agent for 5.6% of the outbreaks associated with swimming venues in the USA (compared to 55.6% caused by *Cryptosporidium*) (Shields et al., 2008). The presence of *Giardia* in swimming pools has also been reported in the Netherlands (Schet et al., 2004).

Giardia cysts are also considered resistant to chlorine, although not as resistant as *Cryptosporidium* oocysts. Rice et al. (1982) found that 5-10% of *Giardia* cysts were still capable of excystation within 10 minutes of contact with 2.5 mg/L chlorine at 5°C and Rubin et al. (1989) found that it took up to 168 minutes of exposure to 1.44 mg/L at 15 °C to achieve a 2-log (99%) of *Giardia* cysts to became uninfectious. Both studies (Rice et al., 1982 & Rubin et al. 1989), however, were undertaken in chlorine-demand-free buffer which maintains a constant chlorine level better than could be achieved under real world pool conditions. In addition, water temperatures of 5 °C and 15 °C are not representative of common pool bathing temperatures in most countries. Jarroll et al. (1981) did test the influence of chlorine on *Giardia* cysts at a range of temperatures and pHs and determined that greater than 99% of cysts were unable to excyst after 30 minutes of contact with 1.5 mg/L chlorine at 25 °C and a pH of 7. Again. the study by Jarroll et al. (1981) was undertaken in buffer, not pool water, thus was undertaken in optimal conditions for chlorine to have an effect on the *Giardia* cysts. Another point for noting between these three studies is that the study by Rubin et al. (1989) used infection of Gerbils as an indication of the impact of chloring on *Giardia* cysts, while the studies of Rice et al. (1982) and Jarroll et al. (1981) used excystation as a measure of cyst inactivation, making comparisons between the three studies less than ideal.

Disinfection processes

The role of disinfection in swimming pools is to remove any microorganisms that could pose a health risk (pathogens) to bathers using the pool. Disinfection needs to be able to not only kill any pathogens in swimming pool water, but also act against pathogens that are present in biofilms and trapped within filtration material (Bertram, 2006). Available disinfectants vary in the mode of killing or inactivating microbial pathogens with each type of disinfectant having pros and cons on their suitability for use in swimming pools. In addition, disinfectants should not be considered the sole barrier against microbial pathogens, but as a part of a larger water treatment system, including filtration, pH control etc., that maintains a high quality of water regardless of the level of use and surrounding conditions (Bertram, 2006).

Chlorine

The most common disinfectants used in pools and spas are the halide based disinfectant compounds chlorine and bromine. Halide compounds are powerful oxidisers that inactivate or kill microorganisms by oxidising the lipid and proteins in microbial cell walls of bacteria and protozoa or affecting the structural integrity the proteins in viral capsids (Abad et al., 1993). Once able to penetrate cell walls halides can enter microbial cells and degrade intercellular enzymes and proteins. Chlorine is by far the most common form of halide disinfectant and usually used in form of chlorine gas, sodium or calcium hypochlorite or chlorinated isocyanurates (Bartram, 2006). The concertation of chlorine to be used in pools is commonly set by local regulations which can vary from 0.5 -2 mg/L.

Chlorine has been used as the major disinfectant of water since first used in England and Germany in the 1890s with the use of chloride of lime (McGuire, 2013) and directly in drinking water plants such as Reading England which started the use of chlorine for routine water treatment in 1910 (The Institute of Water Engineers, 1954). At the turn of the 19th to 20th centuries, there was increasing demand for a range of chemicals for industrial uses including sodium hydroxide (Olsen, 2007). A by-produce of the production of sodium hydroxide was chlorine gas. Some of this chlorine gas was turned into bleaching powders, but the strong demand for alkaline solutions meant that there was an oversupply of chlorine looking for a market. One of these markets was for the disinfection of water, which meant that disinfection by chlorine became significantly cheaper than any other disinfection process on the market (Olsen, 2007).

Following on from the disinfection of drinking water systems, it was recognised in the early 1920s and 1930s that water in swimming pools could be of a less than ideal quality, particularly following heavy bather use (France and Fuller, 1940; Moody, 1945). With chlorine becoming the preferred disinfection process for many drinking water sources, much of the development of swimming pool disinfection processes was easily achieved by modifying what was already developed for drinking water systems (Olsen 2007). Since the 1930’s, chlorine has become the major disinfection process used for pools across most nations and remains the mainstay of regulations by most countries.

Since these early investigations on appropriate maintenance of swimming pools, a large majority of pools, both commercial and private, have settled on the use of chlorine as the main disinfectant.

There are a number of research papers in the literature that provide information on the role and efficacy of chlorine on killing or inactivating microbial pathogens, many of which inform the generation of guidelines by different nations. Almost all these research papers are based on laboratory studies. These laboratory-based assessments of the ability of different forms of chlorine to inactivate different types of microorganisms test the target microorganisms in chlorine demand free buffer at defined pH and temperatures. This provides a CT value for chlorine-based disinfectants under ideal conditions, but does not provide information on how well these disinfectants operate under real world conditions such as swimming pools. Chlorine-based disinfectants can be impacted by conditions in the pool and spa. Pool and Spa temperature and pH are amongst the most common impacts that can affect the treatment capacity of disinfectants. Production of chlorine-based disinfection products increases with increasing water temperature.

Swimming pools and spas are also dynamic environments with nutrients and other contaminants coming from the surrounding environment (dirt, vegetation, and even faecal matter from wildlife). Organics can also come from people using the pools, including urine, sweat and body oils, sunscreen, personal care products and faecal matter. These organic contaminants can interact with chlorine disinfectants reducing the concentration of free chlorine in the water. This necessitates continual careful balancing of disinfectant and pH levels, particularly in heavily used community pools and spas (Berg et al., 2019). For example, De Laat et al. (2001) studied the effect of urea from urine released into swimming pools on chlorine concentrations. They determined that urea could contribute up to 6.3% of the total organic carbon in pool water which could increase the chlorine demand in these pools through the production of disinfection byproducts such as chloramines.

Maintaining an appropriate pH is also very important for the effectiveness of chlorine as the disinfection efficacy for chlorine compounds changes with pH with the most effective disinfection occurring between 7.2 and 7.8 (Bertram, 2006). With swimming pools being dynamic environments, maintaining an appropriate pH can be difficult. A CDC surveillance of swimming pools across five different states in the USA found a large number of detected violations in pool water quality were related to inappropriate pH levels (Sinclair et al., 2009). A number of these infractions were in pools which could be considered to have high organic loads, for example, children's wading pools.

The data of the effectiveness of chlorine rarely takes into account the complex environment of actual swimming pools, particularly those with multiple uses and large variations in user loads. Swimming pools have been recorded to continue to be a source of waterborne disease outbreaks. Bartram (2006) listed several reported waterborne outbreaks from swimming pools. Most of the recorded outbreaks listed were from enteric viruses or the protozoa *Giardia* or *Cryptosporidium*. All the reported viral and Giardia outbreaks apart from one caused by Echovirus and one Giardia caused outbreak were a result of inadequate or malfunctioning chlorination (Bartram, 2006). In comparison, at least eight of the 20 reported Cryptosporidium caused outbreaks occurred in swimming pools with adequate treatment in place. Podewils et al. (2007) traced an outbreak of Norovirus illness back to a swimming pool which had failure of the chlorine dosing equipment and poor training of the pool operators to identify and deal with such equipment failures. Even enteric sourced bacteria that are commonly sensitive to chlorine have been documented to cause outbreaks due to poorly operated facilities that fail to maintain a suitable chlorine concentration (Castor and Beach, 2004).

In a more recent study of the influences on swimming pool quality in Iran, Firuzi et al. (2020) found one instance of the presence of both faecal coliforms and faecal streptococci in a chlorinated swimming pool (out of six sample events). This detection coincided with maximum swimmer load in the pool during summer. The monitored chlorine residual for this sample was 0.5 mg/L which was below the Iranian standards of 1-3 mg/L, indicating that the high user load had decreased the concentration of free chlorine in the pool, reducing the disinfection capability.

An additional influence on the disinfectant capability of chlorine is exposure to sunlight which can lead to increased photodegradation of chlorine disinfectants. To counteract this photodegradation the addition of Cyanuric Acid is commonly used to photo stabilise the chlorine disinfectant. Cyanuric Acid acts as a stabiliser by forming weak bonds with chlorine. This bond formation does reduce the availability of free chlorine and thus reduce the disinfection capability of chlorine doses in pools requiring high chlorine levels than pools not dosed with Cyanuric Acid (Bartram 2006). As a result, it is recommended that indoor pools that are no exposed to sunlight are not dosed with chlorine stabilisers (Bartram, 2006).

There have been several reported research studies that have documented the influence of cyanuric acid on the disinfection capability of chlorine. Shields et al. (2009) studied the addition of 50 mg/L cyanuric acid and 20 mg/L free chlorine into beakers containing chlorine demand free water seeded with *Cryptosporidium parvum* oocysts (simulating hyperchlorination conditions). They found that the combination of cyanuric acid with chlorine resulted in only a 0.7-log reduction in the viability of the oocysts within a 10-hour period compared to a 3.7-log reduction in the same time period in the absence of cyanuric acid. Such a decrease in disinfection capability would be a cause for concern for a pathogen such as *Cryptosporidium* which is already highly resistant to chlorination. These experiments undertaken determined that it would require exposure of *Cryptosporidium* oocysts to 40 mg/L free chlorine in the presence of 50 mg/L cyanuric acid for 28 hours to achieve a 3-log reduction in oocysts (Shields et al. 2009).

Similarly, Yamahita et al (1988) found that 30 mg/L cyanuric acid could reduce the 3-log reduction time (99.9% inactivation) of ten different enteroviruses and two adenoviruses in the presence of 0.5 mg/L free chlorine by between 4.8 and 28.8 times. Examples of these increased 3-log reduction times included a shift from 1.4 minutes to 30.2 minutes for coxsackievirus B3 and 0.12 minutes to 2.1 minutes for Adenovirus 3. The study by Yamahita et al. (1988) was undertaken in chlorine demand free buffer, thus decreases in the effect of chlorine of viruses be even higher under real world pool conditions with other factors compounding the reduced influence of chlorine. Saita et al. (1998) found that in a study of the influence of cyanuric acid on free chlorine for the reduction of Poliovirus that increasing concentrations of cyanuric acid increasingly decreased the effect of 0.4 mg/L chlorine despite the amounts of free chlorine remaining nearly constant. Golaszewki and Seux (1994) noted that the presence of isocyanuric acid in the laboratory under temperatures common in swimming pools could influence the amount of available free chlorine and thus the inactivation rate of *Pseudomonas aeruginosa*, *Staphylococcus aureus* and *Streptococcus faecalis*. They noted that this was a particular issue with excess concentrations of isocyanuric acid.

While chlorine is the most common disinfectant used for swimming pools, it is well documented that chlorine in pools can cause impacts on bathers using the pools. The biggest health concern associated with the use of chlorine as a disinfectant is the formation of chlorine-based disinfection by products (Couto et al., 2021) (discussed in detail below). As well as potential chronic health impacts from disinfection by products, chlorine has been documented to cause eye and mucous membrane irritation (Bartram, 2006), skin irritation (Kelsall and Sim, 2010) and respiratory effects (Nemery, et al., 2002). Many of these chlorine related effects on bathers are influenced by the concentration of chlorine in the pool water. Chlorine concentration may be high or increased to deal with high bather load to reduce the potential reduction in disinfection capacity to remove pathogenic microorganisms, but inadvertently increase unwanted effects on bathers.

Bromine

Bromine is another disinfectant that can be used in swimming pools. It can be used in one of two forms, either bromochlorodimethylhydantoin or as sodium bromide combined with an oxidiser such as hypochlorite (Bartram, 2006). Bromide is generally more effective than chlorine in inactivating bacteria (Johannesson, 1960) and Poliovirus (Keswick et al., 1978). Information from several studies on bromine disinfection of bacteria did indicate that bromine had a greater disinfection effect on vegetative bacterial cells than bacterial spores (Wyss and Stockton, 1947). Wyss and Stockton (1947), however, indicated that bromine had a greater effect on bacterial spores than chlorine, thus it is difficult to predict what effect bromine disinfection may have on protozoan cysts.

In a study of the effect of bromine chloride on poliovirus, Keswick et al. (1978) found that concentrations up to 0.1 mg/l bromine chloride had limited effect on the inactivation of poliovirus whereas increasing the concentration of bromine chloride to 0.15 mg/L could achieve a 4-log reduction of poliovirus within 5 minutes. While all the experiments undertaken in this study were undertaken in halide free buffer, the authors did also investigate the impact of the addition of treated sewage effluent and glycine on Poliovirus inactivation rates in the presence of bromine chloride or chlorine. It was found that while the presence of glycine reduced the impact of bromine chloride on Poliovirus decay, this was less than the effect on corresponding inactivation rates in the presence of chlorine. Similarly, the presence of treated sewage effluent also decreased the inactivation rate of Poliovirus by bromine chloride requiring concentrations above 3.0 mg/L BrCl to achieve greater than 1-log reduction of poliovirus, but the action of chlorine was significantly less under the same conditions (Keswick et al., 1978).

No information could be found in the scientific literature on the effect of bromine on protozoa such as *Cryptosporidium* or *Giardia*. Thus, specific studies would be undertaken on the influence of bromide disinfectants on protozoa for further approval of bromine-based swimming pool disinfectants.

Like chlorine, bromide can produce disinfection by products which are considered to be potentially harmful with long term exposure (Kelsall and Sim, 2010). The disinfection byproducts are produced through the reaction of the bromine-based disinfectant with organic matter in the swimming pool water (Carter and Joll, 2017). Studies have shown that the use of bromine-based disinfectants produce higher concentrations of disinfection byproducts than chlorine disinfected pools (Cater and Joll, 2017).

A major drawback of bromine is that any effective residual is depleted rapidly by sunlight which means that it is less than effective as a disinfectant for outdoor pools and primarily only suitable for indoor pools. This, combined with the ready availability of cheaper chlorine-based disinfection products means that bromine is not commonly used for pool disinfection (Bartram, 2006).

Ozone

Ozone is a powerful oxidant that has been used for the treatment of water since the early 1900s (Manheimer, 1918; von Gunten, 2003). Water sources treated have included swimming pools and is more effective than chlorine for inactivating a range of microorganisms ranging from viruses such as Rotavirus, bacteria including bacterial spores and protozoa such as *Giardia* and *Cryptosporidium* (Lu et al., 2013; von Gunten, 2003; USEPA, 1999; Passos et al., 2014). Ozone is effective against microorganisms through a range of impacts including direct oxidation or destruction of cell walls, the creation of free radicals that damage inter cellular mechanisms and by causing damage to nucleic acids (USEPA, 1999).

Despite being a highly effective treatment method against a broad range of microorganisms in swimming pools (Steinbruchel et al., 1990), the complexity, high set up costs, and high energy requirements (USEPA, 1999) for producing ozone meant that it has been predominantly used for large community pools. It is only recently with the advent of improved electronics that ozone generators are becoming more available for use by domestic pools. Another disadvantage of using ozone as a water disinfectant is that ozone quickly decomposes to oxygen after generation (USEPA, 1999). As such, ozone does not persist in water and does not maintain a residual in the water. Another problem for ozone is its toxicity to humans through inhalation. As a result, any residual ozone needs to be removed via deozonation processes following the ozone disinfection process, particularly if used for indoor pools (Bartram, 2006). The lack of a disinfection residual means that ozone is commonly used in combination with low concentrations of chlorine or bromide to provide an on-going residual in the pool water (Bartram, 2006).

As a powerful oxidiser, ozone can also produce disinfection byproducts in the presence of organic matter (REF). The reactiveness of ozone in combination with chlorine or bromide also has the adverse effect of producing a range of disinfection by-products (von Gunten, 2003), a number of which are considered to be health risks (Bartram, 2006).

UV

UV irradiation is also a disinfection process that has strong capability to inactivate a broad range of microorganisms including *Cryptosporidium* which is known to be resistant to many other chemical disinfectants (Bartram, 2006). UV irradiation involves the use of high intensity short wavelength light to irradiate water. The UV light interferes with DNA my causing cross linking between nucleotides which affects cellular activity and metabolism and/or the ability of microorganisms to reproduce.

UV radiation is a much less complex disinfection process than ozone and most chemical disinfectant dosing systems, but can be expensive and energy intensive, thus is more commonly used in larger commercial swimming pools. Like ozone, despite being very effective in inactivating microorganisms, UV radiation does not leave a disinfectant residual in the pool water and is therefore commonly used in combination with chlorine or bromide-based disinfectants (Bartram, 2006). A combination of UV radiation with chlorine in swimming pools has been observed to reduce chlorine consumption by up to 50% without observing any increase in bacterial numbers (Lenntech, 2012). UV radiation is not directly linked to the production of disinfection by-products (Bartram, 2006) but the need to combine with chlorine or bromine-based disinfectants means that there remains the potential for disinfection by-products to be formed, be it at a lower concentration than if chlorine or bromine were used in higher concentrations as the sole disinfectant. There is some evidence that the combination of UV and chlorine disinfection of pools can result in increasing concentrations of N-nitrosamines (Soltermann et al, 2013) and trihalomethanes and haloacetonitriles (Cheema et al., 2017; Ilyas et al., 2018). In contrast, both Hansen et al. (2013) and Afifi and Blatchley (2016) found that medium pressure UV could be used to decrease the concentration of common disinfection by-products in swimming pool water. UV irradiation of swimming pool water also was found to decrease the concentrations of micropollutants such as pharmaceutical compounds by between 30 and 70% as the UV radiation can break apart bonds in organic molecules (Kudlek et al., 2018).

Copper/Silver complexes

Silver has been recognised as far back as the ancient Greeks for having antimicrobial activity with the ability to help treat wounds. Silver is now frequently used for a range of anti-microbial uses such as in impregnated bandages to aid the healing of skin wounds and prevent or remove topical infections (Maraget et al., 2006), in the lining of catheters and other hospital devices to prevent biofilm growth, and as a coating on domestic drinking water filters to increase the disinfection capability of under bench membrane filters and pot filters (Ehdaie et al., 2020). More recently, copper-silver ionization has become more commonly used for the control of *Legionella* and other opportunistic bacterial pathogens in building systems and hospital environments (LeChevallier, 2023).

The bactericidal effect of silver is broad and varied. At the cell surface, silver ions bind to sulfhydral groups in the cell membrane surface preventing cellular respiration and electron transport causing bacterial cells to lose the ability to generate energy (Thurman et al., 1989). This inability to produce energy has been shown to rapidly increase cell death. Research has also shown that silver can cause leaking of protons through the cell membrane thus disrupting cellular metabolism (LeChevallier, 2023). Disruption of the cell membrane allows silver ions to pass into the cell enabling the silver to bind to DNA proteins preventing DNA replication. A third antimicrobial action by silver ions is through the promotion of radical oxygen species (ROS) in cells using oxygen to respire. All cells produce ROS and have mechanisms to deal with these reactive oxidants, however, the promotion of excess ROS by silver ions can lead to increased cell damage which can overwhelm cellular defences (Mijnendonckx et al., 2013).

Similarly, copper is commonly used as an active agent to control algal growth in pool water and is routinely added to many pools in aqueous form. In addition to its use as an algicide, in an ion form, copper can also assist disinfection processes by binding to bacterial cell membranes. This binding process increases the porosity of areas of cell membrane to other materials such as silver. The bound copper also reduces nutrient uptake and inhibiting the respiratory chain resulting in the disruption of normal cell metabolism (Sicairos-Ruelas et al., 2019; Thurman et al. 1989).

An additional benefit of silver:copper ion disinfection is that, as a non-oxidiser form of disinfection, silver:copper disinfection systems do not form disinfection by-products making the water safer for bathers (Allen et al., 2021). In addition, as non-oxidative metals, silver and copper do not react with organics or degraded by sunlight in pool water meaning they are less likely to be reduced in concentration compared to chlorine disinfectants. Neither does temperature or pH affect the mode of disinfection by silver and cooper ions meaning that pools and spas that are heated will remain protected if using copper:silver ions as part of a disinfection scheme.

Silver ions as a pool disinfectant was first developed in 1934 but was not commercially successful at the time due to the higher energy costs compared to the much cheaper chlorine supplies available on the market (Olsen, 2007). In 1967, NASA developed a silver ionisation system for sterilising the drinking water and wastewater systems aboard the Apollo spacecraft (Albright et al., 1967). The development of this system was only tested on E. coli and Staphylococcus aureus but was found to achieve a reduction of >99.99% of E. coli in less than 2 hours and similar reductions of Staphylococcus aureus in less than 24 hours.

Yahya et al. (1990) studied the ability of using copper:silver ions to reduce the concentration of chlorine in both indoor and outdoor swimming pools. They found that copper:silver ions combined with 0.3 mg/L chlorine provided statistically similar log reductions of total coliform bacteria, *Staphylococcus* spp. and *Pseudomonas aeruginosa* to those achieved by 1.0 mg/L chlorine alone. Copper:silver alone and copper:silver + 0.3 mg/L free chlorine outperformed 1.0 mg/L chlorine in the outside pool for *Staphylococcus* spp. which they surmised was due to the environmental conditions in the outside pool decreasing the concentration of free chlorine. In a related study, Landeen et al. (1989) investigated the efficacy of copper:silver disinfection, either in the presence or absence of 0.2 mg/L free chlorine, on a series of pathogenic bacteria and the bacteriophage MS-2 (as a surrogate for enteric viruses). They used well water as a surrogate for swimming pool, spas (hot tubs) and cooling tower water. They found that copper:silver ions at a concentration of approximately 400 μg/L and 40 μg/L could cause a decay of the gram negative bacteria *E. coli* and *Legionella pneumophila*, but caused very little decay of the gram positive bacterium *Staphylococcus aureus*. All of the microorganisms tested were found to have faster inactivation rates when copper:silver was used in combination with 0.2 – 03 mg/L free chlorine. These inactivation rates were always faster than for free chlorine with no copper:silver ions present. Sicairos-Ruelas et al. (2019) examined the use of silver and copper for use as a secondary disinfectant in drinking water by studying the effect of silver and copper solutions added to demand free buffer on a number of different bacteria (*E. coli*, *Listeria monocytogenes*, *Salmonella enterica* and *Mycobacterium fortuitum*). They determined that silver was a better biocide than copper and that silver could cause a greater than 5 log reduction in *E. coli* and *L. monocytogenes* within three hours and a similar reduction of *S. enterica* within seven hours. *M. fortuitum* was much more resistant than the other bacteria. The authors also noted that silver was not affected by the addition of organic matter to the suspension whereas 0.2 mg/L chlorine was completely removed.

A study commissioned by Enviroswim on their silver:copper ionisation system demonstrated that this disinfection system could inactivate greater than 4-Log of *Pseudomonas aeruginosa* cells in 30 seconds. The Tweed Laboratory Tested also found that 2.0 mg/L of Chlorine could not achieve the same removal rate in less than 15 minutes (Tweed Laboratory Centre, 2004). A complimentary study on the silver:copper ionisation system by Enviroswimin simulated pool conditions by the NSF in the USA demonstrated that there was a >6.4 log removal of *Pseudomonas aeruginosa* cells within 15 minutes (the first sampling event after the test commenced). The other microorganism tested, *Enterococcus faecium* had a 1.3 Log reduction in 6 hours. The NSF also tested the Enviroswim silver:copper disinfection system in the presence of oils and fats (in the form of baby oil (18-22 mg/L) and urea (8.5-9 mg/L). Oils and organic compounds are known to interact with chlorine, reducing the biocidal influence of chlorine-based disinfection. The NSF testing showed that the added organics did not reduce the disinfection capability of the silver and copper ions released by the Enviroswim ES3 system (NSF, 2009). The Enviroswim ES3 system is currently in use in a number of large commercial and community pools which undertake regular microbial testing for compliance purposes. The results from these routine compliance testing have shown that *Pseudomonas aeruginosa* and faecal coliforms are never detected and total heterotrophic count bacterial numbers (bacteria commonly found in all water sources) are almost always as good or better than usually found in drinking water. Anecdotal evidence from the pool operators is that the use of the silver:copper ionisation system produces improvements in water quality compared to traditional chlorine-based disinfection, particularly during heavy use periods (*pers comm* Enviroswim 2022)

The inclusion of MS-2 bacteriophage in the study by Landeen et al. (1989) was one of the first studies that examined the influence of copper and silver ions on a virus. Bosch et al. (1993) and Abad et al. (1994) expanded the investigation of the ability of copper:silver ions to inactivate enteric viruses. Both studies involved investigating the influence of copper:silver in tap water and well water alone or in combination with 0.5 or 1 mg/L chlorine on a range of different human enteric viruses. It was found that Hepatitis A virus and rotavirus had little inactivation in the presence of 1 mg/L chlorine. Adenovirus was inactivated better than Hepatitis A virus or rotavirus while Poliovirus was the most inactivated. Both papers reported that a combination of copper:silver with 0.2 or 0.5 mg/L chlorine had a negligible increase in inactivation in either Hepatitis A virus or Rotavirus and only marginally increased the inactivation of Adenovirus and Poliovirus compared to 1 mg/L chlorine. Bosch et al. (1993) noted that over the time of the study (2 hours) free chlorine levels dropped between 30 and 70% while the concentration of copper and silver remained stable. Both papers surmised that the lack of any increases in inactivation of enteric viruses through the combination of copper:silver with chlorine was most likely due to their inherent resistance to disinfection, particularly when compared to previous reported effects on enteric bacteria, rather than any differences in disinfection capability between chlorine and copper:silver.

There is very limited information available on the effect of copper:silver ions on protozoa, particularly associated with swimming pools. A study by Ehdaie et al. (2020), however, on the use of silver and copper embedded ceramic tablets for removal of viable protozoa and viruses from water found a 98% reduction of bacteriophage and 60% reduction in viable *Cryptosporidium parvum* oocysts within a 24 hour period. This reduction in viable oocysts is comparable to the effect of chlorine on *Cryptosporidium* oocysts (for example the study of Shields et al. (2009) which found that a 3.7-log reduction occurred in the presence of 20 mg/ml free chlorine).

All of the studies discussed above were undertaken under laboratory conditions, using demand-free buffer or suitable water sources from wells and drinking water. In comparison, Beer et al. (1999) studied the efficacy of copper:silver ions in combination with lower levels of chlorine to maintain disinfection capability of swimming pools within a municipal pool complex. The authors reported on the outcomes of routine pool chemical and microbiological monitoring. The study showed that free chlorine was significantly impacted by bather loads requiring continual dosing by the chlorinator system, while copper:silver concentrations remained stable. The microbiological results showed that one instance of detection of total coliforms occurred prior to the use of copper:silver as a secondary disinfectant, and never after copper:silver ions were added to the water. It was also noted that the addition of copper:silver ions decreased the number of heterotrophic bacteria in the water.

Disinfection by-Products

Apart from controlling microbial health risks in swimming pools the other major health concern linked to the use of disinfectants to maintain appropriate pool water quality is the production of disinfection by-products. Disinfection by-products are caused by interactions of organic and nitrogen-based compounds in the water with the disinfectants. In swimming pools, the precursor compounds that interact with disinfectants to produce the disinfection by-products can come from the water used to fill or top up pools, impurities within the disinfectants, and most commonly, compounds released by bathers, both body excretions and personal care products (Kanan and Karanfil, 2011; Cater and Joll, 2017). The production of disinfection by-products from the precursors in swimming pool water is predominantly an issue with oxidative disinfectants such as chlorine and bromine-based disinfectants. There are a wide range of disinfection by-products that can be produced through the interaction of compounds in pool water with disinfectants, however, the majority studied and of concern are produced from the use of chlorine and bromine-based disinfectants (Bartram, 2006). Examples of disinfection by-products produced by different disinfectants are given in Table 2.

There are numerous journal publications that have investigated the range of disinfection by-products that can be present in disinfected pool water that have been considered to be linked to a range of health issues for bathers. The health issues considered range from minor issues such as eye and skin irrigations through to more serious health impacts such as triggering asthma, increase chance of bladder cancer, endocrine effects, and liver and kidney damage (Fantuzzi et al. 2010; reviews by Cater and Joll, 2017 and Zwiener et al., 2007).

Hang et al. (2016) determined that the predicted cancer and health risks of DBPs detected in indoor pools in China trended to be higher than the regulatory limits set by a number of international agencies such as the USEPA, which they surmised were raising the concern of potential health impacts from disinfection by-products to higher levels than necessary. Pándics et al. 2018 also assessed the health risk to recreational and elite swimmers using swimming pools in Hungary. They found that all swimmers exceeded a life time acceptable oral dose which was then used to estimate the human health risk (assessed as both carcinogenic risk and health risk index) with a specific increased carcinogenic risk from chloroform. These health impacts may be even higher for babies and young children (Carter and Joll 2017). Kohlhammer et al. (2006) found that there was a correlation between young children bathing in chlorinated pools with increased rates of allergic diseases such as hay fever in adult. They surmised that the disinfection by-products from the chlorination of pool water could impair the lung epithelial enabling allergens to have a closer contact with the body’s immune system.

Table 2. Examples of disinfection by-products frequently detected in disinfected swimming pool water.

Disinfectant	Disinfection by-products
Chlorine based disinfectants	Trihalomethanes
	Haloacetic acids
	Haloacetonitriles
	Halketones
	Chlorate
	Chloramines
	Choroform
Ozone	Bromate
	Aldehydes
	Kentones
	Ketoacids
	Carboxylic acids
	Bromoform
	Brominated acetic acids
Bromine/hypochlorite	Trihalomethanse (predominantly bromoform)
Bromine based disinfectants	Bromoal hydrate
	Bromate
	Bromamines

From Bartram, 2006; Carter and Joll, 2017; Chu and Nieuwenhuijsen, 2002; Cater and Joll, 2017.

A number of the disinfection by-products are also considered to be mutagenic and carcinogenic (Zweiner et al., 2007). For example, nitriles and NDMA have been shown to have carcinogenic risks in animal trials and all been detected in swimming pools (Cater and Joll, 2017).

The other potential health impact is that many disinfection by-products have been linked to endocrine interference. A direct example of this is a study by Nickmilder and Bernard (2011) who observed that adolescent males that had spent several years swimming in indoor chlorinated pools had decreased levels of total testosterone than those who had not participated in much swimming or had only swum in outdoor chlorinated pools. They surmised that the higher levels of disinfection by-products present in indoor chlorinated pools were able to cross the highly permeable skin of the scrotum to cause the testosterone decrease. They also found that adolescent male swimmers that used a pool disinfected with copper-silver ionization did not have any impacts on testosterone levels.

Conclusions

Maintaining good water quality in pools is imperative for protecting the health of bathers from potential health risks as well as assisting with maintaining appropriate pool operations. A principal for controlling water quality is through the use of appropriate disinfection measures. There are a range of different disinfectants and disinfection processes that can be used for swimming pools, all of which have positive and negative attributes.

Chlorine based disinfectants are the most commonly used for swimming pools and have the largest available data relating to their effect on microbial pathogens. Most of this available data, however, is from laboratory studies that do not replicate real world conditions of swimming pools. Chlorine based disinfectants are known to be impacted by the presence of bather numbers, organic loads, temperature, pH and sunlight, any or all of which can reduce the disinfectant capability of chlorine-based disinfectants. There are additional studies that have shown that microbial contamination of chlorinated pools is possible. In addition, chlorine has very limited effect on *Cryptosporidium* spp. oocysts. To mitigate the effect of sunlight on chlorine in pools, cyanuric acid is used as a chlorine stabiliser, however, cyanuric acid decreases the amount of free chlorine reducing the disinfection capability of chlorine. The biggest concern in the literature relating to the use of chlorine as a disinfectant for swimming pools is the production of disinfection by-products. Some disinfection by-products cause eye and skin irritation, but others have been shown to be carcinogenic and/or mutagenic in cell assays or animal feeding trials. Volatile disinfection by-products such as trihalomethanes can be found in high concentrations in the air above and around pools and have been linked to potential increases in asthma, particularly for bathers using indoor pools.

The other halogen disinfectant bromine is used less than chlorine but has similar or better disinfection capability to chlorine. Despite this, bromine is not commonly used in swimming pools and also a similar drawback to chlorine in the production of a range of disinfection by-products. Ozone and UV are two very effective disinfection processes and are effective against a broad range of microorganisms. Both have the disadvantage of not maintaining a disinfection residual in the pool water requiring the use of another disinfectant, commonly chlorine, to provide a disinfectant residual. The combination of ozone with chlorine has been shown to produce disinfection by-products. UV has one advantage that can reduce the concentrations of disinfection by-products in swimming pools where chlorine is used as the disinfectant to maintain a disinfection residual.

The other disinfection process available is the use of a combination of silver and copper ions. The disinfection capability of silver:copper ions is not effected by pH, sunlight or organic compounds. In addition, as a non-oxidative form of disinfection, there are no reports in the literature of the production of disinfection by-products. Silver:copper is very effective against gram negative bacteria although less effective against gram positive bacteria. The few studies on the disinfection capability of silver:copper on viruses have shown that it was no better than chlorine but a combination of chlorine and silver:copper ions provided a better disinfection rate of viruses than silver:copper ions or chlorine alone.

Overall, a search of the available scientific literature has shown that no one form of disinfection process is perfect and that all the different swimming pool disinfection processes have positive and negative characteristics. It should also be noted that much of the data available on disinfection capabilities have been undertaken under optimal conditions within laboratories and fail to take into account the complexities inherent in swimming pool environments. Information on the behaviour of all the disinfectants under real world conditions for all types of microorganisms of concern would provide greater surety on the effectiveness and safety involved in disinfecting actively used swimming pools.

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