Disinfection of domestic water systems for *Legionella pneumophila*

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ABSTRACT

A literature review was conducted to assess existing information on supplemental treatment of domestic water distribution systems to prevent the proliferation of *Legionella pneumophila*. This review explores some of the critical issues regarding discrepancies frequently observed between the efficacy of various domestic water disinfectants as evaluated in laboratory *in vitro* tests as compared with results observed in full-scale system applications. Secondly, the review summarizes domestic water disinfection technologies currently authorized or with the potential of being authorized in Europe and the United States. These technologies include inorganic oxidants (chlorine, chlorine dioxide, monochloramine, ozone, hydrogen peroxide), ionization (copper and/or silver), thermal procedures and ultraviolet radiation. For each technology, the principle of microbial inactivation, survival curves for various organisms, the method of application, the cost and advantages/disadvantages are reviewed.

Key words | amoebae, disinfection, *Legionella pneumophila*

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INTRODUCTION

Domestic water distribution systems are known reservoirs of microbial contamination, including such opportunistic pathogens as *Legionella pneumophila*. Many epidemiological studies have identified water quality degradation in domestic water systems as the cause of waterborne disease. In fact, in the absence of an adequate disinfectant residual, all water systems are vulnerable to bacterial proliferation. Additional factors that influence the potential for microbial proliferation in domestic water systems include water temperature, the age of water tanks and associated distribution pipework, materials of plumbing construction, system hydrodynamics, the chemical constituents of the water itself, and the diversity of microbial flora present.

Legionella pneumophila is a gram-negative aerobic bacterium which requires warm temperatures (25–42°C) together with a well established biofilm community for growth. As such, *Legionella* is able to proliferate in hot water systems, such as cooling water systems and domestic hot water systems. This pathogenic bacterium is responsible for five declared cases of Legionnaires' disease per million inhabitants in Europe (WHO, 2000). Similarly, more than four cases per million inhabitants are declared in the United States (CDC, 2002). However, underreporting is believed to be a significant problem and the estimated annual incidence rate among the general population in the United States is as high as 18,000 cases (*www.cdc.gov*).

Examples of domestic water systems that may contain *L. pneumophila* include hospitals, nursing homes, apartment and office buildings, and spa resorts, among others. Although the prevalence of guidelines and regulations governing *Legionella* control is increasing, a maximum allowable concentration of *Legionella* in domestic water systems is not regulated in all countries. Even in countries with regulations, trigger levels of

Legionella concentrations are not consistent. In France, health authorities have established a level of 10^3 colony-forming units per litre (CFU/l), above which corrective actions must be taken (DGS, 1997, 1998, 2002). Efficacy of curative measures is commonly evaluated by analysing the cultivable *Legionella* before and after treatment, using a culture method with a detection limit of 50 CFU/l (AFNOR T90-431, ISO 11731). In the United States, there are no federal regulations establishing *Legionella* maximum concentration limits to date. As for other pathogens, the USEPA drinking water standards use the 'treatment technique' approach, requiring the use of a certain 'Best Available Technology' to achieve zero levels of the microorganism.

Excellent reviews on *Legionella* disinfection practices can be found elsewhere (Muraca *et al.*, 1990; Lin *et al.*, 1998*a*,*c*; Cabanes & Geneste, 1999). The objective of this review is to highlight some of the critical issues regarding discrepancies between the efficacy of various disinfection technologies as studied in laboratory *in vitro* tests compared with results observed in full-scale system applications. Additionally, this review summarizes supplemental domestic water disinfection technologies currently authorized or with the potential of being authorized in Europe and the United States. These technologies include inorganic oxidants (chlorine, chlorine dioxide, monochloramine, ozone, hydrogen peroxide), ionization (copper and/or silver), thermal procedures and ultraviolet radiation. For each technology, the principle of microbial inactivation, survival curves for various organisms, the method of application, the cost and advantages/disadvantages are reviewed.

LIMITATIONS OF *IN VITRO* EXPERIMENTS

A significant limitation in assessing the efficacy of disinfection technologies is the difficulty in extrapolating performance results obtained from *in vitro* experiments to predict disinfection efficacy in full-scale water distribution systems. Specific characteristics found in these water systems contribute to this fact. For example, the presence of disinfectant-consuming compounds, both within the bulk water and pipe wall deposits causes a reduction of effective concentrations of the disinfectant. Another consideration is that laboratory experiments are typically designed to address the disinfection performance against planktonic bacterial populations existing within the bulk water whereas actual plumbing systems contain biofilms, complex associations of diverse microbial consortia, extracellular polymers, water channels, detritus and inorganic deposits, which harbour and protect pathogens from adverse conditions (Wright *et al.*, 1991; Armon *et al.*, 1997), including disinfectants. Furthermore, the physiological properties of microbes embedded within a biofilm community may differ significantly from those of freely suspended planktonic cells, again affecting disinfection efficacy.

One of the most important factors for predicting the bactericidal efficacy of a given disinfectant is the CT factor which is defined as the product of the residual disinfectant concentration (C) in mg/l, and the contact time (T) in minutes. *In vitro* studies are usually intended to develop such survival curves. Although these data provide useful information, their interpretation may be limited for various reasons. Firstly, most *in vitro* studies have reported survival curves using batch systems, where the disinfectant concentration decreases during the course of the experiment. Typically, CT curves used for design purposes are developed at constant disinfectant concentration by using a chemostat system capable of providing nutrient-limited conditions (Berg *et al.*, 1988). Secondly, laboratory studies conducted with populations grown at high rates are likely to overlook the presence of a recalcitrant fraction if survival is not observed over at least three orders of magnitude (Berg *et al.*, 1988).

Most *in vitro* experiments described in the current literature are inoculated with *Legionella* species grown on agar media. Scientific evidence has shown that tap-water cultured *L. pneumophila* is more resistant to chlorine than the agar medium-passaged counterpart (Kuchta *et al.*, 1985; Cargill *et al.*, 1992). For example, Kuchta *et al.* showed that 0.25 mg/l of free chlorine resulted in a 2-log inactivation of agar-grown *L. pneumophila* after 10 min, while 60–90 min exposure was required to yield equivalent reductions for the cultures maintained in tap water. Furthermore, exposure to chlorine concentrations up to 2 mg/l of free chlorine can render *Legionella* species more

chlorine resistant than strains not previously exposed (Kuchta *et al.*, 1985).

Another limitation in extrapolating the results from laboratory experiments to full scale systems is the difficulty in reproducing the complex interactions among a diverse microbial community as is typically present within real systems. For example it is well known that, in addition to the ability to infect humans, *Legionellae* are also intracellular bacterial parasites of amoebic and ciliated protozoa (Anand *et al.*, 1983; Rowbotham, 1993; Newsome *et al.*, 1998). Upon infection, *Legionellae* can multiply within the amoebae and may be subsequently liberated to the bulk water by expulsion of phagosomes or upon lysis of the host cell membrane (Anand *et al.*, 1983; Barbaree *et al.*, 1986; Berk *et al.*, 1998). In fact, the presence of free-living amoebae is suspected to be the principal source for *L. pneumophila* contamination of domestic water systems (Breiman *et al.*, 1990; Nahapetian *et al.*, 1991; Wadowsky *et al.*, 1991; Dubrou *et al.*, 1992).

Amplification within protozoan hosts results in significant consequences regarding the transmission and pathogenicity of the bacterium including dissemination of the pathogen across very long distances from the point of contamination, increased resistance to disinfectants and greater virulence (King *et al.*, 1988; Barker *et al.*, 1992; Fields, 1993; Berk *et al.*, 1998; Newsome *et al.*, 1998). For example, it has been reported that *Legionella* can survive free chlorine residuals up to 4 mg/l when protected by amoebic hosts (King *et al.*, 1988). Finally, *Legionellae* are also known to survive within amoebic cysts which are much more resistant to disinfectants than the trophozoite (vegetative) forms, further mitigating attempts to control proliferation of the pathogenic bacterium. Little focus has been placed upon eradication of amoebae from potable water supplies due to the lack of evidence that ingestion of free-living amoebae in water results in human disease (Winiecka-Krusnel *et al.*, 1999). Consequently, little is known about the sensitivity of amoebae to antimicrobial agents although some studies have demonstrated that amoebae can withstand free chlorine residuals as high as 50 mg/l (Perrine & Langlais, 1986; Kilvington & Price, 1990).

In addition to providing protection against biocides, amoebae infection by *Legionellae* results in the generation of more resistant strains. This has important implications regarding the applicability of test results obtained using *L. pneumophila* grown on nutrient-rich media. As opposed to growth on rich media, protozoonotic growth is likely to subject the bacterial cells to iron deficiencies, causing them to express iron-deprived phenotypes, which were found to differ significantly in their susceptibility to chemical inactivation (Kilvington & Price, 1990; Barker *et al.*, 1992; Viswanathan *et al.*, 2000). Illustrating this enhanced resistance to disinfectants, *Legionella* was found to be 50-fold more resistant to free chlorine when ingested by the protozoan *Tetrahymena pyriformis* (King *et al.*, 1988).

INORGANIC OXIDANTS

This section reviews the inorganic oxidant disinfectants: chlorine, chlorine dioxide, monochloramine, ozone and hydrogen peroxide. The principle of inactivation is the disruption of membrane structure by oxidation of essential components. For each oxidant, the survival curves, the method of application, the cost and advantages/disadvantages are discussed.

Chlorine

Inactivation studies

Published results from *in vitro* experiments illustrate the range of performance efficacy achieved with use of chlorine. Domingue *et al.* (1988) demonstrated that 0.3 mg/l free chlorine can yield a 2-log reduction of cultured *L. pneumophila* serogroup 1 in 30–45 min. However, Kuchta *et al.* (1983) found that 0.4 mg/l free chlorine resulted in >3 log reduction in as little as 10 min exposure. Still others found that exposure times as long as 60 min were necessary to achieve 3-log reductions using 4 mg/l of free chlorine (Jacangelo *et al.*, 2001). Similarly, 4–6 mg/l produced a 5–6-log decrease in 6 h in a model plumbing system (Muraca *et al.*, 1987).

Full-scale systems

Despite the chlorine sensitivity often observed in batch experiments, *L. pneumophila* is known to be relatively tolerant to chlorine in domestic water distribution systems. A review of chlorination practices in North American hospitals showed that inactivation and suppression of the organism usually requires chlorine levels greater than 3 mg/l (Muraca *et al.*, 1990). In fact, *L. pneumophila* has even been recovered from water containing up to 7 mg/l free chlorine (Tobin *et al.*, 1986).

Hyperchlorination (chlorine shock)

Method

Hyperchlorination, frequently employed as a remedial treatment option, typically consists of a pulse injection of chlorine in water to achieve 20–50 mg/l of free chlorine in the system during a short period of time. After a predetermined period of contact time, the system is drained and fresh system water is introduced so that chlorine levels are returned to normal concentrations. For example, the hyperchlorination strategy recommended by the French health authorities calls for a 50 mg/l free chlorine dose to be held for 12 h (DGS, 1997). It has been reported that hyperchlorination using cold water is more effective than equivalent dosages applied to hot water (Moreno *et al.*, 1997).

Continuous chlorination

Method

Chlorine for disinfection is typically supplied in one of three forms: chlorine gas, liquid sodium hypochlorite (NaOCl) or solid calcium hypochlorite ($Ca(OCl)_2$). The chlorinated salts are preferred over chlorine gas in water systems in buildings because of the lower flowrates and safety issues. The chlorinator, either continuous or flow-paced, injects metered volumes of chlorinated salts to achieve the desired free chlorine concentration, usually between 2 and 6 mg/l. The recommended dose from the French health authorities for continuous chlorination is from 1 to 2 mg/l (DGS, 1997). The dosage is usually controlled by measuring the redox potential of the dosed solution, or using amperometric or colorimetric methods.

Cost

Costs associated with installation of programme equipment including chlorinator, online analyser, pump and holding tank have been investigated in studies conducted on hospital distribution system applications. A European study estimated costs at 30,000 to 60,000 Euros/1,000 beds, significantly lower than costs previously reported in some US studies where figures of $76,000/940 beds (Helms *et al.*, 1988), and $88,000/800 beds (Lin *et al.*, 1998*a*) were obtained.

Advantages

Chlorination is an inexpensive, well-accepted technology that has an extensive body of literature supporting its efficacy against a wide range of pathogenic microorganisms. It provides a residual concentration throughout the entire system that is easily measured.

Disadvantages

The use of chlorine presents the following disadvantages: (1) dependency of disinfecting efficacy on system pH values <7.6 preferred (Kuchta *et al.*, 1983); (2) difficulty of obtaining stable residuals due to disinfectant consumption by established biofilms, by the incoming water, by the plumbing materials and by corrosion products; (3) chlorine decomposition at increased water temperatures; (4) system corrosion enhancement; (5) formation of disinfection byproducts such as halogenated organic compounds (eg. trihalomethanes) in waters containing organic matter; (6) vulnerability of the system to recolonization within days of chlorine dosing disruption; (7) limited efficacy for protozoa inactivation.

Monochloramine

Despite its use in drinking water disinfection in the USA and the UK, monochloramine (NH_2Cl) has not been

widely used to control *L. pneumophila* in domestic water systems. In fact, use of this disinfectant is not authorized in most European countries. According to some recent studies, potable water systems distributing chloraminated water have 10 times lower incidence of Legionnaires' disease than those distributing chlorinated water (Kool *et al.*, 1999, 2000). A possible explanation for such results is the observation that chloramine is more effective in disinfecting biofilms (LeChevallier *et al.*, 1988).

Inactivation studies

In vitro experiments have shown that 1 mg/l monochloramine yielded a 2-log reduction in viable agar-grown *L. pneumophila* serogroup 1 cells provided with 15 min contact time, whereas a 2 mg/l dose achieved the same kill with a 5 min contact time (Cunliffe, 1990). Interestingly, amoebae appear to be extremely sensitive to monochloramine with a 1 mg/l dose achieving a 2-log reduction of *Tetrahymena pyriformis* within 3 min. Such results illustrate that this protozoan is up to six times more sensitive to monochloramine than either *Escherichia coli* or *Salmonella typhosa* (Haas *et al.*, 1985).

Method

Monochloramines are generated on-site by blending stoichiometric amounts of aqueous chlorine and ammonia.

Advantages

Chloramination presents the following advantages: (1) higher stability than free chlorine, even at high temperatures and pH conditions; (2) greater biofilm penetration; (3) less corrosive than free chlorine; and (4) less disinfection by-products formation.

Disadvantages

Among the disadvantages, chloramination presents: (1) requirement for on-site generation; (2) risk of nitrification generating nitrites (regulated at 0.5 mg/l in Europe); and (3) questionable efficacy against amoebae.

Chlorine dioxide

Inactivation studies

To date limited data exists on *in vitro* inactivation efficacy of chlorine dioxide. One study showed that chlorine dioxide is very active, achieving a 4-log reduction in viable *L. pneumophila* at 0.08 mg/l within 1 min exposure (Bertinchamps & Masschelein, 1990). Another study showed that 0.5 mg/l chlorine dioxide was very effective in reducing planktonic *L. pneumophila* in a pilot scale pipe loop (Pavey & Roper, 1998).

Method

Most commercial generators use sodium chlorite as the precursor for chlorine dioxide generation for domestic water treatment. Chlorine dioxide can be formed by reacting sodium chlorite with gaseous chlorine, hypochlorous acid or hydrochloric acid (HCl). Alternatively, electrochemical generation of chlorine dioxide is also feasible. Chlorine dioxide generators are operated to obtain the maximum yield of ClO_2 while minimizing free chlorine or other residual oxidant formation. It should be noted that 1 g of chlorine dioxide contains 2.63 g 'as Cl_2'.

Cost

The cost of equipment (generator, online analyser and pump) is estimated at 50 to 60,000 Euros/1,000 beds.

Advantages

Chlorine dioxide presents a high biocidal efficacy while minimizing the formation of trihalomethanes.

Disadvantages

The disadvantages include: (1) requirement of on-site generation; (2) limitation of the total dose applied due to production of chlorite and chlorate ions (chlorite and

chlorate concentrations are limited to 0.5 mg/l and 1.0 mg/l in the UK and in the USA, respectively, whereas France has a limit of 0.2 mg/l for chlorites); and (3) its impact on corrosion is not well known.

Ozone

Inactivation studies

In vitro experiments show that ozone is very effective in inactivating *L. pneumophila*. Results of one study illustrated that 0.36 mg/l of ozone in distilled water produced a 5-log reduction of *L. pneumophila* serogroup 1 after 20 min (Edelstein *et al.*, 1982). In another study, 0.1–0.3 mg/l of ozone yielded a 2-log reduction in 5 min. Neither pH nor temperature was observed to have any significant effect on ozone disinfection performance (Domingue *et al.*, 1988). In a model plumbing system, 1–2 mg/l produced a 5–6-log decrease in 3 h (Muraca *et al.*, 1987).

Method

Ozone is an unstable molecule which must be produced at the point of application. Typically ozone is generated on site by electrically exciting oxygen (O_2) to the triatomic state (O_3), which is the potent biocide and oxidizing agent. A 1 to 2 mg/l ozone dosage is recommended for treatment of domestic water (Muraca *et al.*, 1990). Ozone dosage is usually accomplished via a flow-paced generator in proportion to the flowrate of the water.

Cost

The cost of equipment (ozonator, injection system and contact tank) is estimated at 30 to 40,000 Euros/1,000 beds for a dose of 0.5 mg/l of ozone.

Advantages

The major advantages of ozonation include: (1) instantaneous bacterial and viral inactivation, resulting in short contact times; and (2) a synergistic effect with chlorine and chloramine reported for other protozoa (Rennecker *et al.*, 2000).

Disadvantages

Ozonation presents the following disadvantages: (1) on-site generation; (2) high corrosivity to domestic water system materials (except stainless steel); (3) difficult to maintain residuals—additional disinfectant (i.e. chlorine) may be required to provide residual disinfectant throughout the distribution system; and (4) its efficacy in water systems in buildings has yet to be determined.

Hydrogen peroxide

Inactivation studies

Published studies have concluded that hydrogen peroxide (H_2O_2) is not very effective when used as a single disinfectant. Some *in vitro* studies show that up to 10 mg/l are necessary to yield a 3-log reduction of viable *L. pneumophila* despite 24 h contact time (Bertinchamps & Masschelein, 1990). Other inactivation studies demonstrated that 1 g/l of H_2O_2 required 30 min to achieve a 2-log reduction (from 1.9×10^9 CFU/ml), and that up to 10 g/l of H_2O_2 for 30 min are necessary to achieve >4 log reduction (Domingue *et al.*, 1988).

Method

Hydrogen peroxide is typically applied by continuously injecting metered volumes of concentrated H_2O_2 solutions (3 to 30%). Hydrogen peroxide is only authorized for drinking water applications when the system is off service (shock treatment). Some manufacturers propose the use of this disinfectant in combination with silver ions. However, the efficacy of such combinations remains to be determined.

THERMAL TREATMENT

Inactivation studies

Temperatures greater than 60°C rapidly kill *L. pneumophila in vitro* (Stout *et al.*, 1986; Muraca *et al.*, 1987).

Increasing the temperature from 60 to 70°C reduces the time required for a given log reduction by half. Further increasing the temperature up to 80°C reduces the time by a factor of five. For example, a 3-log reduction would require a temperature of 60°C for 8 min, or 80°C for 1.5 min. It is interesting to note that not all *L. pneumophila* serogroups show the same thermal sensitivity. Thus, after 5 min incubation at 60°C, *L. pneumophila* serogroup 1 remained cultivable while serogroup 2 strains were not (Steinert *et al.*, 1998). Also interesting was a result that demonstrated pretreatment with heat (50°C) appeared to make amoebae cysts more susceptible to chlorine (Kuchta *et al.*, 1993).

Method

The 'heat and flush' method consists of elevating the hot water tank temperature to greater than 70°C followed by flushing of all the faucets and shower heads. The recommendation from the French health authorities (DGS) for thermal disinfection is to target 70°C at the outlet for 30 min.

The following protocol, combining chlorination with thermal treatment, has been proposed (Best *et al.*, 1984; Muraca *et al.*, 1990; Lin *et al.*, 1998*a*):

1. Shut down all hot water tanks, then drain them.
2. Physically descale with high-pressure steam.
3. Chlorinate at 100 mg/l chlorine for 12 to 24 h.
4. Flush chlorine solution from the tanks and put the system back in service.
5. Elevate tank temperature to 70–80°C for 72 h, and flush all distal water sites over 30 min three times over the 72 h period (temperatures at the distal outlet exceeding 60°C).

It is important to highlight that thermal disinfection is generally employed as a temporary control strategy. Recolonization is usually observed a few months following the thermal disinfection treatment. There is evidence showing that contamination can be due to regrowth of survivors and not colonization from other sources (Steinert *et al.*, 1998).

The Approved Code of Practices in the UK recommends a continuous thermal treatment which consists of hot water storage at 60°C and distribution at temperatures no lower than 50°C at all points after 1 min of flushing (HSC, 2001). Similar procedures are recommended in the German DVGW codes of practice W551 (1993) and W552 (1996), and French regulations (DGS, 2002).

Recently the use of instantaneous heating systems has been advocated for control of *L. pneumophila* proliferation. These systems function by flash heating water to temperatures greater than 88°C then blending the hot water with cold water to achieve the target temperature. Other methods include pasteurization. Since there is no storage of water, the local environment for *L. pneumophila* proliferation at the production point is eliminated. However, no prevention of *L. pneumophila* growth in the systems is guaranteed if temperatures fall below 50°C.

Cost

This is the least expensive disinfection method. The greatest expense has been personnel costs for overtime, since the disinfection is conducted at night or during weekends. The cost also includes energy costs for temperature elevation and the volume of water used during flushing.

Advantages

Heat treatment requires no chemical additions to the water. In addition, no special equipment is required, therefore minimal cost and immediate implementation can be expected.

Disadvantages

Thermal shock is a labour intensive method, with the potential for scalding if the procedure is not carefully performed. It is important to highlight that shock treatment provides only immediate short-term control: recolonization occurs even at hot water tank temperatures

of 60°C. In some cases, the capacity of the heat production unit may be insufficient to conduct the shock procedure for the whole system. Conducting the procedure in steps can compromise the efficacy of this protocol in such cases. Finally, careful attention has to be paid to the galvanized systems, since the zinc layer cannot withstand temperatures higher than 60°C.

Thermal treatment conducted on a continuous basis has limited efficacy due to the difficulty of obtaining stable temperatures over 50°C throughout the entire system.

COPPER/SILVER IONISATION

Principle

This method works through disruption of cell wall permeability due to the formation of electrostatic bonds between positively charged copper (Cu^{2+}) and silver (Ag^{+}) ions and negatively charged sites on the bacterial cell wall (Slawson *et al.*, 1990).

Inactivation studies

In vitro experiments on copper and silver inactivation of *L. pneumophila* have shown that 0.4 mg/l Cu and 0.04 mg/l Ag are able to achieve a 3-log reduction (Landeen *et al.*, 1989). *Legionella pneumophila* serogroup 1 was completely inactivated (6-log reduction) at copper concentrations of 0.1 mg/l within 2.5 h. More than 24 h was required to achieve a similar reduction with a silver ion dose of 0.08 mg/l (Lin *et al.*, 1996). Other authors reported a requirement for 0.05 mg/l and 6 h of contact to achieve a 4-log reduction (Miyamoto *et al.*, 2000). Synergistic effects were observed at 0.04 mg/l Cu and 0.04 mg/l Ag concentrations, but only an additive effect was observed at 0.02 mg/l Cu and 0.02 mg/l Ag (Lin *et al.*, 1996).

As for its efficacy on amoebae inactivation, one *in vitro* study showed that copper/silver concentrations of 0.1/0.01 mg/l were insufficient to yield reductions in viable numbers of either *Hartmanella vermiformis* or the ciliated protozoan *Tetrahymena pyriformis* (Rohr *et al.*, 2000). Another study showed that even concentrations up to 0.8/0.08 mg/l caused no significant decrease in *Naegleria fowleri* populations after 72 h of contact (Cassells *et al.*, 1995). These results confirm the observations of others (States *et al.*, 1998) regarding the presence of viable amoebae in domestic systems treated with copper/silver ionization. Furthermore, copper/silver ionization has been shown to be inefficient in inactivating other pathogens, such as *Mycobacterium avium* (Lin *et al.*, 1998*b*).

Full-scale systems

Field results on the efficacy of copper and silver ionization in controlling *L. pneumophila* proliferation in hospital water systems are contradictory. While some studies showed that silver/copper concentrations of 0.29/0.054 mg/l were very effective (Stout *et al.*, 1998), others reported concentrations of 0.3/0.03 mg/l as ineffective (Liu *et al.*, 1994). A 4-year study reported that silver concentrations up to 0.03 mg/l were not sufficient to prevent *L. pneumophila* proliferation (Rohr *et al.*, 1999). The results of this study suggest that *Legionella* could develop tolerance to silver ions. Long-term studies on the efficacy of these systems are currently lacking.

Method

Electrolytically generated copper and silver ions are introduced into recirculated hot water from a flow cell containing electrodes made of a copper/silver metal alloy. Because ions may be readily scavenged by organic matter, the water must be recirculated to regenerate the ions. Concentrations of 0.2–0.4 mg/l Cu and 0.02–0.04 mg/l Ag are typically recommended. While maximum allowed concentrations of copper are 1 and 1.3 mg/l in France and the USA, respectively, the levels for silver are not regulated.

Cost

The cost of the ionization unit will be $60,000–$100,000 depending on the size. Some examples of costs are:

$32,000/250 beds (States *et al.*, 1998), $70,000/550 beds (Stout *et al.*, 1998). Electrode replacement ranges from $1,500 to $4,000 (Muraca *et al.*, 1990; Lin *et al.*, 1998*a*).

Advantages

Ionization systems are easy to install and maintain. Temperature does not affect their efficacy. A synergistic effect of temperature and chlorine has been observed (Landeen *et al.*, 1989; Yahya *et al.*, 1992; Cassells *et al.*, 1995). The ions in solution represent a residual protection throughout the water system. A slower recolonization has been observed (6–12 weeks) if treatment is discontinued as compared with other disinfectants (Liu *et al.*, 1994).

Disadvantages

Copper and silver ionization present the following disadvantages: (1) scaling of the electrodes that requires regular cleaning or softening of the water; (2) difficulty of maintaining stable residuals of Cu and Ag in solution; (3) routine monitoring of ion levels (atomic absorption); (4) potential development of bacterial resistance to ions; (5) low efficacy for other bacteria (States *et al.*, 1998); (6) pH dependent activity due to formation of insoluble hydroxides of copper and silver with increasing pH (solubility of Cu complexes); (7) impact on corrosion of galvanized stainless steel; and (8) no efficacy for protozoan inactivation.

ULTRAVIOLET LIGHT RADIATION

Principle

UV light is a physical disinfectant rather than a chemical approach. Ultraviolet light radiation kills bacteria by producing pyrimidine dimers in DNA which subsequently hamper DNA replication.

Inactivation studies

Legionella pneumophila is especially sensitive to UV radiation. Thus, exposures at 1.8 and 2.8 mWs/cm^2 achieved 2- and 3-log reductions, respectively (Antopol & Ellner, 1979). Other authors have reported doses as high as 28 and 45 mWs/cm^2 to result in 2–3 and 4-log inactivation, respectively (Kusnetsov *et al.*, 1994; Miyamoto *et al.*, 2000). Most vegetative bacteria in clean water are effectively inactivated (>3 log) by 16 mWs/cm^2 but higher doses are needed for inactivation of enteric viruses and protozoan cysts (Sobsey, 1989). UV radiation of 40 mWs/cm^2 has been reported to achieve 1-log inactivation of the amoeba *Acanthamoeba castellanii* (Chang *et al.*, 1985).

Experiences in recirculating pilot systems report very different efficiencies. A dose of 3 mWs/cm^2 was able to achieve a 2-log reduction in a recirculating water system (Gilpin *et al.*, 1985). Results from a study using a model plumbing system found that a dose of 30 mJ/cm^2 produced a 5-log decrease in viable counts. No temperature effect was observed (Muraca *et al.*, 1987).

Method

Ultraviolet light (UV) units are usually installed near the 'point of use', such as showerheads and faucets (Lin *et al.*, 1998*a*; Cabanes & Geneste, 1999). Installation of UV units only on the inlets and outlets of hot water tanks fails to prevent colonization. Sterilization occurs from exposure to UV light generated from low-pressure mercury lamps. Usually, heat-and-flush or chlorination is applied before UV to eliminate any existing *L. pneumophila* in the system. Installation of prefiltration and/or water softening is necessary to prevent scale accumulation on UV lamps.

Cost

Some costs have been reported in the literature: $50,000 for four large (70 l/min) and two small lamps (8 l/min) (Lin *et al.*, 1998*a*); $20,000/eight rooms. The expected life of the lamps is 1 year.

Advantages

UV systems are easy to install, and no adverse effects on water chemistry or on plumbing integrity are observed.

Table 1 | Comparison of various disinfection practices for *Legionella pneumophila*

Disinfectant	Survival (*in vitro*) C×T (mg/l×min) for 99% kill*	Survival (*in situ*) C×T (mg/l×min)	Cost 10^3×US$/500 beds	Advantages	Disadvantages
Chlorine, HOCl	2.5–12	>1,440	CAPEX 30–45 OPEX 5–8	• Residual in the system • Recommended by law	• Efficacy is pH and T dependent • Difficult to maintain residual • Corrosive • THM formation
Monochloramine, NH_2Cl	10–15	NR	NR	• Stable residual • No pH or T effect • Low THM formation	• On-site generation • Risk of nitrification
Chlorine dioxide, ClO_2	0.08	NR	CAPEX 25–30 OPEX 3–5	• Residual in the system • No THM formation	• On-site generation • pH sensitive (keep pH > 9) • Chlorite formation • Corrosion needs to be evaluated
Ozone, O_3	0.5–1.5	216 for >5 log	CAPEX 35–60 OPEX 6–9	• Effective disinfectant • Effective for protozoan disinfection • Synergy with Cl_2: sequential disinfection	• On-site generation • Difficult to maintain residual • Lack of experience in domestic systems • Impact on corrosion to be evaluated
Hydrogen peroxide, H_2O_2	30,000	NR	NR	• Low cost • Easy installation and maintenance	• Inefficient disinfectant • Only authorized for off-line disinfection
Copper and silver, Cu/Ag	384/38.4	High variability	CAPEX 20–35 OPEX 1–4	• Low cost • Easy installation and maintenance • Slow recolonization	• Scaling of the electrodes: need to soften the water • Efficacy is pH dependent (formation of insoluble hydroxides) • Difficult to maintain stable ion residual • Development of bacterial resistance to ions • Ag efficient dose higher than potable water MCL • Impact on corrosion (galvanized steel)
UV light radiation	2 mWs/cm^2	2-log: 3 mWs/cm^2 5-log: 30 mWs/cm^2 (1-log: 40 mWs/cm^2 for amoebae)	CAPEX 18–35 OPEX 1–2	• Point-of-use device • Low cost • Easy installation and maintenance • No chemical byproduct	• Lack of residual protection: need to combine with other disinfectant • Scaling of the lamps

NR: not reported. CAPEX: capital expenditures. OPEX: Operating expenditures/year.
*Calculated from C and T values from the literature.

Disadvantages

UV systems provide no residual protection beyond the point of application. Systemic disinfection (i.e. hyperchlorination) is often required to provide additional protection. Turbidity reduces the transmission of UV light. Finally, UV lamps have a limited life, and are susceptible to scale and mineral deposits.

CONCLUSIONS

From this literature review on *L. pneumophila* domestic water disinfection methods, it can be concluded that this bacterium is difficult to eliminate from water distribution systems by any disinfection method currently employed. Each disinfection method has advantages and disadvantages, so careful analysis of the different alternatives and water system characteristics should be conducted before making a decision. The authors summarize their conclusions as follows:

- *Legionella pneumophila* is more resistant than other pathogenic bacteria to chemical disinfection. There is no treatment specifically effective for *L. pneumophila* disinfection. Table 1 summarizes the C × T values for 2-log inactivation for the selected disinfectants.
- Although the efficacy of chemical (oxidants and ions) and physical (temperature, UV light radiation) disinfection has been proven in laboratory scale experiments using pure agar-grown cultures, *L. pneumophila* disinfection of water systems in buildings shows a large variation in results. This may be explained by the fact that *in vitro* results have always focused on inactivating planktonic *Legionella*, ignoring the inactivation of the *L. pneumophila* harboured in biofilms and protozoa. Consequently, effective disinfection strategies should be focused on eradicating/disinfecting both the biofilms and protozoa. Very few studies have addressed this issue.
- Any disinfection attempt should be preceded by a thorough assessment of the system hydraulics. Dead legs and low flow sections should be eliminated.
- The optimum disinfection strategy consists of placing the disinfectant close to the point of use. In this respect, strategies based on continuous treatment (either thermal or chemical) and frequent cleaning and disinfection of plumbing materials (shower heads, faucets, etc.) should provide the best results.
- Point-of-entry disinfection systems can be designed to treat the water system of an entire building, a specific section or wing of a building, or a specific room or site (point-of-use). Installation of point-of-entry devices (UV lamps, ultrafiltration membranes, etc.) will not prevent recolonization from either remaining biofilms or back-contamination from point-of-use devices, even when a thorough disinfection of the water system of the whole building is first conducted.
- UV light radiation is specially recommended for point-of-use installations, given the variability of flow conditions in such cases and the compact devices existing in the market.

Based on this review the authors conclude that existing data from the literature do not allow clear identification of the best available technology for *Legionella* control in domestic water systems. Additional research should be conducted to assess the efficacy of the various disinfection strategies under conditions that allow their comparison.

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