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Plumbing of hospital premises is a reservoir for opportunistically pathogenic microorganisms: a review

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Abstract

Several bacterial species that are natural inhabitants of potable water distribution system biofilms are opportunistic pathogens important to sensitive patients in healthcare facilities. Waterborne healthcare-associated infections (HAI) may occur during the many uses of potable water in the healthcare environment. Prevention of infection is made more challenging by lack of data on infection rate and gaps in understanding of the ecology, virulence, and infectious dose of these opportunistic pathogens. Some healthcare facilities have been successful in reducing infections by following current water safety guidelines. This review describes several infections, and remediation steps that have been implemented to reduce waterborne HAIs.

Keywords

healthcare-associated infection; biofilm; potable water; premise plumbing; opportunistic pathogen

Introduction

Water distribution systems (WDS) and equipment or services using water can serve as reservoirs for waterborne opportunistic pathogens in healthcare facilities. Under favorable environmental conditions, microorganisms can either multiply or remain viable for long periods of time in biofilms coating the interior of WDS pipes (Boe-Hansen et al. 2002; Manuel et al. 2007). Most are autochthonous heterotrophic plate count (HPC) bacteria and are not typically thought of as pathogens by drinking water experts. However, many of these organisms have been associated with infections among susceptible patient populations. The burden of healthcare-associated infections (HAI) attributed to water is unknown; most knowledge has been acquired from sporadic outbreak investigations. These organisms are transmitted by direct contact (eg hydrotherapy, bathing, and debridement), ingestion of water, indirect contact (eg improperly reprocessed medical device), inhalation of aerosols

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This Article is a collaborative work.

generated by a water source, and aspiration of contaminated water (Centers for Disease Control and Prevention [CDC] 2003).

The pathogens responsible for most recognized waterborne HAI typically are natural inhabitants of WDS that are well adapted to growth in low nutrient environments and in many cases do not infect healthy individuals. Patients in the healthcare environment are more susceptible to infection when they have invasive devices, open wounds, have had surgical procedures, or are immunocompromised (eg during chemotherapy, immune deficiencies, solid organ and hematopoietic transplants). The special circumstances that lead to waterborne HAI occur at the three-way intersection of non-sterile potable water, susceptible individuals, and a lapse in infection control practices.

Potable water serves many functions in the healthcare environment in addition to drinking. Some functions include sanitation, heating, ventilation, and air conditioning, laundry, food services, ice production for consumption or for cooling medical compounds, patient bathing, physiotherapy pools, cleaning and reprocessing of medical devices, and laboratory procedures (MWRA online). In a certain combination of circumstances, any of these uses may lead to a HAI by a waterborne pathogen.

Over the past two decades, the delivery of healthcare has shifted away from acute-care facilities to a more complex system consisting of acute, sub-acute, long-term care, outpatient facilities, and homecare, complicating infection prevention efforts (Jarvis 2001). This review will focus on uses of potable water in a variety of modern healthcare settings.

Reviewing case reports of HAI caused by waterborne microorganisms indicates some of the knowledge gaps that need to be filled to reduce opportunistic infections. Reviews in the past few decades have highlighted the occurrence of waterborne infections in the healthcare environment (Anaissie et al. 2002; Exner et al. 2005), but the issue still has not been addressed in a systematic way. Several healthcare facilities have applied prevention and control measures, resulting in various degrees of success in preventing waterborne HAI. Some of these reports and prospective studies will be described, and some current options for infection prevention summarized, concluding with recommendations for directions of future research.

Transmission of waterborne infections

Infections caused by opportunistic pathogens in healthcare are partly determined by the exposure route (Table 1). For instance, localized infections can occur in injection sites (Tiwari et al. 2003), or surgical wound sites. Bacteremia may result from bacteria entering central venous catheter (CVC) exit sites during showering (Kline et al. 2004; Cooksey et al. 2008). Inhalation of aerosols through a variety of exposures (eg showering, ventilators, nebulizers, hydrotherapy pools, and splashing from sinks) may lead to respiratory colonization or infection (Trautmann et al. 2005; Feazel et al. 2009). In addition to infection, pseudo-infections commonly occur in healthcare systems when clinical samples are contaminated while collecting the sample, during laboratory processing, or when patients are colonized without showing signs of disease. Pseudo-infections can have a detrimental

effect on patients, occasionally leading to a misdiagnosis and inappropriate treatment. For instance, a pseudo-infection with non-tuberculous mycobacteria (NTM) may lead to a difficult, prolonged, and unnecessary regimen of antibiotic treatment (Lalande et al. 2001). Although exposure to potable water is a source of HAIs and determination of the exposure route is critical to prevention, most epidemiological investigations of HAI outbreaks focus on the agent, often overlooking the environmental source of the pathogen, which is a critical consideration for primary prevention of waterborne HAIs.

The microbial community of potable water

Potable WDS contain a diverse microbial community of bacteria, protozoa, and fungi (Williams et al. 2004; Revetta et al. 2010; Henne et al. 2012). Surveys of bacterial populations in North American and European WDS have demonstrated that most systems contain a variety of Proteobacteria, Actinobacteria, Cyanobacteria, Bacteroidetes, and Planctomycetes, most of which are considered non-pathogenic and are unregulated. Included in these communities are several opportunistic pathogens, such as *Sphingomonas paucimobilus*, *Methylobacterium mesophilicum,* and *M. extorquens* in the α-proteobacteria, *Ralstonia pickettii, R. mannitolytica,* and the *Burkholderia cepacia* complex in the β-proteobacteria, *Legionella* spp., *Pseudomonas* spp., and *Stenotrophomonas maltophilia* in the γ-proteobacteria, and environmental NTM in the Actinobacteria. With such a wide range of genera that may cause infections, it is impractical with current technology to have rapid screening methods to detect all potentially infectious agents. These species are not monitored in potable WDS, and infections caused by all but *Legionella* spp. are not reportable to the National Notifiable Disease Surveillance System (CDC online) of the US Centers for Disease Control and Prevention, therefore, it is difficult to assess the burden of disease or the cost of care. Since statistics on *Legionella* infections are available from databases such as the Waterborne Disease and Outbreak Surveillance System (CDC online), this review will primarily discuss other waterborne pathogens chosen based on investigations reported in the peer-reviewed literature.

Common causal agents of waterborne HAIs

Nontuberculous mycobacteria

Many species of environmental NTM can cause skin, bloodstream, respiratory, or systemic infections (De Groote & Huitt 2006; Tortoli 2009). In general, NTM species display high tolerance to commonly utilized disinfectants, and are frequently detected in premise plumbing of healthcare facilities and in the main WDS (Covert et al. 1999; Chang et al. 2002; Nishiuchi et al. 2009; Williams et al. 2011). Although a worldwide systematic assessment of disease burden caused by NTM has not been performed, a few authors have determined that NTM respiratory infections, primarily the community-associated *Mycobacterium avium* complex, in Canada, the USA, and Asia occur at ~1–8 per 100,000 people (Cassidy et al. 2009; Prevots et al. 2010; Adjemian, Olivier, Seitz, Falkinham et al. 2012; Adjemian, Olivier, Seitz, Holland et al., 2012). Evidence suggests that the prevalence of NTM clinical isolates is also increasing annually (Marras et al. 2007; Adjemian, Olivier, Seitz, Holland et al. 2012). In one clinic, the median total treatment duration was 14 months,

with drug costs estimated at $4500–10,800 and non-drug costs around $2700 per patient (Leber & Marras 2011). More difficult to quantify is the cost to quality of life of the long treatment period and multi-drug regimens required by NTM respiratory infections, frequently resulting in adverse drug reactions and disease recurrence (Field et al. 2004). Community-onset *M. avium* complex is the most frequent cause of NTM respiratory disease (Falkinham et al. 2008; Nishiuchi et al. 2009). Even less information is available about disease burden caused by other NTM that are commonly linked to HAI, including other slowly growing mycobacteria, such as *M. kansasii* or *M. xenopi*, and the rapidly growing mycobacteria, including *M. abscessus*, *M. chelonae*, *M. fortuitum*, and *M. mucogenicum*.

CVC exit sites are prone to infection by rapidly growing mycobacteria when protection measures are inadequate. In two hospital outbreaks, patients were infected by showering without adequately covering their CVC exit sites (Kline et al. 2004; Cooksey et al. 2008). A third outbreak was linked to an automatic sink faucet in a pediatric hematology–oncology ward (Livni et al. 2004). All three of these outbreaks were caused by *M. mucogenicum*, which is frequently isolated from WDS (Covert et al. 1999).

The use of non-sterile tap or distilled water to rinse medical equipment has been associated with *M. xenopi* and *M. chelonae* infections (Astagneau et al. 2001; Carbonne et al. 2009). Any medical device or surgical instrument rinsed in non-sterile water after high-level disinfection can potentially infect a patient. A wide range of organisms has been associated with bronchoscope or laparoscope infections and pseudo-infections, including rapidly growing NTM (Kressel & Kidd 2001; Chroneou et al. 2008; Leão et al. 2010), sometimes caused by the waterborne organisms surviving in the disinfectant solution used to reprocess the devices.

Sometimes an increase in infections or colonization by waterborne organisms is reported without determining the specific mechanism of transmission from water to patient (Conger et al. 2004; Garrison et al. 2009, Williams et al. 2011). For instance, in an *M. simiae* outbreak associated with contaminated hospital water, 12 respiratory patients were colonized and one patient potentially had pulmonary disease. *M. simiae,* a photochromogenic slow grower, is not often isolated from potable water. Although the colonization was linked to a hospital and military base water supply, a specific route of transmission was not determined. Sporadic surgical site infections, including occasional infections with *M. abscessus* and *M. xenopi,* have occurred in patients following organ transplant (Bishburg et al. 2004; Garrison et al. 2009). In these reports, either an environmental source was not investigated (*M. xenopi*), or the hospital drinking WDS was examined without finding the genetic match to patient isolates (*M. abscessus*). When the ultimate source of NTM in the healthcare environment is identified, it is most frequently biofilm in the premise plumbing and main WDS. From this, when the source is not discovered, it tends to be attributed to WDS biofilm by extrapolation.

Many NTM pseudo-infections occur in healthcare (Wallace et al. 1998). In some instances, apparent contamination occurs from water in the clinical laboratory, although the source cannot always be determined, for example, during an *M. abscessus* pseudo-outbreak linked to a contaminated laboratory incubator (Blossom et al. 2008). In another study, false positive

acid fast staining of histological sections was attributed to NTM contamination of hospital water used in the staining process (Chang et al. 2002). Long-term contamination of a hospital distilled water system led to two pseudo-outbreaks (Lai et al. 1998; Wallace et al. 1998). Pseudo-infections may also occur when respiratory patients rinse their mouths with drinking water immediately before obtaining a bronchoscopy or sputum sample (Arnow et al. 2000; Lalande et al. 2001; El Sahly et al. 2002). One characteristic that may indicate a pseudo-infection is when the species detected is rarely pathogenic, such as *M. gordonae* (Arnow et al. 2000; Lalande et al. 2001).

Legionella pneumophila

Legionella species, in particular *L. pneumophila*, are environmental Gram-negative bacteria that are important pathogens of the built environment. *L. pneumophila* and other species cause legionellosis, a respiratory infection that can be fatal in elderly or immune-compromised patients (Fields et al. 2002). Although the presence of *Legionella* species is not monitored in US drinking water systems, legionellosis is a reportable disease in the USA. The presence of *L. pneumophila* and other pathogenic *Legionella* spp. is a concern in warm water that can be aerosolized (eg cooling towers and showers). However, ice machines and sink faucets have been a source of *L. pneumophila* infections and pseudo-infection also (Brûlet et al. 2008; Schuetz et al. 2009). Some patients who have trouble swallowing may aspirate melted ice, which has resulted in respiratory infection by *L. pneumophila* in two separate cases (Graman et al. 1997; Bencini et al. 2005). A problem with an ice machine design or installation provided optimal conditions for *L. pneumophila* growth. It was discovered that the water supply tube lay close to warm mechanical parts of the ice machine, heating water to 35 °C before entry into the machine (Bencini et al. 2005).

Pseudomonas aeruginosa

Pseudomonas aeruginosa, a non-fermentative Gram-negative bacillus widely studied as a model organism in the field of biofilm research, is an important pathogen for cystic fibrosis and other compromised patients (Trautmann et al. 2005). Sinks, sink drains, faucet aerators, or tubing attached to sink faucets have frequently served as reservoirs for infection by water bacteria (Ferroni et al. 1998), especially *P. aeruginosa* in intensive care units (ICUs) (Reuter et al. 2002; Cholley et al. 2008; Hota et al. 2009; Inglis et al. 2010; Durojaiye et al. 2011; Table 1). The exposure can be due to design flaws in ICU rooms (Hota et al. 2009) in which patients are exposed to aerosols or droplets created by water splashing out of sink drains.

One difficulty in investigating outbreaks involving *P. aeruginosa* is that it survives well in the hospital environment (Muscarella 2004; Kramer et al. 2006), which may result in indirect transfers through fomites and healthcare workers (Bert et al. 1998). Complications in determining outbreak sources of *P. aeruginosa* have prompted several prospective surveys and monitoring experiments with mixed results (Berthelot et al. 2001; Blanc et al. 2004; Vallés et al. 2004; Petignat et al. 2006; Cholley et al. 2008). Blanc et al. (2004) found that the most frequent source of *P. aeruginosa* was water and not patient-to-patient transmission. By contrast, Reuter et al. (2002) found multiple transmission routes, including faucet to patient and patient to faucet. Berthelot et al. (2001) proposed that patients were colonized

from ICU sinks, but that the sinks were contaminated by patients, and not from the WDS. Part of their evidence to support this hypothesis was the inability to isolate *P. aeruginosa* from water supply samples, but no description was provided on the number of water samples or volume analyzed. However, it is difficult to rule out distribution water as a source because of the dynamic nature of bacterial communities in bulk water, biofilm in the main distribution system, and biofilm in the facility premise plumbing.

P. aeruginosa infections have resulted from many other water exposures, including contamination of CVC exit sites while showering (Aumeran et al. 2007), dilution or contamination of antimicrobial soap, cleaning supplies, or disinfectant (Engelhart et al. 2002; Aumeran et al. 2007; Fanci et al. 2009), and waterbaths to thaw plasma (Muyldermans et al. 1998).

Other proteobacteria

Similar to *P. aeruginosa*, other Gram-negative infections and pseudo-infections have been associated with several different water exposures, including *Methylobacterium mesophilicum* in bronchoscopes (Kressel & Kidd 2001), *Sphingomonas paucimobilis* entry through CVC exit sites during showering (Perola et al. 2002), and contamination of ventilators or nebulizers with *Stenotrophomonas maltophilia* (Denton et al. 2003).

Other Gram-negatives have been implicated in outbreaks with sinks or biofilm formed on aerators in sink faucets as the environmental source, including *Acinetobacter baumannii*, *A. junii*, *S. maltophilia, Elizabethkingia meningoseptica,* and *Serratia marcescens* (Debast et al. 1996; Verweij et al. 1998; Kappstein et al. 2000; Horcajada et al. 2006; J-L Wang et al. 2009). As with *P. aeruginosa*, many investigations do not definitively link these pathogens to water as a source. For *A. baumannii*, since it is capable of surviving for months on hospital surfaces (Kramer et al. 2006), most investigations focus on cross-contamination between patients, healthcare workers, and healthcare surfaces (Markogiannakis et al. 2008), even though *Acinetobacter* species are commonly found in drinking water supplies (Pavlov et al. 2004).

Fungi

Filamentous fungi and yeast have been isolated from hospital WDS (Kauffmann-Lacroix et al. 2008; Hayette et al. 2010), and have been associated with pseudo-infections and infections. *Fusarium solani* has been associated with bronchoscope pseudo-infections (Schaffer et al. 2008). Another retrospective hospital study found that most *Fusarium* infections were community based (Raad et al. 2002). However, *Fusarium* infections in one hospital were associated with fungal colonization of the hospital water system (Anaissie et al. 2001). In another investigation, researchers found that the source of *Aspergillus fumigatus* infections may be plumbing systems or the air (Warris et al. 2003), complicating investigations and prevention efforts.

Potable WDS in the healthcare environment

The reservoir for opportunistically pathogenic organisms in WDS is the bulk water and biofilm coating the interior surface of the pipes of various materials (Norton & LeChevallier

2000; Lehtola et al. 2004; van der Kooij et al. 2005; Wang et al. 2012). The numbers of bacteria in the WDS increases with increasing distance from the water treatment plant (Falkinham et al. 2001). Surveys of NTM in WDS confirm that a wide variety of potentially pathogenic species are recoverable from the main distribution system and hospital water systems (Schulze-Röbbecke et al. 1992; September et al. 2004).

Premise plumbing inside buildings typically harbors higher microbial populations in the bulk water and biofilm than in main WDS (Pepper et al. 2004; Hilborn et al. 2006). Many factors contribute to an increased microbial population, including reduced disinfectant residual (Kline et al. 2004), deadends, and intermittent water use leading to changes in flow rate and periods of stagnation.

Construction in or near a facility can exacerbate the situation when water is turned off in the construction zone, leading to water stagnation and biofouling in pipes for long periods (Mermel et al. 1995; Cooksey et al. 2008). When water flow is restarted, biofilm may slough off pipe surfaces to enter the hospital water supply. Partial, intermittent pressure differentials, or complete loss of pressure may allow stagnant water to backflow into other sections of the plumbing during construction, breakage, or repairs that may lead to increased risk of infection (Nygård et al. 2007; Cooksey et al. 2008). Nygård et al. (2007) assessed acute gastrointestinal illness in family residences, but the results may have meaning for the healthcare community as well. WDS are typically run under positive pressure to reduce extrinsic contamination from microorganisms that may seep into the WDS from the surrounding soil following negative pressure events (LeChevallier et al. 2003). Most reported HAIs that have been associated with potable water often involve extra intestinal infections. Events in the main distribution system may contribute to healthcare outbreaks but most investigators do not pursue this as a specific cause (Mermel et al. 1995).

Challenges in linking clinical isolates to water source

It can be difficult to establish an epidemiologic link between causative agent and the environmental source or reservoir since infectious agents in the water and biofilm in the premise plumbing may be transitory (J-L Wang et al. 2009). The pathogen may also be difficult to detect among other flora or the infection or pseudo-infection could become evident weeks or months after the exposure, as is often the case with NTM (Bettiker et al. 2006). Frequently, a related species will be isolated from the suspected water source, but not the species associated with the infection. If the matching species is isolated from the environment, it may differ genetically from the isolates recovered from the patients. Often the infection source will be suggested by temporal associations, as was seen in a hospital that had three *L. pneumophila* outbreaks during three periods of construction near the facility (Mermel et al. 1995). However, it would be challenging to confirm the association without frequent monitoring of water in the hospital and in the main supply for *Legionella* before, during, and after construction occurs.

Frequently, investigators have difficulty in finding an identical genotypic match between patient and water isolates. In one case, at least 11 *M. avium* isolates in a respiratory patient's home showerhead were related to the clinical isolate, as demonstrated by IS1245/

IS1311 restriction fragment length polymorphism analysis, but none were indistinguishable (Falkinham et al. 2008). Researchers that have published prospective epidemiological and microbiological studies of infections by waterborne pathogens in healthcare settings, especially ICUs, have stressed the need to include a rigorous environmental sampling strategy (J-L Wang et al. 2009). However, when the clinically similar species is isolated repeatedly from the premise plumbing, and several environmental isolates are closely related but not geno-typically identical to the patient isolates, this suggests that the target species may be a long-term resident of the biofilm in the premise plumbing that is genetically drifting. Ideally, the background genetic diversity of each relevant species found in premise plumbing biofilm and other drinking water environments should be determined to know the significance of finding isolates that are closely related genotypic matches to patient isolates.

Current infection prevention and control measures, and future directions

Preventing waterborne HAI requires a variety of measures that may be tailored to specific patients, pieces of medical equipment, or entire healthcare facilities. Although some large hospitals use point-of-entry (POE) supplemental treatment systems to treat incoming water, this may not be feasible, efficacious, or necessary in other settings. The published investigations suggest that two targeted prevention strategies may be warranted, depending on the opportunistic pathogen of concern: one for healthcare premise plumbing and another for the environment in direct contact with the patient. The source for NTM and *Legionella* spp. is most often biofilm within premise plumbing and fixtures in healthcare facilities. In contrast, certain non-fermentative Gram-negative species, such as *P. aeruginosa*, are rarely isolated from WDS systems, yet found frequently in moist environments close to the patient (eg sink basin, faucet, or drain, but not in the sink supply water). Although it is not currently possible to evaluate every healthcare water system for all possible opportunistic pathogens, it is a reachable goal to take lessons from previous investigations to target prevention efforts more effectively. Some examples of equipment or plumbing remediation that facilities have implemented are described.

Ice machines

NTM pseudo-outbreaks linked to contaminated ice machines in hospitals have been caused by *Mycobacterium fortuitum* (Gebo et al. 2002; LaBombardi et al. 2002) and *M. paraffinicum* (S-H Wang et al. 2009). In some cases, even after following cleaning guidelines, ice machines became intractably contaminated with environmental mycobacteria (Gebo et al. 2002). In one case, two machines were replaced to stop the pseudo-outbreak (LaBombardi et al. 2002). In other situations, installing inline bacteriostatic water filters resolved the problem (Gebo et al. 2002; S-H Wang et al. 2009). In these incidents, the organisms were not isolated from other sections of the hospital water supply, suggesting that environmental mycobacteria may amplify in ice machines beyond the background level present in the incoming water.

Although specific problems sometimes contribute to ice contamination, a more common problem seems to be neglected maintenance. In an audit of ice machine maintenance in three hospitals, only one out of three hospitals had scheduled cleaning for their ice

machines, and the one hospital had no records of the cleaning taking place (King 2001). No scheduled maintenance was performed, and manufacturer manuals were not available for any of the 22 machines examined. Testing the microbiological quality of six machines by examining ice and swab samples demonstrated that yeast, *Pseudomonas*, coliforms, and other bacteria heavily colonized the inside walls and ice of all six machines. Despite the heavy bacterial contamination, no known infections were caused by the evaluated ice machines, suggesting that additional factors may contribute to infection or colonization after exposure to opportunistic pathogens in ice.

The CDC has published guidelines on maintenance of ice machines in the healthcare environment, from guidance on hygienic maintenance of the ice scoop, to scheduled cleaning and disinfection of all surfaces (Manangan et al. 1998; CDC 2003).

Sinks, sink drains, faucet aerators, and attachments

Measures to control infections caused by organisms in sinks sometimes involve extreme actions, for example, replacing sinks, as well as continued disinfection of sink traps with chlorine to control *P. aeruginosa* infections in an ICU (Bert et al. 1998). One outbreak was resolved by renovating sinks and surrounding areas in the following manner: sink traps were replaced, water pressure was decreased, patient care materials were moved more than 1 m from sinks, a barrier was placed between the sinks and medication preparation areas, and faucet spouts were replaced with ones that did not cause water to flow directly into the drain (Hota et al. 2009). This group performed an extensive investigation that tied an isolate from the sink drain to clinical isolates, and determined the extent of splashing that occurred during sink usage.

Electronic-eye or non-touch faucets are frequently used in healthcare facilities for hand washing. They can minimize water usage and prevent cross-contamination because dirty hands do not touch surfaces (manual valve handles) that could promote pathogen transmission. However, recent investigations have found that electronic faucets are more contaminated with bacteria than older manual faucets in the same facility (Merrer et al. 2005; Sydnor et al. 2012). The clinical implications of those findings are unknown. Three published outbreaks identified electronic faucets as the source of pathogen transmission (Livni et al. 2004; Durojaiye et al. 2011; Yapicioglu et al. 2012). *M. mucogenicum* bloodstream infections in a pediatric hematology–oncology ward (Livni et al. 2004), *P. aeruginosa* infections in an adult ICU (Durojaiye et al. 2011), and *P. aeruginosa* infections in a neonatal intensive care unit (NICU) (Yapicioglu et al. 2012) were associated with electronic faucets. All three investigators performed some degree of environmental testing to confirm water from electronic faucets as the infection source. Possible causes of increased bacterial load may be that electronic faucets contain more components (larger surface area) on which to harbor biofilm than manual faucets (Sydnor et al. 2012), or stagnant water is held in the faucet after mixing at a temperature conducive for bacterial growth. Although more extensive studies are needed to demonstrate that electronic faucets increase infection risk in patients, the current data are suggestive and merit additional research.

Clear guidelines about faucet aerators in healthcare facilities have not been developed beyond recommending monthly cleaning and disinfection in areas with high-risk patients

to control *Legionella* (CDC 2003). However, some infection control experts have recommended regular cleaning of aerators, or removal of aerators from high-risk areas (Kappstein et al. 2000).

Showerheads

Community analysis of biofilm inside showerheads has demonstrated that several opportunistic pathogens, especially NTM such as the *M. avium* complex, are frequently present, possibly in numbers amplified above those in the main WDS (Feazel et al. 2009). Aerosol and water exposure from residential showering or bathing has been associated with *M. avium* pulmonary infections (Falkinham et al. 2008; Nishiuchi et al. 2009). In healthcare environments, since showering is sometimes the source of catheter exit site infections, the most effective prevention measure is to ensure adequate protection of catheter exit sites (CDC 2000; Perola et al. 2002; Kline et al. 2004; Aumeran et al. 2007; Cooksey et al. 2008).

One hospital evaluated ‘electric showers’, devices to instantly heat water for showers, as an intervention to control *L. pneumophila* after an outbreak of legionellosis in their renal transplant unit (Oliveira et al. 2007). In follow-up testing, only one sample contained *L. pneumophila* after monitoring for more than 5 years. Constant maintenance is required to clean the shower heaters each month. Although this prevention measure has not been validated in other hospitals, the authors determined that it was more effective than super heating or hyperchlorinating the water system (Oliveira et al. 2007).

Invasive procedures, including surgery, endoscopy, bronchoscopy, and laparascopy

L. pneumophila infections have occurred following organ transplant (Oren et al. 2002). Supplemental water treatment, including heat and chlorine treatment of the hot water system, successfully reduced infection reoccurrence without using genotyping to confirm the infection source.

Improperly cleaned bronchoscopes, endoscopes, and laparoscopes are common sources of outbreaks and pseudo-outbreaks (Weber & Rutala 2001; Leão et al. 2010). Many times infections or colonization of patients are caused by inadequate reprocessing of endoscopic or laparoscopic equipment caused by equipment malfunction, user error, a defect in the instrument, or design issues that make reprocessing difficult. The source of contamination may be water, a cross-contamination event from a previous patient, or contamination from another scope. If proper remediation can be performed to stop the transmission, then it may not always be necessary to find the original source of the organism. For instance, during a massive outbreak of *M. abscessus* subsp. *massiliense* infections following laparoscopic or arthro-scopic surgery, the interventions focused on improving disinfection methods for the scopes between uses, rather than determining the original source of the rapidly growing *Mycobacterium* (Duarte et al. 2009; Leão et al. 2010). Guidelines have long been developed to reduce contamination during reprocessing. After cleaning, endoscopes or bronchoscopes should be rinsed in tap, filtered, or sterile water followed by 70% ethanol or isopropanol, then thoroughly air-dried (Alvarado & Reichelderfer 2000; Rutala & Weber 2008).

Soaps, cleaning solutions, and antiseptics

Antiseptics and other solutions diluted with tap water, and stored for multiple uses, occasionally can be sources of infection (Engelhart et al. 2002; Tiwari et al. 2003; Nasser et al. 2004; Fanci et al. 2009). In a series of *B. cepacia* bloodstream infections that were traced to an ethanol solution prepared on site with drinking water for skin and vial preparation, once the hospital switched to commercial pre-packaged single use alcohol and antiseptic swabs, the infection rate was greatly reduced (Nasser et al. 2004).

Hydrotherapy pools

Hydrotherapy pools, whirlpools, hot tubs, and physiotherapy tanks have been used traditionally to treat a variety of conditions, including arthritis, orthopedic impairments and injuries, amputations, kidney lithotripsy, septic ulcers, lesions, burns, and birthing tanks (McCandlish & Renfrew 1993; Rutala & Weber 1997). Infections associated with the use of hydrotherapy equipment include incidental ingestion of water, sprays, and aerosols, and direct contact with wounds and intact skin. Several organisms have caused infections among patients, including *Acinetobacter baumannii* (Simor et al. 2002), *Alcaligenes (Achromobacter) xylosoxidans* (Fujioka et al. 2008), *Enterobacter cloacae* (Mayhall 2003), *Legionella* sp. (Marrie et al. 1987), *M. avium* (Angenent et al. 2005), *P. aeruginosa* (Hollyoak et al. 1995; Berrouane et al. 2000; Green 2000), and *Staphylococcus aureus* (Embil et al. 2001). Although some infections were traced to water organisms in biofilm in the hydrotherapy pool fixtures or plumbing, some of these cases represent cross-contamination of the hydrotherapy pool from patients. Hydrotherapy tanks contain closed-cycle water systems that circulate, aerate, and agitate warm water in a temperature range that is ideal for microbial growth if maintenance lapses. Proper maintenance is particularly important in larger therapy or exercise pools that cannot be drained for cleaning and disinfection between patient uses. In this case, maintenance includes the use of pH and chlorine residual levels appropriate for an indoor pool as provided by local and state health agencies (CDC 2003).

Construction or renovation of healthcare facilities

Architectural guidelines have been developed when designing or renovating water systems in healthcare facilities to limit dead ends and stagnant sections of the distribution system (American Society for Healthcare Engineering [ASHE] 2010). CDC and others recommend the inclusion of infection control personnel in planning construction activities, or in monitoring water quality during construction in or near the healthcare facility (CDC 2003; Bartley et al. 2010). Additionally, they emphasize the importance of flushing water systems that have been damaged or shut off during construction before patients are exposed to the water. The pressure changes that occur when water flow is stopped and restarted may dislodge sediment, corrosion products, and biofilm that contain opportunistic pathogens (Bartley et al. 2010).

Single treatment remediation of healthcare facility premise plumbing, such as shock treatment with hypochlorite, chlorine dioxide (Leoni et al. 2006; García et al. 2008), peracetic acid or heat (Ditommaso et al. 2005), typically have short-term success. Frequently, the pathogen will regrow in premise plumbing biofilm or recolonize the

premise plumbing system from the main water supply. To make shock treatments effective, consistent monitoring is required. The length of time between treatments must be determined in each facility by initial monitoring to ensure success in limiting regrowth of the problem organism. If frequent shock treatments are required, assessing feasibility of this prevention method must take into account the time when the WDS will be offline during each treatment.

Long-term POE water treatment systems include supplementing incoming water with chlorine, monochloramine, chlorine dioxide, or copper-silver ions. Somewhat limited data have suggested that these systems can be efficacious, if disinfectant level is consistently maintained to prevent regrowth in the plumbing (Kusnetsov et al. 2001; Shih & Lin 2010; Marchesi et al. 2012).

An alternative to POE treatment of the entire premise plumbing system in a healthcare facility is to target the sinks and showers of susceptible patients with point-of-use (POU) filters. It has been determined that carbon-based filters may remove microbes when initially installed, but tend to seed water with HPC bacteria and opportunistic pathogens as the filter ages (Chaidez & Gerba 2004). However, several companies produce POU membrane filters, which have been demonstrated to significantly reduce HPC bacteria and/or opportunistic pathogens such as *L. pneumophila*, *P. aeruginosa*, and NTM when used according to the manufacturer's instructions to avoid issues with possible retrograde contamination (Hall et al. 2004; Vonberg et al. 2005; Daeschlein et al. 2007; Williams et al. 2011). One group assessed practices in 10 UK hospitals for providing potable water to immune-compromised patients (Hall et al. 2004). During the survey, the group tested membrane filters attached to sink faucets for post-use bacterial levels, and confirmed that the filters provided a barrier to opportunistic pathogens. After considering issues of patient and staff safety, logistics, patient confidentiality, and cost, the authors determined that POU membrane filtration was the most cost-effective way of providing immune-compromised patients with safe drinking water.

Current prevention measures can be found within published CDC recommendations (a list of CDC guidelines is accessible online at http://www.cdc.gov/hicpac/pubs.html). In 2003, the Healthcare Infection Control Practices Advisory Committee (HICPAC) and CDC issued recommendations for the prevention and control of infectious diseases that are associated with healthcare environments, including new water quality guidelines for healthcare facilities. The recommendations included strategies for controlling the spread of waterborne microorganisms within the healthcare environment, preventing contamination of the WDS, including special considerations for construction (eg pressure drops) and emergency events (eg extreme weather), prevention of and response to *Legionella* contamination, and specific guidelines for medical equipment and water system components commonly implicated in outbreaks of waterborne infectious diseases, such as cooling towers, dialysis water, ice machines, and hydrotherapy tanks. Whereas previous infection control guidelines focused on acute-care hospitals, the 2003 guidelines were expanded to reflect the shift toward an increase in outpatient care, including outpatient surgical centers, urgent care centers, clinics, outpatient dialysis centers, physicians' offices, and skilled nursing facilities.

In 2011, the World Health Organization (WHO) updated their guidelines for drinking water quality. The 2011 guidelines recommend that all hospitals and other healthcare facilities adopt a water safety plan (WSP) as part of their infection control program, in order to reduce the number of HAIs potentially acquired from water. The WSP includes drafting health-based targets, performing a water system assessment for the facility, monitoring microbial counts for organisms of interest, disseminating information and communicating recommendations, and maintaining surveillance activities. A healthcare facility's WSP must include both prevention and control measures for infectious diseases associated with water. The guidelines were based on the multiple-barrier approach and the Hazard Analysis and Critical Control Points frame-work utilized by the US Food and Drug Administration, among other previously published infection control guidelines. The WSP should address issues specific to the facility, including relevant water quality and treatment requirements, protocols for the cleaning of specialized equipment used by the facility, and the control of microbial growth in water systems and equipment connected to the water lines.

In 2007, a multi-center university clinic in Germany reported on their successful implementation of a WSP, based on the 2004 WHO guidelines, after microbial water quality surveillance for 3 years (Dyck et al. 2007). They found that water quality was significantly improved after implementing the hospital's WSP, and observed a decrease in neonatal sepsis (reduced from 46 to 11% in very low birth weight neonates) and no new cases of nosocomial *L. pneumophila*, despite screening each case of pneumonia for *Legionella* sp. This demonstrates how HAI from drinking water may be decreased, even with incomplete knowledge of waterborne disease burden.

Research needs

For the future, interdisciplinary study is required to fully understand disease burden caused by WDS opportunistic pathogens (Table 2). Standardized detection methods should be developed to increase the success in finding the environmental source of the opportunistic pathogen, and to enable comparison of results between facilities. A thorough multi-site study of waterborne HAI that includes infection surveillance, epidemiology, clinical, and environmental microbiology would fill some knowledge gaps and take an important step toward defining exposure and infection risks for patients. Ideally, a thorough comparison of supplemental POE and POU water treatments would allow healthcare facilities to choose the most cost effective prevention measures to suit their circumstances (National Research Council [NRC] 2006).

Conclusions

Although opportunistic pathogens in drinking water belong to many kingdoms (bacteria, fungi, and protozoa), with different growth characteristics, virulence, and types of infections that they cause, the same general parameters of water conditions in the built environment may encourage or discourage growth of these organisms in biofilm within premise plumbing. To develop a quantitative risk assessment of waterborne HAI, research is needed to better understand the quantity, viability, and virulence of opportunistic pathogens in potable water system biofilm and their rate of release from biofilm into potable water.

Meanwhile, thoroughly implementing current infection control guidelines has proven to reduce water-related HAI in some healthcare facilities. Limiting severely compromised patient access to non-sterile water is a practical approach to reducing infection, especially with ever-changing technological developments that frequently lead to new and unforeseen exposure routes.

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Table 1.

Summary of HAI with potable water as the probably source.

Organism	Reservoir/infection route	Corrective action	Reference
Nontuberculous Mycobacteria			
M. abscessus	Pseudo-infections/infections, distilled water contaminated	Switched to commercial, sterile water and reagents in lab and in endoscope reprocessing	Lai et al. (1998)
M. abscessus	Injection site infections due to contaminated benzalkonium chloride	Recommended that the clinic stop use of benzalkonium chloride or other quaternary ammonium compounds as an injection site disinfectant	Tiwari et al. (2003)
M. abscessus	Surgical, unknown exposure	Antibiotics, surgical excision, no remediation of water system	Garrison et al. (2009)
M. abscessus (*massiliense*)	Localized, post-surgical infections after laparoscopy and other procedures	Improved cleaning and sterilization protocols	Duarte et al. (2009); Leão et al. (2010)
M. avium complex	Hydrotherapy pools, aerosols	None	Angenent et al. (2005)
M. chelonae	Injection site infections	Automatic injectors for mesotherapy rinsed with tap water between uses, infection control response not specified	Carbonne et al. (2009)
M. chelonae	Pseudo-outbreak, automated bronchoscope washer	Began changing filters on schedule	Chroneou et al. (2008)
M. chelonae (and Methylobacterium mesophilicum)	Pseudo-outbreak, automated endoscope washer	Replaced endoscopes and switched from glutaraldehyde to peracetic acid disinfection	Kressel and Kidd (2001)
M. chelonae	Laparoscopy port-site infections	Stopped rinsing laparoscopic equipment with tap water, switched from glutaraldehyde to ethylene oxide sterilization	Vijayaraghavan et al. (2006)
M. chelonae	Respiratory colonizations/infections, unknown exposure route from drinking water	POU membrane filters installed and maintained on sink faucets	Williams et al. (2011)
M. fortuitum	Pseudo-infections; sputum samples; contaminated with ice	Disinfected ice machine and installed filter; replace ice machines	Gebo et al. (2002); LaBombardi et al. (2002)
M. gordonae	Pseudo-infections; sputum samples; contaminated with drinking water	Advise patients not to rinse mouths with tap water before sampling; replaced rubber tubing in drinking fountain	Arnow et al. (2000); Lalande et al. (2001)
M. mucogenicum	Bacteremia, CVC exit site infection	Removed catheters; protected CVC exit sites from water during bathing; replaced contaminated faucets, and achieved optimal water chlorination	Kline et al. (2004); Cooksey et al. (2008); Livni et al. (2004)
M. paraffinicum	Pseudo-infections and colonizations from ice	Installed inline membrane filters in ice machines	S-H Wang et al. (2009)
M. simiae	Pseudo-infections, unknown exposure route from drinking water	Hyperchlorination	El Sahly et al. (2002)
M. xenopi	Spinal infections	Stopped rinsing surgical devices with tap water after disinfection	Astagneau et al. (2001)
M. xenopi	Pseudo-infections, bronchoscope-associated	Stopped rinsing bronchoscopes with tap water	Bennett et al. (1994)
M. xenopi	Surgical, unknown exposure	Antibiotics, no remediation of water system	Bishburg et al. (2004)

Organism	Reservoir/infection route	Corrective action	Reference
Legionella pneumophila			
	Ice machine	Disinfection of ice machine: 2h flush with 2.6% sodium hypochlorite, replace tubing connecting machine to water system; cold water supply: 83 ppm sodium hypochlorite for 48 h; follow-up surveillance: microbiological environmental sampling	Graman et al. (1997)
	Ice machine	Ice from machine was not intended for consumption, hospital had *Legionella* control policy for drinking water	Bencini et al. (2005)
	Ice and contaminated syringes	Cleaned ice machine, replaced filter, improved aseptic practices	Schuetz et al. (2009)
	Water taps, shower heads	Superheated water, cleaned shower heads with a sonicating washer, and raised the hot water storage tank temperature from 43 to 52 °C	Mermel et al. (1995)
	Showers/central hot water	Replaced showers heated by central hot water with electric showers	Oliveira et al. (2007)
	Nebulizers in a clinical spa	Restructured (updated) water system and heat shock treatment, superheated steam for nebulization machines	Leoni et al. (2006)
	Wash basin	Replaced faucet mixing valves, installed filters, chlorinated hot water system	Brûlet et al. (2008)
	Pseudo-infections, Bronchoscopes	Introduction of regular water filter maintenance program and microbiological surveillance	Mitchell et al. (1997)
	Drinking water, unknown exposure of bone marrow transplant patients	Supplemental heat and chlorine treatment of hot water system	Oren et al. (2002)
	Central hot water system	Peracetic acid, repeated short term treatments only effective temporarily	Ditommaso et al. (2005)
Pseudomonas aeruginosa			
	Sinks	Repaired plumbing, replaced sinks, and disinfected sink traps with bleach on a maintenance schedule	Bert et al. (1998)
		Pasteurize taps weekly, use sterile water for food and medicine in patients' gastric tubes	Bukholm et al. (2002)
		Cleaning and disinfection unsuccessful due to biofilm formation, necessitated a structural review of the hospital's water system, repeated dismantling and disinfection of drains	Gillespie et al. (2000)
		Treated sink with chlorine	Berthelot et al. (2001)
		Used contact precautions (healthcare workers wore gowns and gloves, patient isolation) for all colonized or infected cases; staff education; enhanced environmental cleaning; disinfection of hand hygiene sink drains; and renovation of hand hygiene sinks to prevent splashing of drain contents Outbreak controlled only after sink renovation	Hota et al. (2009)
		Replaced faucet taps	Ferroni et al. (1998)
		Sterilized faucet aerators, installed single-use filters on ICU water outlets	Trautmann et al. (2001); Reuter et al. (2002); Trautmann et al. (2005)
	Sensor mixer sink faucets	Silver nitrate, replaced sensor taps with non-sensor mixer taps	Durojaiye et al. (2011)
	Bacteremia, sink or shower probable source	Installed disposable sterile filters on all taps and showers, replaced weekly	Vianelli et al. (2006)

Organism	Reservoir/infection route	Corrective action	Reference
	Bacteremia, CVC exit site infection	Chlorination of water lines and use of disposable seven-day filters on all taps and showers, use of microbiologically controlled water for high risk patients	Aumeran et al. (2007)
	Water bath to thaw frozen plasma	Replaced waterbath with a dry heat incubator	Muyldermans et al. (1998)
	Disinfectant hand soap, sink faucets	Installation of water filters and water network hyperchlorination, follow-up surveillance of environmental samples	Fanci et al. (2009)
	General patient room environment	Changed room surface cleaning solution to a disinfectant, added filters to patient room faucets and showerheads, disinfected drains with peroxides	Engelhart et al. (2002)
Other Gram-negative bacteria			
Serratia marcescens	Drinking water	Provided sterile drinking water for critical care patients	Horcajada et al. (2006)
Acinetobacter baumannii	Sinks	Changed surface cleaning solution to a disinfectant effective against *A. baumannii*	Debast et al. (1996)
Stenotrophomonas maltophilia	Sinks in a NICU	Reinforced hand disinfection, switched to sterile water for bathing newborns	Verweij et al. (1998)
S. maltophilia	Faucet aerators, water taps, shower heads, decorative fountain	Disinfection of aerators with bleach	Weber et al. (1999)
Acinetobacter junii	Faucet aerators, sink faucets	Removed aerators	Kappstein et al. (2000)
N on-fermentative Gram-negative bacilli (NFGNB)	Faucet aerators	Use of sterile water in ICU, infection control education of hospital staff	J-L Wang et al. (2009)
Sphingomonas paucimobilis	Catheters (showering)	Instituted routine removal and hypochlorite disinfection of faucet aerators and showerheads	Perola et al. (2002)
Burkholderia cepacia	Antiseptics, clinical solutions, soaps, mouthwash	Patient skin and heparin vial caps were disinfected with alcohol diluted with tap water. Hospital switched to single-use alcohol swabs	Nasser et al. (2004)

Table 2.

A summary of research needs to improve prevention of waterborne HAI.

Within healthcare facilities	Understand the influence of the microbial biofilm community on opportunistic pathogen survival, growth, dispersal, and virulence Determine how conditions in facility plumbing contribute to waterborne HAI, including plumbing design, pipe materials, age of the plumbing (ie age of the biofilm), temperature, and patterns of water use Define exposure and infection risks of patients with various levels of susceptibility to tailor prevention measures to the patient Develop standardized culture- and molecular-based methods to detect and isolate environmental opportunistic pathogens Increase effort to determine the environmental source of a pathogen during outbreaks Evaluate the efficacy of supplemental water treatment in facilities Assess new appliances or plumbing fixtures (eg electronic faucets) to determine if the item enhances or degrades microbial water quality
Outside of healthcare facilities	Determine the role that water source or treatment plays in opportunistic pathogen presence in healthcare facility plumbing Evaluate conditions in the main WDS that impact microbial water quality in healthcare facilities, such as pressure changes, age of the infrastructure, major weather events Develop collaboration between healthcare facilities and water utilities for research and infection prevention efforts