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# Healthcare Outbreaks Associated With a Water Reservoir and Infection Prevention Strategies

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Hospital water may serve as a reservoir of healthcare-associated pathogens, and contaminated water can lead to outbreaks and severe infections. The clinical features of waterborne outbreaks and infections as well as prevention strategies and control measures are reviewed. The common waterborne pathogens were bacteria, including *Legionella* and other gram-negative bacteria, and nontuberculous mycobacteria, although fungi and viruses were occasionally described. These pathogens caused a variety of infections, including bacteremia and invasive and disseminated diseases, particularly among immunocompromised hosts and critically ill adults as well as neonates. Waterborne outbreaks occurred in healthcare settings with emergence of new reported reservoirs, including electronic faucets (*Pseudomonas aeruginosa* and *Legionella*), decorative water wall fountains (*Legionella*), and heater-cooler devices used in cardiac surgery (*Mycobacterium chimaera*). Advanced molecular techniques are useful for achieving a better understanding of reservoirs and transmission pathways of waterborne pathogens. Developing prevention strategies based on water reservoirs provides a practical approach for healthcare personnel.

**Keywords.** waterborne outbreaks; healthcare-associated infections; water; outbreaks.

Hospital water and water-related devices as well as moist environments and aqueous solutions can serve as a reservoir of waterborne pathogens in healthcare settings [1, 2]. The hospital environment may allow contamination by waterborne pathogens, in part because water temperatures are suitable for bacterial growth, and the complex structure of hospital water systems often leads to stagnation, corrosion, and biofilm formation [3]. A variety of water reservoirs have been linked to nosocomial outbreaks including potable water, sinks, faucet aerators, showers, tub immersion, toilets, dialysis water, ice and ice machines, water baths, flower vases, eyewash stations, and dental-unit water stations [4]. Waterborne pathogens have included *Legionella*, other gram-negative bacilli, nontuberculous mycobacteria (NTM), fungi, protozoa, and viruses [3–5]. Transmission of these pathogens from a water reservoir may occur by direct and indirect contact, ingestion and aspiration of contaminated water, or inhalation of aerosols [1, 2]. Waterborne outbreaks caused by these pathogens and reservoirs have occurred among patients in healthcare settings and have been a serious threat to high-risk patients, especially critically ill patients and immunocompromised hosts, leading to substantial morbidity and mortality [3–5].

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The aim of this review article was to (1) review healthcare-associated outbreaks and infections associated with a water reservoir from the published literature, and (2) provide infection prevention strategies and control measures by water reservoirs based on the published scientific evidence and available guidelines.

## SEARCH AND SELECTION CRITERIA FOR REVIEWING THE LITERATURE

We searched the published literature via PubMed using the following Medical Subject Headings (MeSH) and keywords: (hospital OR hospitals OR hospital units OR nursing homes OR ambulatory care facilities OR ambulatory care OR dental facilities OR assisted living facilities OR healthcare settings OR patient) AND (waterborne pathogens OR *Legionella* OR Legionnaires' disease OR bacterial infections OR *Mycobacterium* infections OR fungal infections OR mycoses OR protozoan infections OR healthcare-acquired infection OR nosocomial OR cross infection OR outbreak) AND (hospital water OR drinking water OR potable water OR ice OR sink OR faucet OR faucet aerator OR shower OR tub or toilet OR water fountain OR water bath OR dialysis water OR decorative fountain OR ice machine OR air conditioning OR heater-cooler unit OR water microbiology OR disease reservoirs).

From January 1967 to July 2015, 2445 publications were identified as a result of our search and were reduced to 1746 by filters of availability in English and abstracts. The 1189 references (January 1997–July 2015) were screened using titles and abstracts, then selected articles were carefully reviewed. For the references published before 1997, we cited a previous review article [4] because of limited numbers of citable references. We excluded articles without abstracts, non-English-language articles, articles that were unavailable in PubMed, reported cases of contaminations or pseudo-outbreaks, and articles that did not include human infections. We identified 179 references by our initial screening process, and then prioritized listed citations to include at least 1 article from each reservoir and organism. Finally, 73 original articles [6–78] were selected and data were retrieved for further analysis. Table 1 provides the features of waterborne healthcare-associated outbreaks and infections by each category, including author, publication year, reservoir, organism, transmission, patient population, infection type, molecular typing, and study type.

## HEALTHCARE-ASSOCIATED OUTBREAKS AND INFECTIONS CAUSED BY WATERBORNE PATHOGENS

A review of the literature revealed multiple outbreaks in healthcare facilities due to a variety of pathogens associated with a water reservoir (Table 1). Infections included bloodstream infections, pneumonia, and disseminated diseases (Table 1). Patient populations at risk for waterborne outbreaks and infections included those with hematological and other malignancies or stem cell transplants, immunocompromised patients, location in an intensive care unit (ICU), premature infants in a neonatal intensive care unit (NICU), burn patients, and patients during/after surgery (Table 1).

Causative pathogens included bacteria (*Legionella*, *Pseudomonas*, *Acinetobacter*, *Serratia*, *Stenotrophomonas*, *Enterobacter*, *Klebsiella*, *Alcaligenes*, *Burkholderia*, *Chryseobacterium*, *Elizabethkingia*, *Halomonas*, *Ochrobactrum*, *Sphingomonas*, NTM), fungi (*Aspergillus*, *Mucor*, *Trichosporon*, *Fusarium*, *Exophiala*), and viruses (norovirus) (Table 1). Details of overall waterborne pathogens in healthcare-associated infections [3, 5, 79–82], and specifically *Legionella* [83–86], *Pseudomonas aeruginosa* [87, 88], *Aspergillus* [89], and NTM [90], have been previously reviewed. *Legionella* and NTM can reside in hospital water distribution systems, while other gram-negative bacteria and fungi can form biofilms [3, 79]. We briefly updated key points from recent literature on healthcare-associated pathogens in waterborne outbreaks and infections as described below.

### Legionella

*Legionella* can be detected in most water sources at low levels [91]. The level of contamination of *Legionella* in hospital water systems associated with disease remains unclear. A large healthcare-associated *Legionella* outbreak occurred at a Pennsylvania hospital despite implementing a *Legionella* disinfection program with a copper-silver ionization system of hospital water [40]. In this outbreak, a link between clinical isolates of *Legionella* and hospital environmental samples was confirmed by molecular typing, and *Legionella* was viable and transmissible despite the presence of copper and silver ion concentrations within the manufacturer's recommended range [40].

### Multidrug-Resistant Gram-Negative Bacteria

As antimicrobial resistance in bacteria has become a global concern, multidrug-resistant gram-negative bacteria (*Klebsiella*, *Enterobacter*, *Pseudomonas*, *Acinetobacter*), including bacteria producing extended-spectrum β-lactamases or carbapenemases (eg, *Klebsiella pneumoniae* carbapenemase [KPC] and New Delhi metallo-β-lactamase), were described as waterborne pathogens causing healthcare-associated infections [19, 21, 22, 48, 50, 52, 54, 55, 57–59, 70, 71]. Multidrug-resistant organisms were most commonly linked to contaminated sinks as a reservoir (Table 1). Notably, an outbreak of 6 infections due to KPC-2–producing *Klebsiella oxytoca* in patients with hematological malignancies was linked to contaminated handwashing sinks [57].

### Nontuberculous Mycobacteria

Our review found that a variety of NTM, including both rapid-growing and slow-growing species, has led to waterborne healthcare-associated outbreaks and infections as follows: *Mycobacterium abscessus* with tap water, *Mycobacterium avium* with potable water, *Mycobacterium chelonae* with ice and ice machines, *Mycobacterium chimaera* with heater-cooler units, *Mycobacterium fortuitum* with hospital water systems and showers, *Mycobacterium genavense* with tap water, *Mycobacterium mucogenicum* with bathing and tub immersion, electronic faucets, sinks, showers, and hospital water systems, *Mycobacterium neoaurum* with hospital water systems, *Mycobacterium phocaicum* with showers, *Mycobacterium porcinum* with ice and ice machines and tap water, and *Mycobacterium simiae* with tap water [7, 13, 20, 27, 28, 31, 34, 35, 37, 41, 45, 51, 60, 62, 66]. NTM can be present in municipal water systems and is relatively resistant to chlorination as well as being difficult to eradicate from contaminated water systems [3].

### Fungi

Waterborne fungal outbreaks and infections occurred among patients with hematological malignancies or stem cell transplantation. *Aspergillus* can be detected from hospital water samples and has been reported to cause invasive aspergillosis [25, 43, 68, 89]. However, there are no criteria for contamination levels of hospital water associated with fungal infections. Furthermore, whether *Aspergillus* can cause waterborne healthcare-associated infections via aerosols generated from contaminated hospital water remains controversial [92]. Other fungal outbreaks associated with water reservoirs included *Mucor* with water-damaged plaster, *Trichosporon asahii* with wash basins, *Fusarium* with showers and sinks in a hospital water distribution system, and *Exophiala jeanselmei* with deionized water from the hospital pharmacy [11, 24, 74, 78].

**Table 1. Characteristics of Waterborne Outbreaks and Infections in Healthcare Settings, 1997 January–2015 June**

| Reservoir | Organism(s) | Transmission | Patient Population | Type of Infection | Molecular Typing | Study Type | First Author, Year |
|---|---|---|---|---|---|---|---|
| Bathing and tub immersion (bathing tub drain) | *Pseudomonas aeruginosa* | Tub immersion water contaminated from drain when whirlpool bathtub filled | Patients with hematological malignancies (leukemia) | Bloodstream infection, pneumonia, UTI | PFGE | Outbreak – strong causation | Berrouane, 2000 [6] |
| Bathing and tub immersion (showering) | *Mycobacterium mucogenicum* | Water contamination of CVCs during bathing or showering | BMT and oncology patients | Bacteremia | RAPD | Outbreak – strong causation | Kline, 2004 [7] |
| Bathing and tub immersion | *Legionella pneumophila* | 24 h bath water contaminated | An elderly patient with dementia admitted to a nursing home | Pneumonia | PFGE | Case report (single) – strong causation | Mineshita, 2005 [8] |
| Bathing and tub immersion (bathing mattress) | *Alcaligenes xylosoxidans* | Bathing procedures and hydrotherapy in burn unit | Burn patients | Cholecystitis, meningitis | PFGE | Case report (single) – strong causation | Fujioka, 2008 [9] |
| Decorative water fountain | *Legionella pneumophila* | Exposure to contaminated water from decorative fountain | Allogeneic stem cell transplant patients | Pneumonia | PFGE | Outbreak – strong causation | Palmore, 2009 [10] |
| Deionized water from the hospital pharmacy | *Exophiala jeanselmei* | Contaminated deionized water solution that was used to prepare antiseptic solutions | Hematological malignancies | Fungemia | RAPD | Outbreak – strong causation | Nucci, 2002 [11] |
| Dialysis water supply | *Burkholderia cepacia* | Inadequate cleaning and a leak in the reverse osmosis tubing connection | Hemodialysis patients | Bacteremia | RAPD | Outbreak – strong causation | Souza, 2004 [12] |
| Electronic faucet | *Mycobacterium mucogenicum* | Exposure of CVC sites to contaminated water during bathing | Cancer patients (leukemia, rhabdomyosarcoma, neuroblastoma) | Catheter-associated BSI | RAPD | Outbreak – strong causation | Livni, 2008 [13] |
| Electronic faucet | *Pseudomonas aeruginosa* | Contamination of outlet, magnetic valve, and mixing device of the electric faucets | Patients in NICU | Bloodstream infection, ventilator-associated pneumonia | PFGE | Outbreak – strong causation | Yapicioglu, 2012 [14] |
| Faucet (aerator) | *Stenotrophomonas maltophilia* | Contaminated water after aeration | Patients in surgical ICU | Pneumonia, peritonitis, bacteremia, UTI | PFGE | Outbreak – strong causation | Weber, 1999 [15] |
| Faucet | *Pseudomonas aeruginosa* | Contaminated faucets | Patients in ICU | *P. aeruginosa* infection | PFGE | Case series (multiple) – strong causation | Blanc, 2004 [16] |
| Faucet | Nonfermentative gram-negative bacilli (eg, *Chryseobacterium meningosepticum*) | Unknown | Patients in ICU | Nosocomial infections | PFGE | Case series (multiple) – strong causation | Wang, 2009 [17] |
| Faucet (outlet) | *Pseudomonas aeruginosa* | Potential transmission from contaminated flow straighteners in the water outlets | Neonates in NICU | Bacteremia | VNTR | Case series (multiple) – strong causation | Walker, 2014 [18] |
| Faucet (water-saving device) | MDR-*Pseudomonas aeruginosa* | Water-saving device (aerator) in a staff hand basin and biofilm in the basin's plumbing contaminated | Patients in high dependency units | Nosocomial infection | PFGE | Case series (multiple) – strong causation | Inglis, 2010 [19] |
| Heater-cooler unit for cardiac surgery | *Mycobacterium chimaera* | Airborne transmission from contaminated heater-cooler unit water tanks | Patients who received open-chest heart surgery | Endocarditis, bloodstream infection, vascular graft infection | RAPD | Outbreak – strong causation | Sax, 2015 [20] |

*Table 1 continued.*

| Reservoir | Organism(s) | Transmission | Patient Population | Type of Infection | Molecular Typing | Study Type | First Author, Year |
|---|---|---|---|---|---|---|---|
| Hospital waste water system | MDR *Pseudomonas aeruginosa* | Contaminated hospital waste water systems (sink, shower, and toilet) | Patients in ICU and hematology units | Bacteremia | PFGE, VNTR | Outbreak – strong causation | Breathnach, 2012 [21] |
| Hospital waste water system | IMP-type metallo-β-lactamase-producing *Klebsiella oxytoca* | Contaminated water | Patients in medical and surgical ICU | Bacteremia, ventilator-associated pneumonia, UTI, peritonitis | PFGE | Outbreak – strong causation | Vergara-Lopez, 2013 [22] |
| Hospital water system | *Legionella pneumophila* | Contaminated water supply | Immunocompromised patients | Pneumonia | PFGE | Case series (multiple) – strong causation | Rangel-Frausto, 1999 [23] |
| Hospital water system | *Fusarium* | Aerosols from showers and sinks | Patients with leukemia, neutropenia, BMT or stem cell transplant | Invasive fusariosis | RAPD, RFLP, IR-PCR | Case series (multiple) – strong causation | Anaissie, 2001 [24] |
| Hospital water system | *Aspergillus fumigatus* | Unknown | BMT patients | Invasive pulmonary aspergillosis | AFLP | Case series (multiple) – strong causation | Warris, 2003 [25] |
| Hospital water system | Amoeba-associated bacteria (mainly *Legionella anisa, Bosea massiliensis*) | Unknown | Patients receiving mechanical ventilation in ICU | Ventilator-associated pneumonia | Seroconversion | Case series (multiple) | La Scola, 2003 [26] |
| Hospital water system | *Mycobacterium avium* complex | Contaminated hospital hot water system | Hospitalized patients | NTM pulmonary disease | PFGE | Case series (multiple) – strong causation | Tobin-D'Angelo, 2004 [27] |
| Hospital water system | NTM (*Mycobacterium mucogenicum, Mycobacterium neoaurum*) | Exposure of CVC sites to contaminated water during showering | Patients with hematological malignancies | Bacteremia | NA | Outbreak | Baird, 2011 [28] |
| Hospital water system | Rapidly growing mycobacteria (eg, *Mycobacterium chelonae*) | Contaminated water and ice machines | Hematopoietic cell transplant patients | Mycobacterial infection | NA | Outbreak | Iroh Tam, 2014 [29] |
| Hospital water system | *Pseudomonas aeruginosa* | Contaminated water outlet and shower hydrotherapy | Burn patients | Nosocomial infection | Whole-genome sequencing | Case series (multiple) – strong causation | Quick, 2014 [30] |
| Hospital water system | *Mycobacterium fortuitum* | Contaminated shower water | A postoperative patient with breast cancer | Breast infection | Repetitive extragenic palindromic PCR | Case report (single) – strong causation | Jaubert, 2015 [31] |
| Ice and ice machine | *Legionella pneumophila* | Microaspiration of ice or ice water | A patient with interstitial pneumonia and mechanical ventilation treated with steroids | Respiratory tract infection | NA | Case report (single) | Graman, 1997 [32] |
| Ice and ice machine | *Enterobacter cloacae* | Contaminated ice used for cardioplegia in cardiac surgery | Patients who received coronary artery bypass grafting | Postoperative wound infection | PFGE | Outbreak – strong causation | Breathnach, 2006 [33] |
| Ice and ice machine/ tap water | *Mycobacterium chelonae* | Application of contaminated nonsterile ice to the skin | Patients after cosmetic dermal filter injections at a plastic surgery clinic | Cutaneous infection | PFGE | Case series (multiple) – strong causation | Rodriguez, 2013 [34] |
| Ice and ice machine/ tap water | *Mycobacterium porcinum* | Contaminated water | Patients with pulmonary disease or extrapulmonary disease | Pulmonary infection, localized abscess, infected port, peritonitis | PFGE | Case series (multiple) – strong causation | Brown-Elliott, 2011 [35] |
| Ice bath | *Pseudomonas fluorescens* | Contaminated ice bath used for cardiac output infusion | Patients with cardiac diseases in a CCU | Bacteremia | PFGE | Outbreak – strong causation | Benito, 2012 [36] |
| Potable water | *Mycobacterium avium* | Contaminated water | Patients with AIDS and non-AIDS | Disseminated infection | PFGE | Outbreak – strong causation | Aronson, 1999 [37] |

*Table 1 continued.*

| Reservoir | Organism(s) | Transmission | Patient Population | Type of Infection | Molecular Typing | Study Type | First Author, Year |
|---|---|---|---|---|---|---|---|
| Potable water | *Pseudomonas fluorescens* | Contaminated water dispenser that supplied bottled water in a BMT unit | Patients with hematological malignancies | Nosocomial infection and febrile neutropenia | RAPD, PFGE | Outbreak – strong causation | Wong, 2011 [38] |
| Potable water | *Stenotrophomonas maltophilia* | Contaminated drinking water of the cooling unit in the ICU kitchen and mouth care to patients | Patients in ICU | Pneumonia | PFGE | Outbreak – strong causation | Guyot, 2013 [39] |
| Potable water | *Legionella pneumophila* | Unknown | Patients with Legionnaires' disease | Healthcare-associated Legionnaires' disease | Sequencing | Outbreak – strong causation | Demirjian, 2015 [40] |
| Shower | *Mycobacterium fortuitum* | Showerhead used by patients | A neutropenic patient with leukemia | Disseminated infection | AP-PCR typing | Case report (single) – strong causation | Kauppinen, 1999 [41] |
| Shower | *Pseudomonas aeruginosa* | Potential transmission via hand shower contaminated | Patients in a BMT ward | Bacteremia | PFGE | Outbreak – strong causation | Lyytikainen, 2001 [42] |
| Shower (wall) | *Aspergillus* | Potential aerosolization of fungal propagules | Patients in BMT units | Aspergillosis | RAPD | Case report (single) – strong causation | Anaissie, 2002 [43] |
| Shower (hot water supply) | *Legionella* spp (mainly *Legionella pneumophila*) | Inhalation of shower aerosols | Older people in nursing homes | Pontiac fever | NA | Case series (multiple) | Bauer, 2008 [44] |
| Shower | *Mycobacterium mucogenicum*, *Mycobacterium phocaicum* | Exposure to contaminated water via hand shower | Oncology patients | Catheter-associated BSI | Repetitive element PCR, RAPD, PFGE | Outbreak – strong causation | Cooksey, 2008 [45] |
| Shower | *Acinetobacter ursingii* | Unknown | Immunocompetent pregnant patients in an obstetrics ward | Bloodstream infection | PFGE (unrelated) | Case series (multiple) | Horii, 2011 [46] |
| Sink | *Serratia marcescens* | Soap and soap bottles contaminated | Infants in NICU | Multiple (eye, respiratory, blood, urine, wound, rectum) | PFGE | Outbreak – strong causation | Archibald, 1997 [47] |
| Sink / Faucet | MDR *Pseudomonas aeruginosa* | Contamination of water basin sinks and water taps (potential) | Patients who received invasive treatment (surgery, cancer therapy) | Pneumonia, UTI | PFGE | Case series (multiple) – strong causation | Pitten, 2001 [48] |
| Sink | *Enterobacter* | Unknown | Patients in ICU | Pneumonia | PFGE | Case report (single) – strong causation | Wagenlehner, 2002 [49] |
| Sink (trap) | MDR *Acinetobacter baumannii* | Unknown | Patients in medical/surgical ICU | Respiratory tract infection, ventilator-associated pneumonia, bloodstream infection, abscess, wound infection | Restriction endonuclease analysis | Outbreak – strong causation | La Forgia, 2010 [50] |
| Sink | *Mycobacterium mucogenicum* | Probable exposure when intravenous medication was prepared near the sink and implanted ports were accessed | Patients with sickle cell disease in an outpatient clinic | Bloodstream infection | Repetitive-sequence-based PCR | Outbreak – strong causation | Ashraf, 2012 [51] |
| Sink | KPC-producing *Klebsiella pneumoniae* | Sinks contaminated from waste water | Patients in surgical/medical ICU | Bacteremia | PFGE, MLST | Outbreak – strong causation | Tofteland, 2013 [52] |
| Sink | *Elizabethkingia meningoseptica* | Contaminated handwash sink and water | Bedside hemodialysis patients on mechanical ventilation in ICU | Bacteremia, lower respiratory tract infection, ventilator-associated pneumonia | NA | Case series (multiple) | Ratnamani, 2013 [53] |
| Sink | ESBL-producing *Enterobacter cloacae* | Contaminated sink | Patients in ICU | Pneumonia | AFLP | Outbreak – strong causation | Wolf, 2014 [54] |

*Table 1 continued.*

| Reservoir | Organism(s) | Transmission | Patient Population | Type of Infection | Molecular Typing | Study Type | First Author, Year |
|---|---|---|---|---|---|---|---|
| Sink | GIM-producing *Pseudomonas aeruginosa* | Inappropriate use of surface areas around washbasins as placement of clean items | Patients in a tertiary care hospital | *P. aeruginosa* infection | PFGE, MLST | Outbreak – strong causation | Wendel, 2015 [55] |
| Sink | *Pseudomonas aeruginosa* | Contaminated water from sink | Infants in NICU | Pneumonia | Whole-genome sequencing, ERIC-PCR typing | Outbreak – strong causation | Davis, 2015 [56] |
| Sink | KPC-producing *Klebsiella oxytoca* | Contaminated handwashing sink | Patients with hematological malignancies | Pneumonia, abdominal wall abscess | Repetitive-sequence-based PCR, MLST | Outbreak – strong causation | Leitner, 2015 [57] |
| Sink / Shower | NDM-producing *Klebsiella pneumoniae* | Interhospital transfer of patients and contaminated sink trap | Older or chronically ill patients | *K. pneumoniae* infection | PFGE, MLST | Outbreak – strong causation | Seara, 2015 [58] |
| Sink / Tap water | MDR *Pseudomonas aeruginosa* | Contaminated water or patient-to-patient transmission | Patients in a neurosurgery ICU | Multiple (urinary infection, pneumonia, sinusitis) | PFGE | Outbreak – strong causation | Bert, 1998 [59] |
| Tap water | *Mycobacterium abscessus* | Inadequate sterilization of surgical instruments | Postsurgical patients | Wound infection | NA | Outbreak | Chadha, 1998 [60] |
| Tap water | Small round structured viruses | Transient contamination of the taps | Patients in a reeducation ward | Gastroenteritis | Sequencing | Outbreak – strong causation | Schvoerer, 1999 [61] |
| Tap water | *Mycobacterium genavense* | Ingestion of contaminated water | HIV-infected patients treated with HAART | Disseminated mycobacteriosis | NA | Case series (multiple) | Hillebrand-Haverkort, 1999 [62] |
| Tap water | *Ochrobactrum anthropi* | Unknown | Immunocompromised patients (leukemia) in hematology unit | Bacteremia | PFGE (unrelated) | Case series (multiple) | Deliere, 2000 [63] |
| Tap water | *Chryseobacterium* (*Flavobacterium*) *meningosepticum* | Contaminated sink drain and biofilm inside the sink tap | Neonates in NICU | Pneumonia, meningitis with septicemia | PFGE | Outbreak – strong causation | Hoque, 2001 [64] |
| Tap water | *Sphingomonas paucimobilis* | Contaminated taps and showers used in a hematology ward | A neutropenic patient with leukemia | Bacteremia | RAPD | Case report (single) – strong causation | Perola, 2002 [65] |
| Tap water | *Mycobacterium simiae* | Potential transmission via showering | Pulmonary cancer, chronic pulmonary disease | Pulmonary infection | PFGE | Outbreak – strong causation | Conger, 2004 [66] |
| Tap water | *Burkholderia cepacia* | Alcohol skin antiseptic diluted by contaminated tap water that was applied to intravenous catheter site | Patients with cardiovascular disease or cancer | Bacteremia | RFLP | Outbreak – strong causation | Nasser, 2004 [67] |
| Tap water | *Aspergillus flavus* | Contamination of hospital environment (air, tap water, surface) | Patients in BMTU, ICU, and NICU | Invasive aspergillosis | RAPD | Case report (single) – strong causation | Ao, 2014 [68] |
| Tap water | *Pseudomonas aeruginosa* | Contaminated tap water | Patients in ICU | Nosocomial infection | NA | Case series (multiple) | Venier, 2014 [69] |
| Tap water / Wash basin | MDR *Pseudomonas aeruginosa* | Contaminated water taps and wash basins | Patients receiving mechanical ventilation in ICU | Lower respiratory infection and bloodstream infection | AFLP | Outbreak – strong causation | Bukholm, 2002 [70] |
| Toilet | MDR *Pseudomonas aeruginosa* | Potential cross transmission via toilet brush | Hospitalized patients | Nosocomial infection | PFGE | Case series (multiple) – strong causation | Kouda, 2011 [71] |
| Toilet / Shower | Norovirus | Possible transmission via hand contact and contaminated items within toilets and the bedside environment | Hospitalized patients with symptoms of gastroenteritis | Gastroenteritis | RT-PCR | Case series (multiple) | Morter, 2011 [72] |

*Table 1 continued.*

| Reservoir | Organism(s) | Transmission | Patient Population | Type of Infection | Molecular Typing | Study Type | First Author, Year |
|---|---|---|---|---|---|---|---|
| Wash basin / Potable water | *Legionella pneumophila* | Contaminated water in wash basins | A patient with leukemia | Pneumonia | PFGE | Case report (single) – strong causation | Brulet, 2008 [73] |
| Wash basin / Sink | *Trichosporon asahii* | Contaminated wash basins | Patients with malignancies, burns, and surgery in ICU | Disseminated infection | Sequencing | Case series (multiple) – strong causation | Fanfair, 2013 [74] |
| Water bath | *Pseudomonas aeruginosa* | Transfusion of contaminated fresh frozen plasma or human albumin | Infants in NICU | Bloodstream infection | RAPD | Outbreak – strong causation | Muyldermans, 1998 [75] |
| Water bath | *Halomonas phocaeensis* sp nov | Administration of fresh frozen plasma warmed by contaminated water baths | Neonates in NICU | Bacteremia | 16S rRNA gene sequencing | Outbreak | Berger, 2007 [76] |
| Water birthing | *Legionella pneumophila* | Aspiration of pool water contaminated | A neonate | Pneumonia | NA | Case report (single) | Franzin, 2001 [77] |
| Water-damaged plaster | *Rhizomucor pusillus* | Water damage in a linen room and parents' shower room | Patients with leukemia | Rhinocerebral mucormycosis | NA | Outbreak | Garner, 2008 [78] |

In study type, each article's definition of "case series (multiple)" or "outbreak" was used. "Case series (multiple)" or "case report (single)" was determined based on the number of human infections linked to a water reservoir. "Strong causation" was added when at least 1 molecular typing method indicated relatedness to a water reservoir.

Abbreviations: AFLP, amplified fragment length polymorphism; AP-PCR, arbitrarily primed polymerase chain reaction; BMT, bone marrow transplant; BMTU, bone marrow transplant unit; BSI, bloodstream infection; CCU, coronary care unit; CVC, central venous catheter; ERIC-PCR, enterobacterial repetitive intergenic consensus polymerase chain reaction; ESBL, extended-spectrum β-lactamase; GIM, German imipenemase; HAART, highly active antiretroviral therapy; HIV, human immunodeficiency virus; ICU, intensive care unit; IMP, imipenem; IR-PCR, interrepeat polymerase chain reaction; KPC, *Klebsiella pneumoniae* carbapenemase; MDR, multidrug resistant; MLST, multilocus sequence typing; NA, not applicable; NDM, New Delhi metallo-β-lactamase; NICU, neonatal intensive care unit; NTM, nontuberculous mycobacteria; PCR, polymerase chain reaction; PFGE, pulsed-field gel electrophoresis; RAPD, random amplification of polymorphic DNA; RFLP, restriction fragment length polymorphism; rRNA, ribosomal RNA; RT-PCR, reverse transcription polymerase chain reaction; UTI, urinary tract infection; VNTR, variable number tandem repeat.

## RESERVOIRS AND TRANSMISSION ROUTES OF WATERBORNE PATHOGENS AND INFECTION PREVENTION STRATEGIES AGAINST WATERBORNE OUTBREAKS IN HEALTHCARE SETTINGS

All water with the exception of sterile water and filtered water is contaminated with microbes (eg, potable water, tap water, showers, and ice). In healthy persons, contact or ingestion of such water rarely leads to infection. However, contact or ingestion of such water may cause infection in immunocompromised persons or when applied to nonintact skin. Water-related reservoirs in healthcare settings during 1997–2015 were as follows: bathing and tub immersion, decorative water fountains, deionized water, dialysis water, electronic faucets, faucets, heater-cooler units, hospital wastewater systems, hospital water systems, ice and ice machines, ice baths, potable water, showers, sinks, tap water, toilets, wash basins, water baths, water birth, water-damaged plaster, and water-saving devices (Table 1). Transmission routes were primarily direct contact with contaminated water and water-related devices/activities or inhalation via aerosols generated from the contaminated water (Table 1). Waterborne healthcare-associated outbreaks and infections continue to occur and were mostly associated with well-recognized water reservoirs as previously described [4]. Moreover, recent studies document electronic faucets (*P. aeruginosa*, *Legionella*, *M. mucogenicum*) [13, 14, 93–95], decorative water wall fountains (*Legionella*) [10, 91], and heater-cooler devices used for cardiac surgery (*M. chimaera*) [20, 96] as water reservoirs. Infection prevention and control measures by each reservoir category are summarized in Table 2. The Centers for Disease Control and Prevention (CDC) has published recommendations of infection prevention and management for hospital water [1, 2].

### Potable Water, Tap Water, and Hospital Water Systems

Various healthcare-associated infections were linked to contaminated potable/tap water and hospital water systems, especially among immunocompromised and severely ill patients [21–26, 28, 29, 37–39, 62–65, 68–70]. The common pathogens included gram-negative bacilli (eg, *Pseudomonas*, *Stenotrophomonas*) [21, 30, 38, 39, 69, 70], *Legionella* [23, 40], and NTM [27–29, 31, 37, 60, 62, 66]. Waterborne organisms may exist in potable water at acceptable levels of coliform bacteria (<1 coliform bacterium/100 mL) [4]. Standards for potable water should adhere to public health guidelines, and hot water temperature at the outlet should be maintained at the highest temperature allowable [1, 2].

### Sinks

Some studies demonstrated a transmission link between sinks colonized with a pathogen and patients using molecular typing methods [47–52, 54–59]. The most frequent pathogens associated with sinks were gram-negative bacilli (eg, *Pseudomonas*, *Acinetobacter*, *Serratia*), as gram-negative bacilli can survive in wet

**Table 2. Summary of Key Issues and Infection Prevention Strategies Against Waterborne Outbreaks by Major Water Reservoir in Healthcare Settings**

| Reservoir | Key Issues | Infection Prevention Strategies |
|---|---|---|
| Potable water, tap water, and hospital water systems | Potable water is not sterile, and pathogenic waterborne organisms may exist in potable water at acceptable levels of coliform bacteria (<1 coliform bacterium/100 mL).<br>Healthcare-associated outbreaks have been linked to contaminated potable water.<br>Semicritical devices are often rinsed with potable water, which may lead to contamination of the equipment and subsequent healthcare-associated infections.<br>Common pathogens include nonenteric gram-negative bacilli (eg, *Pseudomonas aeruginosa*), *Legionella*, NTM. | Follow public health guidelines.<br>Hot water temperature at the outlet at the highest temperature allowable, preferably >51°C.<br>Water disruptions: post signs and do not drink tap water.<br>Maintain standards for potable water (<1 coliform bacterium/100 mL).<br>Rinse semicritical equipment with sterile water, filtered water, or tap water followed by alcohol rinse.<br>Some experts have recommended periodic monitoring of water samples for growth of *Legionella*.<br>*Legionella* eradication can be technically difficult, temporary, and expensive.<br>Potential methods of eradication include filtration, ultraviolet, ozonization, heat inactivation (>60°C), hyperchlorination, and copper-silver ionization (>0.4 ppm and >0.04 ppm, respectively). |
| Sinks | Colonization of sinks with gram-negative bacilli has been reported.<br>Some studies demonstrate a transmission link between a colonized sink and infected patients.<br>Some studies describe that multidrug-resistant gram-negative bacilli are associated with contaminated sinks.<br>Gram-negative bacilli can survive wet environments, including sinks, for a long time (>250 d)<br>Transmission can be caused by splashing of water droplet from contaminated sinks to hands of healthcare personnel, followed by transient colonization of hands.<br>Common pathogens include gram-negative bacilli (eg, *Pseudomonas*, *Acinetobacter*, *Serratia*). | Use separate sinks for handwashing and disposal of contaminated fluids.<br>Decontaminate or eliminate sinks as a reservoir if epidemic spread of gram-negative bacteria via sinks is suspected. |
| Faucet aerators | Faucet aerators may serve as a platform for accumulation of waterborne pathogens.<br>Potential pathogens include *Pseudomonas*, *Stenotrophomonas*, and *Legionella*. | Routine screening and disinfection or permanent removal of all aerators are not warranted at present.<br>No precautions necessary at present.<br>For *Legionella* outbreaks, clean and disinfect faucet aerators in high-risk patient areas periodically, or consider removing them in the case of additional infections. |
| Showers | Some outbreaks are linked to contaminated shower heads or inhalation of aerosols.<br>Potential pathogens include *Legionella*, *Pseudomonas*, NTM, group A *Streptococcus*, and *Aspergillus*. | Prohibit use of showers in neutropenic patients.<br>Control *Legionella* colonization of potable water. |
| Ice and ice machines | Patients can acquire pathogens by sucking on ice, ingesting iced drinks, or use of contaminated ices for cooling medical procedure and patients' skin.<br>Large outbreaks occurred when ice machines have become contaminated and ice used for cooling drinking water.<br>Common pathogens include *Pseudomonas*, *Enterobacter*, *Legionella*, NTM, and *Cryptosporidium*. | Do not handle ice by hand.<br>Do not store pharmaceuticals or medical solutions on ice for consumption.<br>Use automatic dispenser rather than open chest storage compartments in patient areas.<br>Clean and disinfect ice-storage chests regularly.<br>Meaningful microbial standards for ice and ice machines do not exist.<br>Routine culturing of ice machines are not recommended.<br>A regular disinfection program for ice machines is recommended. |
| Eyewash stations | Stationary and portable eyewash stations may not be used for months or years.<br>The water source may stand in the incoming pipes at room temperature for a long period.<br>Pathogens, including *Pseudomonas*, *Legionella*, amoebae, and fungi, could be transmitted. | Use sterile water for eye flush or regularly (eg, monthly) flush eyewash stations. |
| Dental-unit water systems | Potable water usually supplies dental units.<br>Water delivered to dental devices (eg, dental handpieces and air/water syringes) as well as dental unit water lines may be contaminated.<br>Immunocompromised patients may be at risk for infection.<br>Pathogens, including *Sphingomonas*, *Pseudomonas*, *Acinetobacter*, *Legionella*, and NTM, have been recovered from water supplies in dental units. | Clean dental water systems.<br>Flush with water and disinfectant solution, or use of clean-water systems that put sterile water into the dental unit.<br>Flush dental instruments with water and air for 20–30 sec from any dental device connected to the dental water system that enters the patient's mouth (eg, handpieces).<br>Ensure that water in dental unit meets standards (<500 CFU/mL). |
| Dialysis water | Excessive levels of gram-negative bacilli in the dialysate were responsible for pyrogenic reactions in patients or bacteremia, which was caused by bacteria or endotoxin entry into the blood from the contaminated dialysate. | Follow AAMI standards for quality assurance performance of dialysis devices.<br>Disinfect water distribution system on a regular basis.<br>Perform microbiological testing and endotoxin testing for water in dialysis settings regularly.<br>Maintain dialysis water (input) <200 CFU/mL and dialysate (output) <200 CFU/mL per CMS. |
| Water and ice baths | Contaminated water baths were used to thaw or warm blood products (fresh plasma, cryoprecipitate) or peritoneal dialysate bottles, followed by contamination of the infusates occurred during preparation.<br>Contaminated ice baths were used to cool syringes or bottles of saline in measuring cardiac output.<br>Potential pathogens include *Pseudomonas*, *Acinetobacter*, *Burkholderia*, *Staphylococcus*, and *Ewingella*. | Consider routine cleaning, disinfection, and changing of water in water baths.<br>Add germicide to water bath or use plastic overwrap of blood products and keep the surfaces dry.<br>Use sterile water in ice baths (or at room temperature) used for thermodilution catheters. |

Table 2 continued.

| Reservoir | Key Issues | Infection Prevention Strategies |
|---|---|---|
| Bathing, tub immersion, and hydrotherapy | Tub immersion used in hospitals for physical hydrotherapy and for cleaning of burn wounds can cause cross-transmission, transmission from environmental reservoirs, or autotransmission.<br>Skin infections such as folliculitis and cellulitis occurred related to water immersion.<br>Water contamination of central venous catheters during bathing was related to bloodstream infection.<br>Potential pathogens include *Pseudomonas*, *Enterobacter*, *Citrobacter*, *Acinetobacter*, *Legionella*, *Alcaligenes*, and NTM. | Adhere strictly to proper disinfection of tub between patients.<br>Drain and clean tanks and tubs after use of each patient, and disinfect surfaces and components according to the manufacturer's instructions.<br>Add disinfectant to the water: 15 ppm in small hydrotherapy tanks and 2–5 ppm in whirlpools per CDC.<br>Disinfect after using tub liners.<br>Cover catheter sites with transparent occlusive dressing. |
| Toilets | Transmission can be caused by aerosolization of fecal bacteria via flushing or surface contamination by fecal bacteria.<br>Transmission could happen in healthcare facilities caring for mentally or neurologically impaired patients, or children.<br>Potential pathogens include enteric bacteria, *Pseudomonas*, *Clostridium difficile*, and norovirus. | Facilitate good handwashing practices.<br>Maintain clean surfaces with disinfectants.<br>Clean bowl with a scouring powder and a brush.<br>No reason to pour disinfectant into bowl.<br>Separate toilet bowl from clean hospital surfaces. |
| Flowers and vases | Flower vases and potted plants are heavily colonized with potential pathogens, including *Acinetobacter*, *Klebsiella*, *Enterobacter*, *Pseudomonas*, *Serratia*, *Burkholderia cepacia*, *Aeromonas hydrophila*, and *Flavobacterium*.<br>No healthcare-associated outbreaks directly linked to flower vases or potted plants have been reported. | Prohibit fresh flowers and potted plants in the rooms of immunocompromised and ICU patients.<br>Or add antimicrobial agent to vase water and disinfect vases after use. |
| Electronic faucets | Electronic faucets were likely to be contaminated by several waterborne pathogens than handle-operated faucets.<br>Issues associated with electronic faucets include a longer distance between the valve and the tap, resulting in a longer column of stagnant, warm water, which favors production of biofilms; reduced water flow; reduced flushing effect (growth favored); valves and pipes made of plastic (enhances adhesion of *P. aeruginosa*). | Electronic faucets need to be designed so that they do not promote the growth of microorganisms.<br>No guideline (but some authors have recommended) to remove electronic faucets from high-risk patient care areas [eg, BMTU]).<br>Some have recommended periodic monitoring of water samples for growth of *Legionella*. |
| Decorative water wall fountains | *Legionella* pneumonia cases associated with decorative water fountain were reported.<br>There is an unacceptable risk in hospitals serving immunocompromised patients (even with standard maintenance and sanitizing methods). | Avoid installation, especially in healthcare facilities serving immunocompromised patients or in areas caring for high-risk patients.<br>Perform maintenance regularly and monitor water safety strictly unless removed. |
| Heater-cooler units | Healthcare-associated *Mycobacterium chimaera* outbreak due to heater-cooler units during cardiac surgeries as a water source has been recently reported.<br>Airborne transmission from contaminated heater-cooler unit water tanks. | Ensure that heater-cooler units are safe and properly maintained according to the manufacturer's instructions.<br>Enhance vigilance for NTM infections in patients after cardiac surgeries using heater-cooler devices.<br>If NTM infections are suspected, review microbiology database (NTM-positive cultures) and medical records of surgical procedures within several years after cardiac surgeries. |
| Miscellaneous | Potential reservoirs include distilled water or containers (outbreaks with *Enterobacter cloacae* and *B. cepacia*), wash basins (*Salmonella urbana* infection, *Trichosporon asahii* infection, *Legionella* pneumonia), intraaortic balloon pump (*B. cepacia* bacteremia), humidifier water in ventilator systems (*Acremonium kiliense* postoperative endophthalmitis), water cooler (gastrointestinal illness), holy water (*Acinetobacter baumannii* infection), deionized water (*Exophiala jeanselmei* fungemia), water-damaged plaster (mucormycosis), water birth (*Legionella* pneumonia), water-saving device (*P. aeruginosa* infection), rinse water during endoscope reprocessing (gram-negative bacteria). | Consider control measures based on risk assessment by each reservoir when available. |

The information used in this table is based on references in this review. The infection prevention and control section was updated from our previous review [4] and recommendations from CDC and the Healthcare Infection Control Practices Advisory Committee [1, 2].

Abbreviations: AAMI, Association for the Advancement of Medical Instrumentation; BMTU, bone marrow transplant unit; CDC, Centers for Disease Control and Prevention; CFU, colony-forming unit; CMS, Centers for Medicare and Medicaid Services; ICU, intensive care unit; NTM, nontuberculous mycobacteria; ppm, parts per million.

environments, including sinks, for a long time [4]. Sinks should be decontaminated if epidemic spread of gram-negative bacteria via sinks is suspected [4]. Further, multidrug-resistant gram-negative bacilli have been linked to contaminated sinks and healthcare-associated infections as stated above [48, 50, 52, 54, 55, 57–59]. Although hand hygiene is an essential precaution against healthcare-associated infections in healthcare personnel, transmission from contaminated sinks to their hands during hand washing can occur [3]. Separate sinks should be used for handwashing and disposal of contaminated fluids [1, 4].

### Showers

Healthcare-associated infections have been linked to use of contaminated showers or inhalation of aerosols by immunocompromised patients [41–43, 45]. Potential pathogens related to showers were *Legionella*, *Pseudomonas*, NTM, and *Aspergillus* [41–45]. The use of showers in immunocompromised patients (eg, neutropenic patients) should be avoided [4].

### Bathing and Tub Immersion

Tub immersion used in hospitals for physical hydrotherapy and for cleaning of burn wounds can cause cross-transmission and transmission from environmental reservoirs [4]. Water contamination of central venous catheters during bathing was linked to bloodstream infection [7]; therefore, catheter sites should be covered with transparent occlusive dressing. Pathogens associated with bathing and tub immersion were *Pseudomonas*, *Legionella*, *Alcaligenes*, and NTM [6–9]. Tubs should be drained and cleaned after use of each patient, and strict adherence to proper disinfection of tubs between patients is essential [1, 4].

#### Electronic Faucets

Electronic faucets have been introduced in healthcare facilities, mainly to save water consumption and costs and avoid healthcare personnel's hands from being contaminated by touching the handle [93]. However, several studies have revealed that water samples from electronic faucets were heavily or frequently contaminated by *P. aeruginosa* and/or *Legionella*, compared with handle-operated faucets [93–95], and a *P. aeruginosa* outbreak due to electronic faucets among immunocompromised patients in a NICU has been reported [14]. Electronic faucets are more likely to be colonized because of low amounts of water flow, more favorable conditions for growth of waterborne pathogens (temperature of about 35°C in the column; materials made of rubber, plastic, and polyvinylchloride), and less flushing. Although the degree of risk posed by electronic faucets has not been quantified and there is no guideline for the water quality of electronic faucets, some authors have recommended monitoring water samples periodically from electronic faucets as well as removing electronic faucets from high-risk patient areas (eg, stem cell transplant units), given the difficulty of decontamination even with hyperchlorination [14, 93–95].

#### Decorative Water Wall Fountains

Two immunocompromised patients were exposed to a decorative water fountain in radiation oncology, which was heavily contaminated despite standard maintenance and disinfection (ozone generator, filter, and weekly cleaning), and developed *Legionella* pneumonia [10]. Another study described laboratory-confirmed Legionnaires' disease (pneumonia) in 8 patients, 6 of whom had exposure to a decorative fountain near the main hospital entrance; high counts of *Legionella* were detected from foam materials on the fountain despite routine maintenance [91]. A fountain's water has a closed recirculating system that can stagnate, and the spraying function may generate aerosols [91]. The results from both studies suggested that decorative water fountains can pose a risk for transmission of waterborne pathogens and should not be installed in healthcare facilities serving immunocompromised patients, even with standard cleaning, disinfection, and maintenance; at a minimum, water safety should be strictly monitored [10, 91].

#### Heater-Cooler Units

Heater-cooler devices are frequently used in cardiopulmonary bypass during cardiac surgeries to warm and cool patients' blood [97]. A *M. chimaera* outbreak associated with heater-cooler units during cardiac surgeries as a water source has been recently documented [20, 96]. Patient infections included prosthetic valve endocarditis, bloodstream infection, and vascular graft infection. The transmission was potentially caused by aerosols generated from stirred water in contaminated heater-cooler unit water tanks. In a report of surgical site infections due to *Mycobacterium wolinskyi*, a cold-air blaster and a self-contained water system in a heater-cooler unit was identified as a potential reservoir [98]. The CDC's recommendations for healthcare facilities are as follows: (1) ensure that heater-cooler units are safe and properly maintained according to the manufacturer's instructions; (2) enhance vigilance for NTM infections in patients after cardiac surgeries using heater-cooler devices; and (3) if NTM infections are suspected, review microbiology data (NTM-positive cultures) and medical records of surgical procedures within 4 years after cardiac surgeries [97]. The US Food and Drug Administration recommended the following maintenance of heater-cooler units: (1) use sterile water or filtered water (≤0.22 µm) to rinse or fill water tanks or when making ice for cooling patients during a surgical procedure (avoid using tap water); (2) monitor cleaning, disinfection, and maintenance for heater-cooler units regularly with written documentations of the quality control program; and (3) avoid using heater-cooler units with cloudiness or discoloration in the fluid lines or circuits (http://www.fda.gov/MedicalDevices/Safety/AlertsandNotices/ucm466963.htm).

## WATER SAMPLING AND MOLECULAR STRAIN TYPING IN OUTBREAK INVESTIGATION OF WATERBORNE HEALTHCARE-ASSOCIATED INFECTIONS

Infectious disease physicians and infection preventionists should recognize the emergence of waterborne healthcare-associated pathogens and the unusual change of these rates, and begin an initial investigation if waterborne healthcare-associated cases are suspected [3]. Microbiologic sampling can be considered to enhance epidemiological investigations and to develop infection prevention and control measures. Microbiologic water sampling is not routinely recommended, but can be performed in the following situations: support of outbreak investigations, research purposes, evaluation of a potentially hazardous environmental situation, and quality assurance (eg, biological monitoring of dialysis water or assessment of infection control measures) [1, 2]. Established water sampling methods (eg, volume, media, and incubation temperature) should be utilized to ensure recovery of waterborne pathogens; water samples should be filtered before culturing when low counts are expected and large volumes are needed (>100 mL) [1].

Molecular typing has been increasingly applied to outbreak investigations in healthcare settings, and the advantages as well as disadvantages of molecular methods have been described by other authors [99–101]. In our review, molecular typing methods used for waterborne healthcare-associated pathogens when applicable were mostly pulsed-field gel electrophoresis, followed by random amplification of polymorphic DNA (Table 1). Recent studies using whole-genome sequencing demonstrated more powerful evidence of water reservoirs in transmission dynamics of waterborne pathogens, including an outbreak of *P. aeruginosa* (1 pneumonia/17 colonizations) from contaminated water via sinks among infants in a NICU; transmission of *P. aeruginosa* from contaminated water outlets and a thermostatic mixer valve among burn patients receiving hydrotherapy even in plumbing of a new hospital; and 2 healthcare-associated cases of pneumonia caused by *Legionella pneumophila* serogroup 1 from a contaminated hospital water distribution system [30, 56, 102]. Thus, whole-genome sequencing is now promising for genomic comparative analysis in investigations of waterborne healthcare-associated outbreaks and can provide more accurate and informative strain typing to assess the relatedness of pathogens isolated from clinical and environmental water sources.

## CONCLUSIONS

We reviewed waterborne healthcare-associated outbreaks and infections and summarized current infection prevention and control. With emergence of reservoirs and pathogens that have been unrecognized so far, waterborne healthcare-associated outbreaks and infections continue to occur and affect patients' health and safety, underscoring the significant role of water as a reservoir for healthcare-associated infections. Water contamination can cause pseudo-outbreaks [3, 80] as well as outbreaks/infections, both of which require substantial efforts and resources for investigation and control. Waterborne healthcare-associated infections are preventable for some pathogens and reservoirs, but eliminating contamination of waterborne pathogens as natural inhabitants of water systems may be difficult in healthcare settings. It is essential for healthcare personnel to understand reservoirs and transmission pathways of waterborne pathogens for developing prevention strategies and control measures of healthcare-associated infections. Multiple approaches of engineering and hygiene measures as well as surveillance and clinical management for hospital water can reduce the risk for contracting waterborne healthcare-associated infections [3]. Advancement of pathogen identification and molecular typing methods has enhanced outbreak investigations as well as provided better understanding of reservoirs and transmission routes of waterborne pathogens. The safe level of microbial water contamination, which would preclude healthcare-associated infections for any waterborne pathogen in susceptible patients, remains to be determined. Further scientific and practical evidence on hospital water reservoirs, pathogens, and healthcare-associated infections is needed to address unresolved issues on infection prevention and control.

## Notes

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