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New Technologies and Advances in Infections Prevention (A Marra, Section Editor)

Challenges in the Hospital Water System and Innovations to Prevent Healthcare-Associated Infections

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Opinion statement

Healthcare-associated infections (HAI) related to hospital water distribution systems have been well-described. More recently, outbreaks linked to the wastewater system as well as water-containing medical devices have increased awareness of potential environmental sources of water-related HAI. In this review, we summarize outbreaks and challenges associated with hospital water distribution and wastewater systems, as well as potential mitigation strategies. The heightened attention on water-related HAI has sparked new strategies and innovations to mitigate these risks, including engineered or structural modifications to plumbing components, enhanced disinfection of premise plumbing, and novel tools to reduce biofilm formation. Bundled approaches are often used. Focus should remain on basic infection prevention strategies and physical separation of clean items from surfaces potentially contaminated by water sources. Hospital premise plumbing is a reservoir of opportunistic pathogens, which presents unique challenges for infection prevention. Although numerous mitigation strategies have been described in the literature, basic infection prevention practices remain key. Additional investigation is needed to find effective and sustainable techniques to reduce the risk of water-related HAI and improve patient safety.

Introduction

Water distribution systems are a well-known reservoir and potential source of healthcare-associated infections (HAI). Colonized water sources result in infections in susceptible patients through multiple transmission routes. Patients may be directly inoculated through inhalation of aerosols, aspiration or ingestion of colonized water, or by contamination of indwelling devices or open wounds. Likewise, indirect transmission occurs through contamination of equipment or supplies in the healthcare environment which are in turn used for patient care, or through transfer to patients via the hands of healthcare workers. Outbreaks of multidrug-resistant gram-negative bacteria related to hospital wastewater systems, including sinks and drains, and non-tuberculous mycobacterial (NTM) infections related to water-containing medical devices, such as heater-cooler devices used in cardiac surgery, have led to a heightened awareness of other potential sources of water-related HAI. Understanding the potential sources and modes of transmission is vital to develop and implement effective infection prevention and control strategies. This review is intended to provide an overview of infection control challenges associated with hospital water distribution and wastewater systems and potential mitigation strategies.

Overview of hospital water distribution and wastewater systems

Premise plumbing refers to the portion of the water distribution system beyond the property lines. Within hospitals, the complex structure of water distribution systems can allow for intermittent stagnation, low disinfectant residual, and biofilm formation [1]. Optimal conditions select for the persistence of certain microorganisms, termed opportunistic premise plumbing pathogens (OPPP). These waterborne pathogens are diverse, including gram-negative bacilli, *Legionella*, NTM, fungi, protozoa, and viruses, and can result in an array of clinical manifestations ranging from colonization to disseminated infection [2]. Patients with hematologic malignancies, stem cell transplants, other immunocompromising conditions, and critical illness requiring ICU care are particularly vulnerable to OPPP [3]. Despite the significant morbidity associated with nosocomial outbreaks of water-related infections, water distribution and wastewater systems are often overlooked as a significant source of healthcare-associated infections. HAIs have been linked to multiple water sources in the built environment including potable water, sink drains, showers, immersion tubs, decorative fountains, water channels in heater-cooler units, and ice [4].

In addition to the challenges created by the ubiquitous nature of water and plumbing features, many of the organisms that colonize the plumbing grow in biofilms and are relatively resistant to disinfectants. When outbreaks related to wastewater sources do occur, identifying and remedying the problem can be difficult due to the typical extended duration of outbreaks, high prevalence of environmental colonization yet relatively low attack rate, and logistically difficult or limited mitigation strategies. Evaluating and responding to a potential water-related issue requires at least a basic understanding of the structural anatomy and components of the water distribution and plumbing systems (Fig. 1).

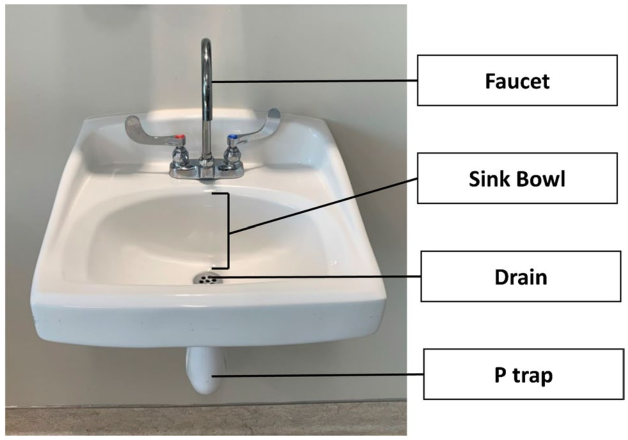

Fig. 1 Components of a standard sink

Water supply and distribution

OPPPs persist in the municipal water supply and distribution system (Table 1). Anything that leads to stagnation of water within the water distribution system promotes degradation of disinfectants, growth of microorganisms, and biofilm formation [5]. Stagnation within the distribution system can be permanent, related to dead legs or dead ends in the water distribution system, or temporary, related to low water utilization due to inoccupancy or water and energy conservation measures. Dead legs within water distribution systems have been linked to *Legionella* outbreaks and should be avoided or mitigated in hospital construction [6, 7]. Additionally, a recirculating hot water circuit, designed to conserve energy, was implicated in a large outbreak of *Mycobacterium abscessus* that occurred after a newly constructed hospital building was opened for patient care [8].

Water outlets

Distal water outlets and water features are the interface between the water distribution system and humans. Features of distal outlets that promote biofilm formation and/or aerosolization such as faucet aerators, shower heads, decorative fountains, and ice machines can increase risk of transmission from colonized water sources to vulnerable individuals. Contaminated faucet aerators have been linked to outbreaks of environmental gram-negative organisms including *Stenotrophomonas* and *Acinetobacter spp.* [9–11]. Numerous outbreaks of *Legionella* [12, 13] have been linked to decorative fountains, and, for this reason, the Centers for Disease Control and Prevention (CDC) recommends against water features in healthcare settings [14]. Furthermore, ice and ice machines have been associated with numerous outbreaks and pseudo-outbreaks of opportunistic pathogens including *Legionella* and NTM

Table 1. Opportunistic premise plumbing pathogen (OPPP) risk and potential risk mitigation strategies by water system component

Water system component	Related outbreak pathogens	Risk mitigation strategies
Water distribution system	Legionella [6, 7] Non-tuberculous mycobacteria (NTM) [8]	• Establish and follow water management plan to prevent Legionella and other OPPPs • Avoid dead legs and recirculating loops • Establish flushing protocols
Decorative fountains	Legionella [12, 13]	• Avoid water features in healthcare settings
Ice	Legionella [15, 16] NTM [17, 18]	• Avoid use of non-sterile ice for storage of medications or for use in sterile procedures • Use automatic dispensers • Establish protocols for routine cleaning and disinfection of ice machines
Water-containing medical devices	Pseudomonas [19] NTM [20] *Burkholderia cepacia* complex [21]	• Use filtered tap water or sterile water • Follow manufacturer's instructions for use for disinfection of equipment reservoirs and surfaces
Faucets and showerheads	Gram-negative bacteria [9–11] NTM [64]	• Use point-of use filters in high-risk settings • Maintain aerators
Wastewater drains	Gram-negative bacteria, including multidrug-resistant organisms [22–25]	• Modify water flow rates and sink design to reduce splatter • Install splash guards to prevent contamination of adjacent surfaces • Designate different sinks for hand hygiene versus disposal of contaminated fluids

[15–17]. Often, these outbreaks have occurred when non-sterile ice was used peri-procedurally [18].

Water-containing devices

Water-containing medical devices are commonly used in healthcare. Water's high heat capacity makes it well-suited for thermal regulation devices requiring precise temperature control. However, water-containing devices are at risk for becoming colonized and may be sources of transmission of OPPPs. Water-containing devices must be carefully maintained, and infection prevention practitioners should consider multiple potential transmission routes related to contaminated devices. For example, an outbreak of *Pseudomonas* endophthalmitis after cataract surgery procedures was linked to a phacoemulsifier device with a water-containing channel. The device had a faulty backflow prevention valve which allowed direct contamination of operative sites during surgery [19]. More recently, heater cooler units used in cardiac bypass surgeries have been linked to a large number of post-operative NTM infections. The units contain a large water reservoir, which can become colonized during the manufacturing process or at the point of use through the use of tap water to fill the reservoir [8, 20]. Transmission to patients occurred through aerosolization of NTM from contaminated devices. In another example, contaminated ECMO water heaters were linked to *Burkholderia cepacia* complex infections among ECMO recipients [21]. Investigators of this outbreak postulated that contamination of the heater reservoirs with tap water during reprocessing led to cross transmission and colonization of multiple heater devices, which then served as fomites for transmission to critically ill patients.

Wastewater drains

The wastewater drainage system has been increasingly recognized as an environmental reservoir of multidrug-resistant organisms (MDROs) [22–25]. Sink drains have been most often implicated in outbreak transmission, but other wastewater drains, including commodes, have been linked to outbreaks [26]. By design, the P-trap of wastewater drains provides a continuously wet, nutrient-rich environment that promotes biofilm formation. The complexities of the interplay of factors that allow for drain colonization, biofilm persistence, and dispersal of organisms are not fully understood. It is possible that propensity for bacteria to colonize biofilms may relate to the age of the biofilm, P-trap material, or be specific to the bacterial strain [27]. Certain features may influence colonization of drain biofilm by multidrug-resistant organisms. Specifically, disposal of nutrients in the form of tube feeds or other nutrient-rich substances promote drain colonization [26, 28]. Pathogens reach patients when they are dispersed up to 1 m from the P-trap or strainer and contaminate adjacent surfaces or patient care equipment through droplet spread [29••, 30•]. After a sink is implicated in transmission to patients, understanding the pathway of transmission is important in order to devise an effective mitigation strategy. For example, one prolonged outbreak of *Pseudomonas* in an ICU was linked to a practice of emptying ultrafiltrate bags into a sink and reusing the bag for multiple times for the same patient [31]. In another case, an outbreak of *Pseudomonas* was related to contamination of adjacent medication preparation surfaces in the room and was terminated when splash guards were installed [32].

Innovations in mitigation strategies

Along with increasing recognition of the importance of the water distribution and wastewater drainage systems in OPPP transmission in healthcare settings, there is increasing interest in new technology, devices, and strategies to mitigate risk for patients.

Water supply and distribution

Flushing of water lines is the primary intervention to address stagnation in the water distribution system. Many hospital water management plans establish temperature and/or disinfectant levels at distal outlets as control measures. When an action limit is exceeded, the response plan calls for manual flushing of distal outlets. Totaro et al. installed timed flow taps at distal outlets in close proximity to dead legs within the hot water distribution system and set the taps to automatically flush for 1 min every 2 h. This intervention was associated with a substantial decrease in *Legionella* detected in routine water monitoring at these distal outlets [33]. Others have explored the utility of continuously monitoring temperature and water utilization at thermal mixing valves, but additional study is needed to understand the impact of such technology on OPPP transmission in healthcare settings [34].

Water outlets

Numerous interventions aim to reduce the contamination of the sink bowl and adjacent surfaces by water flow and splatter. Aerators and flow restrictors are often applied to the end of faucets to control the stream of water. Although both the structure of and flow through sink aerators impact the degree of particle aerosolization, water outlets with laminar flow or lower flow rates typically reduce the degree of splatter and environmental contamination by OPPPs [35]. However, the benefit of decreased splatter must be balanced with the increased risk of biofilm formation in low-flow states. Contamination of the aerator and accumulation of biofilm can affect the aerosol production regardless of aerator type, and ultimately negate the initial advantage [35]. More investigation into the impact of biofilm formation and long-term aerator usage in healthcare facilities is needed to inform best practices.

Point-of-use (POU) filters are another mitigation measure employed at water outlets. Disposable 0.2 μM filters are commercially available for installation at sinks and shower heads and have been shown to effectively reduce microbiological growth of *Legionella*, *Pseudomonas*, and other OPPPs from tap water [36, 37•]. POU filters have been employed for both short-term outbreak mitigation and long-term use to reduce patient colonization and infections with OPPPs in high-risk areas [36, 37•, 38–40]. However, POU filters can become contaminated over time [41], so education for healthcare personnel, staff, and patients is essential to maintain conditions for proper care and use of the filter. Additional clinical data are needed to inform cost-effectiveness and optimal settings for use of POU filters in healthcare settings.

In addition to modifications to water outlet fixtures, sink design can also contribute to water splatter and environmental contamination. Gestrich et al. found the dispersal of fluorescent gel and colonizing fluoroquinolone-resistant gram-negative bacilli from sink drains to sink bowls and nearby surfaces was inversely related to the depth of the sink bowl [42]. In addition to deep sinks, drain configuration offset to the faucet, rather than immediately below the tap, resulted in reduced dispersal of bacteria to the adjacent care environment [30•].

Wastewater system

Sink drain covers have effectively prevented dispersal of bacteria from drains to sinks and adjacent surfaces [43]. Similarly, the covers applied over in-room toilets prior to flushing effectively reduced nosocomial acquisition of carbapenemase-producing bacteria endemic in the facility plumbing [44]. However, most evaluations of these covers have been limited to single-center studies for relatively short durations of use, so the durability and long-term efficacy is not known.

Cleaning and disinfection of wastewater drains with various chemical solutions, including bleach, hydrogen peroxide, and acetic acid, has been employed with limited success [45]. Chemical disinfection has been shown to reduce the bioburden of organisms in sink drains; however, the impact is typically transient as sinks become recolonized over time [32]. The use of closure valves to permit prolonged dwell times of chemical instillations within proximal drainage systems has shown modest improved efficacy of disinfection lasting for a few days [46]. In efforts to improve the delivery of a cleaning solution to the premise plumbing, a pilot of automated ozonated water flushes reduced the colonization of the strainer and P-trap with *Pseudomonas aeruginosa* and *Candida auris* over a 2-week study period [47]. Initial results of this innovation in a single-sink study design are encouraging; however, widespread and long-term application of this type of system has not been evaluated.

Given the limitations with chemical disinfection, several studies have evaluated novel devices fixed externally to drains and P-traps that employ heat and electromechanical vibration to reduce biofilm formation and improve the durable eradication of pathogens colonizing sink drains. Installation of these devices reduced endemic carbapenemase-producing *Klebsiella pneumoniae* within the plumbing [44] and aerosolization of plumbing pathogens [48]. In response to a prolonged outbreak of MDR *Pseudomonas* within an ICU, placement of a similar device significantly reduced contamination of sink drains and colonization of ICU patients [49•].

Replacement of plumbing fixtures has been explored as a more durable solution. Replacing sinks and plumbing components colonized by gram-negative bacilli has correlated with short-term decreased incidence of infections caused by these pathogens in hospitalized patients [32, 50–52]. However, this approach is laborious and often infeasible. Furthermore, when biofilm persists in plumbing components distal to those replaced, new plumbing components may be recolonized over time [53, 54••]. Thus, replacement of colonized plumbing is not routinely recommended.

Physical environment

Physical separation of water from patient supplies and devices may be a more practical solution given the challenges with implementation and lack of robust data showing durability of many of the aforementioned proposed interventions. Installation of barriers or splash guards between sinks and adjacent preparatory areas decreases the direct contamination of those surfaces and patient care items [32]. Alternative locations away from the sink should be designated for the storage of clean linen and patient care items. Medication preparation and priming of intravenous tubing should also not occur near sinks. Guidance for the best practices of in-room sinks should be reinforced with nursing staff and other healthcare personnel in order to reduce environmental contamination and possible transmission of OPPPs.

Water-sparing protocols

Elimination of water reservoirs is challenging, and measures to disinfect premise plumbing are often limited or unsuccessful. An alternative approach to reduce nosocomial water-related infections is avoidance of tap water for consumption and patient care–related activities, particularly in intensive care units, organ transplant recipients, or other vulnerable cohorts. In response to an outbreak of hospital-acquired *Mycobacterium abscessus* associated with a colonized water supply, the adoption of a sterile water protocol terminated the outbreak and led to a significant reduction in hospital-onset respiratory isolation of *M. abscessus* and other NTM species [8, 55].

A similar but more restrictive measure is the water-free hospital room with complete removal of sinks and tap water exposure. Despite a multimodal response to an outbreak of VIM-producing *Pseudomonas aeruginosa* in an ICU, only after implementing a water-free patient care room was the outbreak controlled. Sinks were removed from all patient rooms and most of the medication preparation areas, and alternative protocols and products were used for patient care activities that typically required water [56]. This intervention could eliminate a significant reservoir of OPPPs; however, waterless hospital rooms have not been widely implemented outside of the ICU [56, 57] and may create challenges for patient care–related activities and affect the workflow of healthcare personnel.

Bundled approach

In practice, multiple interventions are often deployed simultaneously or in close succession to attempt to control an outbreak, and it is challenging to determine the effectiveness and sustainability of single interventions. Typically, bundled practices, including general infection prevention and control measures, have been employed to mitigate outbreaks related to premise plumbing [45]. Similarly, multimodal interventions including structural modifications to water outlets and wastewater systems, heightened cleaning procedures, and staff education to reduce contamination of clean supplies have been used to mitigate outbreaks of multidrug-resistant *Pseudomonas* [54••, 58, 59].

Emerging strategies

The complex dynamics within a biofilm yields a robust and relatively impenetrable matrix that can be challenging for long-term elimination within hospital premise plumbing. Bacteriophages are natural bactericidal agents with the ability to permeate biofilms, attach to and infect specific bacteria, and lead to bacterial cell lysis [60]. Additionally, phage replication within a host cell results in autonomous propagation and the potential for spread along a biofilm or plumbing fixture. Although bacteriophages have been studied for other applications within medicine, there are relatively few investigations into the use of bacteriophages for disinfection of hospital surfaces and premise plumbing. In one single-center study, the addition of an aerosolized active bacteriophage to standard terminal cleaning procedures resulted in a significant reduction in carbapenem-resistant *Acinetobacter baumannii* infections in the ICU [61]. Using a model P-trap, Santiago et al. found a significant reduction of carbapenemase-producing *Klebsiella pneumoniae* in a multispecies biofilm following phage inoculation [62]. As more applications of bacteriophages for biocontrol are explored, additional study is needed to assess for potential risks, including selection of phage-resistant bacterial strains, horizontal gene transfer between non-pathogenic and pathogenic bacteria, and possible resultant dysbiosis within the applied environment [63]. Bacteriophages may provide an alternative or supplemental mode of disinfection to other less selective processes, but more widespread implementation of this strategy will require further study with attention to the interaction of the virus, host, and unique environmental conditions of premise plumbing.

Conclusions

Hospital water distribution and wastewater systems are significant reservoirs of opportunistic pathogens and present unique challenges for infection prevention. Understanding the potential sources for water-related healthcare-associated infections, associated pathogens, and modes of transmission is key to identifying and mitigating outbreaks. Few high-quality data exist regarding the effectiveness of individual interventions to mitigate risk of infection from water sources as multiple infection prevention measures are often implemented simultaneously in the context of an ongoing outbreak investigation. Current available data are largely derived from single-center, retrospective observational studies. Prevention of infections related to water sources is an area of acute need for ongoing laboratory-based and translational research. Prospective, controlled, clinical trials of the most promising interventions are needed to determine interventions that are effective, feasible, and sustainable. Basic infection prevention practices, including physical separation of patient care items from water sources, will always play an important role in reducing the risk of healthcare-associated infections.

Declarations

Human and Animal Rights and Informed Consent.
This article does not contain any studies with human or animal subjects performed by any of the authors.

Conflict of Interest
The authors declare no competing interests.

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•• Of major importance

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