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Review

Association between healthcare water systems and *Pseudomonas aeruginosa* infections: a rapid systematic review

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S U M M A R Y

Background: *Pseudomonas aeruginosa* is an opportunistic pathogen with a particular propensity to cause disease in the immunocompromised. Water systems have been reported to contribute to *P. aeruginosa* transmission in healthcare settings.
Aim: To systematically assess the evidence that healthcare water systems are associated with *P. aeruginosa* infection; to review aspects of design that can increase their potential to act as a reservoir; and to compare the efficacy of strategies for eradicating contamination and preventing infection.
Methods: A rapid review methodology with a three-step search strategy was used to identify published studies. Scientific advisors were used to identify unpublished studies.
Findings: Twenty-five relevant studies were included. There was plausible evidence of transmission of *P. aeruginosa* from water systems to patients and vice versa, although no direct evidence to explain the exact mode of transfer. Two studies provided plausible evidence for effective interventions: point-of-use filters and increasing chlorine disinfection. Non-touch taps and aspects of water system design were identified as probable risk factors for *P. aeruginosa* biofilm formation and subsequent transmission to patients. Poor hand hygiene or compliance with contact precautions were identified as potential contributory factors; plausible evidence to confirm this was not available.
Conclusions: Water systems can act as a source of *P. aeruginosa* infection in healthcare settings, although the route of transmission is unclear. Contamination appears to be confined to the distal ends of a water system and can persist for prolonged periods. Further studies are required to establish effective methods of preventing transmission and eradicating *P. aeruginosa* from plumbing systems.

Introduction

Pseudomonads are aerobic, non-fermentative Gram-negative bacilli that are widespread in soil, water and other moist environments. *Pseudomonas aeruginosa* is the species most

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frequently associated with disease in humans, where it acts as an opportunistic pathogen with the potential to cause infections in almost any organ or tissue, especially in patients compromised by underlying disease, age or immune deficiency. The capacity of *P. aeruginosa* to cause disease is enhanced by both innate and acquired resistance to many antimicrobials and disinfectants, virulence factors and ability to adapt to a wide range of environments.[1,2]

Data on the incidence of healthcare-associated infections caused by pseudomonads are not readily available. Laboratory reports of bacteraemia are the most reliable indicator of severe infection. In the UK, *Pseudomonas* spp. are the seventh most frequent cause of bacteraemia, accounting for ~4% of these infections and with an incidence of 7.3 per 100,000 population. There is evidence of an increase in severe disease caused by *Pseudomonas* spp. with a recent significant increase in reports of bacteraemia in England and Wales.[3] There have also been a number of outbreaks of *P. aeruginosa* affecting intensive care units (ICUs) that have highlighted the potential for *Pseudomonas* spp. to establish microbial reservoirs in the healthcare environment.[4—10]

In contrast with other waterborne pathogens, *P. aeruginosa* thrives in the environment over a wide range of temperatures and is very adept at exploiting relatively nutrient-poor circumstances. Its polysaccharide capsule enables it to adhere to surfaces and under favourable conditions the cells multiply rapidly on surfaces in contact with water delivery systems to form a biofilm. Although most bacteria are retained within the biofilm, some will become free-floating in the water (planktonic) especially when it is static for prolonged periods.[11]

Standard water treatment removes most microbial contamination from mains water. However, in large buildings, such as hospitals, there are many locations within a plumbing installation where bacteria are able to proliferate and form biofilms. These locations include parts of the system where there is stagnation or higher levels of nutrients from accumulated organic material, such as infrequently used outlets and dead legs, non-metallic materials used for pipework, and terminal outlets where the flow depends on outlet use and hence is more variable.[12] As an aerobic bacterium that relies on oxidation to metabolize carbohydrates, *P. aeruginosa* thrives best in the distal parts of the water distribution system, such as taps and sinks where there is sufficient access to oxygen.[11] Once biofilms are established, particularly in dead-legs, biocides may not be able to penetrate them and bacteria may remain deep within the biofilm.[13]

In the past, strain typing of *P. aeruginosa* relied on phenotypic techniques such as serotyping; however, in the last decade the development of molecular typing techniques has demonstrated the limitations of these methods in characterizing the relatedness of clinical and environmental strains.[2,10] Studies using molecular typing have implicated environmental sources in the acquisition of *P. aeruginosa* colonization and infections in patients on ICU and other healthcare settings.[14] These investigations have generally been related to outbreaks of highly antibiotic-resistant strains. They have suggested that *P. aeruginosa* colonizing or infecting patients may contaminate the plumbing system, which then becomes a reservoir and contributes to transmission of infection over prolonged periods.[6—10,15] Investigations of the most recent outbreaks in Northern Ireland and Wales have added to concerns about the link between infections, tap design and biofilms in hospital water systems.[4,5,16,17]

Whereas there is a considerable body of published literature, much of it is derived from outbreak reports, it is of variable detail and quality, and has not been subjected to systematic assessment. This paper describes a rapid systematic review (RR) of evidence to determine the extent to which transmission of *P. aeruginosa* from water sources presents a risk to patients, the role of specific components of the plumbing system and the efficacy of strategies for preventing and eliminating contamination of the system.

Methods

The aim of the RR was to assess the epidemiological and technical literature with the specific objectives of identifying evidence that healthcare water systems are associated with patient colonization and/or infections in augmented care units (ACUs); to investigate aspects of design that can increase the potential for the system to act as a reservoir; and to assess the effectiveness of engineering and infection prevention interventions in eradicating or controlling *P. aeruginosa* in water systems in healthcare facilities (Box I).

A rapid review methodology was employed. The RR is characterized by the application of the systematic review process with limitations applied due to the need for prompt answers to policy or therapy questions.[18] This RR used an expedited process, as suggested by The Magenta Book (SSRC) and limited database searches to Medline, Embase (Ovid), Aqualine (Cambridge Scientific Abstracts) and the National Guidelines Clearing House; only published peer-reviewed literature in English was retrieved within the period 1998—2012. 'Grey' literature was not retrieved.[19]

For the purpose of this review, a plumbing system was taken to represent those fixtures and fittings responsible for conveying water from its entry into a building to its immediate collection after use. ACUs were defined as neonatal, paediatric and adult intensive care, burns, organ transplant, oncology, haematology, cystic fibrosis and renal units.

The review considered both experimental and epidemiological study designs including non-clinical experiments (plumbing systems), randomized controlled trials (RCTs), non-RCTs, quasi-experimental, before-and-after studies, prospective and retrospective cohort studies, case—control

Box I

Objectives of the review

1 Evidence that healthcare water systems are associated with patient colonization/infection with *Pseudomonas aeruginosa* in augmented care units.
2a Effectiveness of engineering and water safety interventions for reducing *P. aeruginosa* growth in healthcare water distribution/plumbing systems and water outlets.
2b Aspects of the water system, e.g. design and type of fixtures and fittings that can lead to systems acting as a potential reservoir for the transmission of *P. aeruginosa* in augmented care settings.
3a Effectiveness of infection prevention interventions for reducing the transmission of *P. aeruginosa* from potable water from healthcare water distribution systems to vulnerable patients.
3b Effectiveness of other infection control interventions, e.g. hand hygiene and antimicrobial stewardship.

studies and analytical cross-sectional studies for inclusion. In the absence of the aforementioned designs, it considered descriptive epidemiological studies, including case series, individual case reports and descriptive cross-sectional studies for inclusion.

Search strategy

A three-step search strategy was used to identify published studies. An initial search of Medline was undertaken to identify keywords in titles and abstracts and index terms used to describe articles. A second search, using the keywords and index terms was repeated in Medline and Embase. The following MESH heading and search words/terms were used:

- pseudomonas aeruginosa, multidrug-resistant pseudomonas aeruginosa, outbreak(s)
- infection, healthcare associated infection, nosocomial infection, waterborne infection
- infection control
- biofilm(s), colonization
- water, tap water, water quality, water temperature
- water distribution, water network, plumbing, plumbing installations, water supply, water outlet(s), water system(s), pipe(s), u-bend(s), water fittings, water source(s)
- respirators, ventilators, incubators, humidifiers
- faucets, taps, sensor taps, electronic taps, electronic faucets, showers, aerators, rosettes, thermostatic mixer valves, basins, sinks, sink traps
- point of use water filters, end-line filters, filters, silver ions, copper ions, ionization, ozone, ultraviolet, chlorine dioxide, chemical disinfection, monochloramine, free chlorine, thermal disinfection, thermal shock

For studies which focused on plumbing systems, a separate search in Aqualine (Cambridge Scientific Abstracts) was conducted using keywords. Third, the reference lists of all identified reports and articles were searched for additional studies. Finally, as this RR was limited to three databases, scientific advisers were asked to verify that no important published studies, or recent unpublished studies, had been missed. Two members of the review team independently assessed the title and abstract of the search results for relevance against the following criteria: reported primary research or epidemiological data related to an outbreak of *P. aeruginosa*; clinical studies were situated in ACUs; evaluated infection prevention, engineering, materials and plumbing factors or interventions; used genotyping to confirm associations between *P. aeruginosa* colonization or infection.

Assessment of abstracts for methodological quality and microbiological methods was carried out independently by two reviewers using the standardized appraisal tools from the Joanna Briggs Institute.[20] Data were extracted from papers using a standardized data extraction tool adapted from the Joanna Briggs Institute and used to develop a narrative summary of the data. Due to the heterogeneity of the studies, criteria for plausibility were developed to determine the extent to which studies were valid and reliable in terms of study design and outcome measurement (Table I). Twenty-five studies were assessed, of which eleven studies were deemed to provide plausible evidence. Data were then synthesized using a narrative approach.

Results

The search identified 196 potentially relevant studies (Figure 1). Following a review of title and abstracts, 116 studies were retrieved for further assessment. Of these, 43 were identified for assessment of methodological quality and data extraction, and 25 included in the RR. The majority (19) of studies addressed objective 1; these were predominantly outbreak reports based on retrospective analyses and short-term prospective follow-up in ICUs or haemo-oncology units. Only two involved case—control or comparison groups and therefore no studies were considered to be highly plausible. Eleven of these studies provided plausible evidence relevant to one or more of the objectives of the review.

Evidence that healthcare water systems are associated with patient colonization and/or infection with P. aeruginosa in ACUs (Objective 1)

Only seven studies were assessed as providing plausible evidence of a link between a plumbing system acting as reservoir for *P. aeruginosa* and colonization and/or infection in patients.[21—27] These were prospective observational or cohort studies undertaken during endemic periods which investigated the contribution of endogenous and exogenous transmission of *P. aeruginosa* to colonization/infection of patients, using molecular methods to identify temporal relationships between environmental reservoirs and the onset of colonization/infection. They used surveillance specimens taken from patients on admission and at a minimum of weekly until discharge, to identify colonization with *P. aeruginosa* and sampled multiple water system outlets, including tap water, sink siphon or overflow and/or sink U-bends at intervals ranging from every 72 h, twice weekly, to every 2 weeks.[21—27] In two studies, samples were taken from taps with aerators fitted, but the aerators were removed and decontaminated at regular intervals.[23,26]

Table II summarizes the evidence from these studies for the transmission of *P. aeruginosa* from plumbing systems to patients and vice versa based on the temporal relationship in the sequence of positive cultures with indistinguishable genotypes. Whereas the data demonstrated that plumbing reservoirs of *P. aeruginosa* were responsible for patient colonization and infection, there was also evidence of transmission of *P. aeruginosa* between patients involving clones that were not recovered in the water or plumbing systems, presumably via staff or equipment. Several authors reported poor hand hygiene as a contributory factor.[23,24,26]

There was little evidence to explain the exact mode of transfer from plumbing to patient and vice versa. Examples cited for the use of tap water, which could have acted as the vehicle of transmission in addition to contaminated staff hands, were making up enteral feeds and personal care activities such oral care and patient washing.[22,25] The disposal of wash water and ventilator traps was considered probable means by which *P. aeruginosa* was transferred from patient to plumbing.

A further 14 studies were considered to provide descriptive evidence of low plausibility for Objective 1.[6—8,28—36] They reported outbreaks of *P. aeruginosa* in a range of ACU settings but, in the absence of surveillance results, temporal relationships

Table I
Criteria for plausibility

Objective	Plausibility criteria
1	Prospective design +/− comparison group. Data collection during epidemic or endemic period. Patient sampling includes surveillance specimens at baseline (admission or intubation) and clinical specimens as appropriate. Molecular typing of ≥1 colony using robust methodology. Matched profiles of strains isolated from patients and water/plumbing systems. Methods allow temporal relationship to be identified between plumbing system being a reservoir for *Pseudomonas aeruginosa* and identification of colonization/infection in patients OR exposure to water system/specific component shown to be associated with acquisition of *P. aeruginosa*. Examination of multiple outlets of water and plumbing system. Includes repeated sampling during the observation period.
2a	*Chemical treatment of water supply/treatment of fixtures and fittings:* applied to plumbing installations at a single location (i.e. under a limited set of water quality conditions) and comparison made using before-and-after treatment measures. *Model rig systems:* demonstrate that chemical treatment reduces the amount of biofilm formation, and/or reduction in numbers of *P. aeruginosa* or bacteria generally and there is a parallel comparison of efficacy in reducing bacterial numbers. The intervention is defined and introduced at a defined point. If more than one intervention, these are introduced in a stepwise way. Robust sampling and microbiological methods used.
2b	*P. aeruginosa* consistently recovered in association with a design feature (e.g. sink traps, flow straighteners). Consistent results obtained from repeated sampling undertaken on multiple devices on more than one occasion. Robust sampling methods used.
3	Prospective design+/− comparison group. Data collection during epidemic or endemic period. Patient sampling includes surveillance specimens at baseline (admission or intubation) and clinical specimens as appropriate. Molecular typing of ≥1 colony using robust methodology. Matched profiles of strains isolated from patients and water/plumbing systems. Methods allow temporal relationship to be identified between plumbing system being a reservoir for *P. aeruginosa* and identification of colonization/infection in patients OR exposure to water system/specific component shown to be associated with acquisition of *P. aeruginosa*. Examination of multiple outlets of water and plumbing system. Includes repeated sampling during the observation period. Clearly reported intervention, introduced at a defined point in an epidemic or endemic period. If more than one intervention, these are introduced in a stepwise way. Repeated outcome measurement of interventions. Intervention associated with reduction in number of patients colonized/infected with *P. aeruginosa*.

between strains from patients and the environment were not established. In addition, sampling of water and plumbing systems was undertaken on a single occasion, infrequently or from a limited number of outlets, and inadequately reported. However, some of these studies described interventions of interest for Objectives 2 and 3, respectively.

Effectiveness of engineering and water safety interventions for reducing P. aeruginosa growth in healthcare water distribution/plumbing systems and water outlets (Objective 2a)

There were no RCTs or quasi-experimental studies that demonstrated a causal relationship between water safety interventions and reductions or control of *P. aeruginosa* in the literature. A small number of technical studies, conducted under laboratory conditions, were excluded at the retrieval stage as they did not address the review objectives. The majority of the 11 studies retrieved described interventions, often several implemented at the same time, undertaken in order to eradicate *P. aeruginosa* from the plumbing system during outbreaks and were assessed as being of low plausibility.[8,9,15,22,29,31,34–38] The poor design of studies, absence of data and lack of long-term follow-up meant that it was not possible to determine whether attempts at eradication of *P. aeruginosa* from the plumbing system were effective or to distinguish the effect of multiple interventions. Reported interventions involved: avoiding use of water; replacement of fixtures and fittings; dismantling outlets followed by cleaning and disinfection with chlorine, hydrogen peroxide; autoclaving or increasing temperature of water at the outlet; system-wide chlorination at higher than normal concentrations; installation of outlet filter devices or filtered water systems.[7–9,15,22,23,26,29,31,35,37,39] Some studies used several methods, and often repeated attempts were required to eradicate *P. aeruginosa* from the water system. The removal of fixtures and fittings, e.g. aerators, and the installation of devices such as point-of-use filters and systems for ensuring microbiologically safe water have been reported as effective but costly.[34,38,39] Chemical treatment and

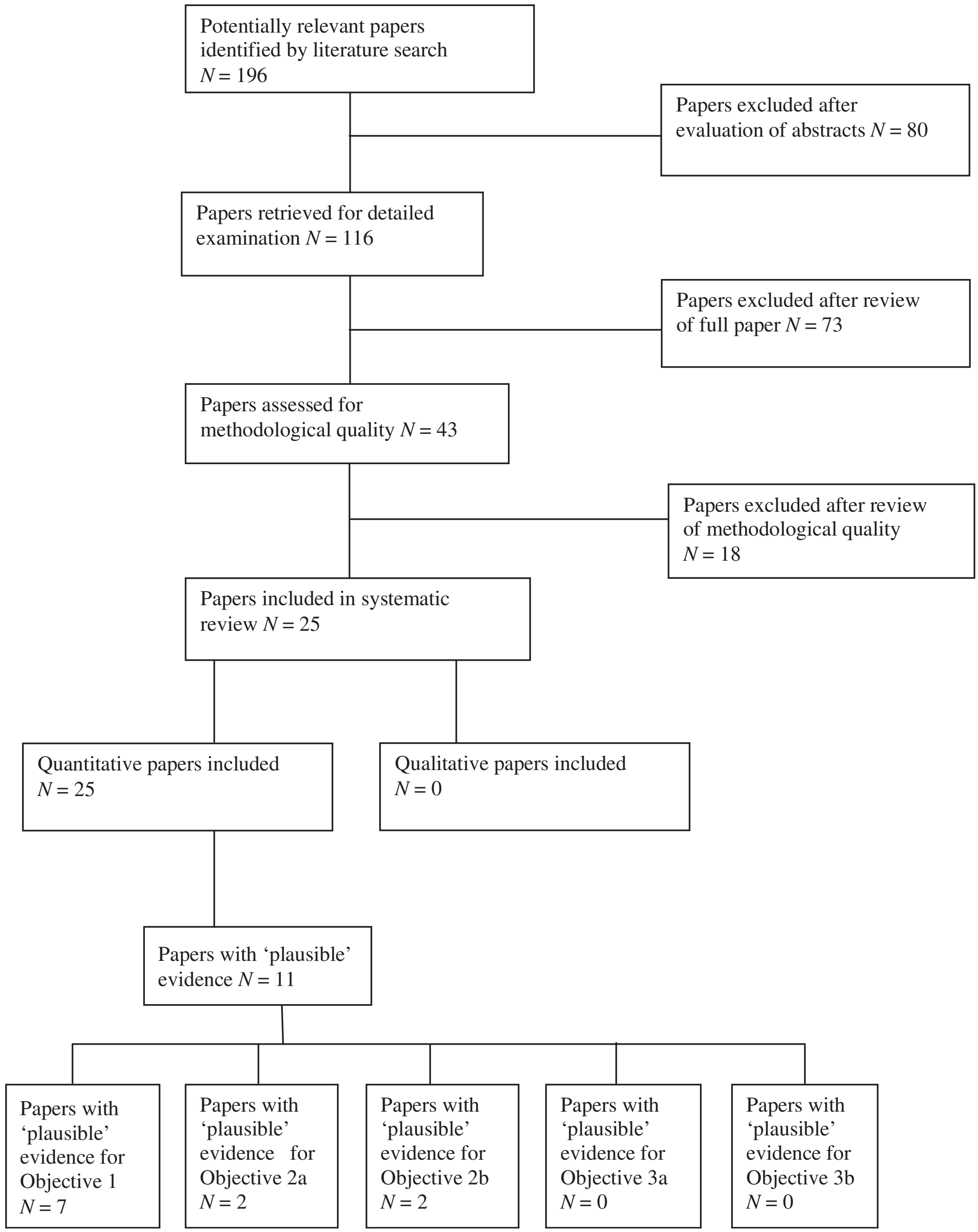

Figure 1. Selection and evaluation process for included papers.

increasing water temperature was reported as effective by some studies but not others.[7,22,36]

Only two studies undertaken in the clinical setting were assessed as providing plausible evidence for the effect of intervention. The first of these was an outbreak investigation, in which *P. aeruginosa* associated with catheter-related bloodstream infections (BSIs) in a paediatric onco-haematology unit was recovered from shower heads and hoses. The introduction of 7-day filters fitted to showers and chlorine disinfection at 0.5 mg/L was associated with a reduction in *Pseudomonas* spp. recovered from the plumbing system.[7] No further *Pseudomonas* spp. were recovered from the plumbing system when chlorination was increased to 2.7 mg/L. Concern about the effect of chlorination on plumbing materials and the cost of filters resulted in these measures being replaced by the installation of a water loop, which produced microbiologically controlled water and sustained the quality of the water beyond the outbreak period.

The second study employing point-of-use filters to reduce endemic *P. aeruginosa* infections in a surgical ICU was conducted over a 3-year period.[39] The rates of *P. aeruginosa* colonization and infections among a random sample of 50% of

Table II
Probable sources of patient-acquired *P. aeruginosa* (PA) on intensive care unit (ICU) as determined by surveillance or clinical cultures

Study	No. of patients admitted/ included	No. of patients with PA (no. with infection)	No. of endogenous[a] acquisitions (% of all patients with PA)	No. of patient-to-patient transmissions (% of all patients with PA)	No. of tap-to-patient transmissions (% of all patients with PA)	No. of patient-to-tap transmissions (% of all patients with PA)	No. of other route/not known (% of all patients with PA)
Berthelot *et al.*[21]	59	26 (10)	21 (81%)	0	5 (19%)	0	–
Reuter *et al.*[23]	53[b]	31	–	–	13 (42%)	4 (13%)	14 (45%)
Rogues *et al.*[26]	152[c]	38	6 (16%)	6 (16%)	7 (18%)	11 (29%)	5 (3[d]) (21%)
Trautmann *et al.*[22]	390	17 (17)	5 (29%)	5 (29%)	4 (24%)	–	3 (18%)
Trautmann *et al.*[24]	–	16 (9)	–	–	8 (50%)	2 (13%)	5[e] (31%)
Vallés *et al.*[25]	72	31 (4)[e]	9[f] (29%)		19 (61%)	3[g] (10%)	
Cholley *et al.*[27]	123	17	–		1 (6%)	0	13 (76%)

[a] Strain not previously isolated from the environment/other patients.[21]
[b] Admission with stay in ICU >4 days, no acute respiratory distress.
[c] Stay in ICU >72 h.
[d] Cases associated with bronchoscope.
[e] Recruited ventilated patients, included those who acquired colonization >48 h after admission; infections = ventilator-associated pneumonia.
[f] Association defined as the same genotype in tap water in same room as patient (but eight of these patients had a strain that was present in tap water of other rooms – extracted from data).
[g] Same genotype recovered from patient and water at same time.

patients admitted to the ICU >3 days (154 pre-filter vs 141 post-filter) were compared. *P. aeruginosa* colonization was reduced by 85% ($P < 0.0001$) and invasive infections by 56% ($P < 0.0003$) following the introduction of point-of-use filters. Collection of tap water samples showed no *P. aeruginosa* recovered after the introduction of the filters, and no changes in hand hygiene behaviour, as monitored by alcohol gel use, were detected.

Aspects of the water system, e.g. design and type of fixtures and fittings that act as a reservoir for the potential transmission of P. aeruginosa in ICUs (Objective 2b)

Six papers addressing this question were identified, only two of which were assessed as plausible.[8,28,34,38,40,41] The first plausible study evaluated water quality in two models of non-touch taps (NTTs) newly sited in a clinical area, one with fixed water temperature (23 taps) and the second with cold and warm temperature selection (15 taps).[40] Ten taps of conventional design adjacent to NTTs without temperature selection were also included in the assessment. Seventeen (74%) NTTs without temperature selection and one with temperature selection (7%) were contaminated with *P. aeruginosa* ($P < 0.001$) and in some NTTs the magnetic valve and outlet were highly contaminated. Adjacent conventional taps were not contaminated and some NTTs had total cell counts that were 100 times higher than in conventional taps. This study did not provide any indication as to how long it took for the NTTs to become contaminated, nor did it allow for the possibility that taps were contaminated on arrival from the manufacturer; this was a potential problem that was only identified 5 years later.[42]

In the second plausible study, an outbreak of *P. aeruginosa* in a haemo-oncology unit was attributed to a whirlpool bath used by patients.[28] A case–control study confirmed that the use of the whirlpool bath was a significant risk factor for infection. All seven of the case patients compared with nine out of 28 control patients had used the bathtub ($P < 0.003$) and case patients used the bath 4.3 times compared with 1.7 times in the control group. The design of the bath meant that the drain closed 2.54 cm below the surface of the bath and was hence contiguous with the bath water. *P. aeruginosa* was not recovered from tap water but contamination was probably derived from patients using the bath since it was used as treatment for perianal fissures or ulcers and all the case patients and 79% of control patients had diarrhoea. In the 5 years following replacement of the bath no further clusters of *P. aeruginosa* were identified.

Although the other four studies were assessed as low plausibility, they did indicate that the design of both plumbing systems and the area around patient bed spaces may pose a risk to vulnerable patients.[8,34,38,41] A number of short communications, not considered in this RR, have commented on outbreaks of *P. aeruginosa* coinciding with the introduction of NTTs and aerators/flow straighteners and ending after their subsequent removal.

Effectiveness of infection prevention interventions for reducing the transmission of P. aeruginosa from the use of potable water from healthcare water distribution systems to vulnerable patients (Objective 3a)

A number of studies suggested that colonization of patients with *P. aeruginosa* arose from the use of potable water for nursing and clinical care activities such as personal care (bathing and showering), enteral feeding and oral care.[22,25,35,37] However, studies introduced a number of interventions aimed at minimizing this route of transmission, often simultaneously with other general infection control precautions, such as isolation, using alcohol hand rub and using sterile or bottled water for drinking, suspending medications, enteral feeds, washing patients' faces and oral care.[15,26,30,31,37–39] No studies providing plausible evidence for interventions to minimize the transmission of *P. aeruginosa* from potable water to patients were found.

Some studies suggested that contamination of handwash basins with *P. aeruginosa* could have occurred as a result of washing soiled utensils or disposal of waste water, such as from ventilator traps, cascade humidifiers or patient wash water and, in one study, use as a temporary sluice for body fluids.[15,28,34,35] However, there was little evidence that these explanations were based on structured observation of healthcare worker behaviour and they were therefore deemed to be of low plausibility.

Effectiveness of other infection control interventions, e.g. hand hygiene, antimicrobial control (Objective 3b)

Standard infection control interventions such as hand hygiene, alcohol hand disinfection, contact isolation and restriction of antimicrobial agents were reported as being implemented as a control measure during outbreaks.[15,30,31,34,36,37] No studies providing plausible evidence for the efficacy of these measures were identified. Some studies reported that healthcare workers' hands were sampled as part of the outbreak investigation; however, compliance with infection control procedures, such as hand hygiene and alcohol hand disinfection, was not measured. Contact precautions were instigated as a matter of course in outbreak periods, but again, none of the studies observed staff adherence. In the absence of data on compliance it is difficult to determine the relative contribution of patient-to-patient and handwash basin/sink-to-patient transmission. In four studies, antibiotic selective pressure was addressed by implementing changes to antimicrobial prescribing policies.[29–31,35] However, these changes were one of several interventions and outbreaks continued despite them.

Discussion

This rapid systematic review found a limited number of publications that provided plausible evidence for the role of water and plumbing systems in colonization or infection of patients with *P. aeruginosa* in ACUs. Most of the literature was descriptive and based on outbreak reports, and it was not possible to determine the route or order of transmission of *P. aeruginosa* between water fittings and patients. Evidence from prospective studies during endemic periods, using molecular typing and frequent surveillance of both the plumbing system and patients, provides plausible evidence that strains of *P. aeruginosa* found in handwash basins, showers/taps and tap water can be a source of *P. aeruginosa* in both the colonization and infection of patients in ACUs. *P. aeruginosa* contamination appears to be confined to the distal ends of a plumbing installation (tap fittings, flow straighteners, shower heads, and sink drains), rather than the entire system. A number of different strains of *P. aeruginosa* may be present in the water system without being linked to colonization/infection of patients but water systems may also remain contaminated with the same strain of *P. aeruginosa* over prolonged periods.

The studies do not provide any direct evidence for how handwash basins/sinks become contaminated. They postulate that contamination occurs through exposure to patient material, e.g. washing water and respiratory system water, with the sink then acting as a reservoir for onward transmission to other patients through contact with staff hands or use of water for patient care, e.g. washing, brushing teeth and preparation of enteral feeds. Other possibilities are that *P. aeruginosa* may be present in the incoming water or that taps are contaminated during the handwashing procedure. The association with the tap outlet indicates a physiological niche for *P. aeruginosa* to establish a reservoir, regardless of route of acquisition.

Patient-to-patient transmission is mostly assumed to be via hands of staff and studies suggest that this is a more common route than sink-to-patient or patient-to-sink transmission.[22,26] However, this assumption, while reasonable, is not based on any consistent or prolonged measurement of staff hand carriage or observation of compliance with infection control procedures, such as hand hygiene, alcohol gel use or contact precautions. It is therefore difficult to determine the relative contributions of patient-to-patient and handwash basin/sink-to-patient transmission. Staff may also transfer *P. aeruginosa* between hand basins.[23]

Whereas the studies included described methods of monitoring and testing water and plumbing fittings, the approach to sampling was often not well reported. Water temperature was often not specified, i.e. hot or cold or mixed, some studies only sampled water fittings once, whereas others took samples over several weeks. These methods are likely to vary in their ability to detect *P. aeruginosa* and in the reliability with which they identify contaminated water systems as the source of *P. aeruginosa* in patients. Additionally, if healthcare workers use a handwash basin or sink immediately prior to taking the sample from the tap, contamination with *P. aeruginosa* may be missed. Studies mostly do not describe whether the tap was preflushed or when it was last used prior to the sample being collected. Some studies reported outbreaks of *P. aeruginosa* that could not be linked to water systems, although inadequate water sampling may have obscured a relationship.[17]

Microbiological methods also have an influence on the interpretation of epidemiological data on routes of transmission of *P. aeruginosa*. Selection of single colonies from environmental cultures for typing may fail to identify contamination of water/fittings associated with multiple strains. Phenotypic characteristics such as colonial morphology do not reliably correlate with genotypes; thus, studies which have genotyped only single or morphologically distinct colonies may have resulted in incomplete characterization of the relationship between clinical and environmental isolates.[2,8,9,14] Selection of multiple colonies for genotyping of isolates is likely to provide a more reliable indication of epidemiological links.[25] Similarly, focusing only on strains with particular resistance phenotypes may have missed potential transmission by genotyping only those isolates that expressed the resistance pattern of interest. Moreover, *P. aeruginosa* in patients is generally identified through screening swabs (rectal and respiratory tract). The reliability with which these detect low-level colonization is unknown and this may affect the attribution of *P. aeruginosa* acquisition to an endogenous or exogenous route.

There is little plausible evidence for the efficacy of interventions to eradicate *P. aeruginosa* from the plumbing system, since the majority of the studies were poorly designed and unable to distinguish the effect of multiple interventions during an outbreak. The main interventions were removal and replacement of components of the plumbing system, use of filtration devices or methods of disinfection or decontamination of water and delivery systems, including systematic treatment of the incoming water supply with chlorine, thermal disinfection of taps, autoclaving of tap aerators and increasing the temperature of water within taps to >50 °C. Dismantling and mechanical cleaning of taps and aerators was also described. The introduction of point-of-use filters was described as effective in eliminating *P. aeruginosa* from water taken from outlets and preventing colonization/infection of patients, but costly.[7,39] There is no robust evidence to support the efficacy of infection control precautions in limiting transmission from water systems in ACUs.

The ability of *P. aeruginosa* to form biofilms readily may be facilitated by some types of plumbing materials and plumbing locations, with the design of fittings having the potential to exacerbate this growth. NTTs have been found to be contaminated with *P. aeruginosa*; outbreaks have coincided with their introduction and have stopped when replaced, although none of this evidence was assessed as plausible.[40] The presence of a magnetic valve constructed from rubber plastic and a polyvinylchloride membrane, where fitted, is also likely to encourage bacterial growth and formation of biofilms.[2] Flow straighteners are prone to accumulate scale that may subsequently harbour biofilm and have been implicated in outbreaks. However, several studies have found no effect on water contamination or patient colonization if they are regularly removed, descaled and autoclaved.[23,26] Robust studies to underpin policy recommendations about the fitting of these devices in healthcare plumbing systems are not available.

In conclusion, this RR has provided a narrative synthesis of the limited literature describing outbreaks of *P. aeruginosa*, and links to plumbing systems and the use of water in ACUs. This literature suggests that strains of *P. aeruginosa* may persist in water systems over prolonged periods but are confined to the distal parts in sinks and associated fittings. Strains of *P. aeruginosa* recovered from tap water or the water system can also be found in patient surveillance and clinical specimens and, although patient-to-patient transmission remains a frequent route, there is plausible evidence that both sink-to-patient and patient-to-sink transmission occurs. Further, well-designed studies are required in order to determine effective methods of preventing or eradicating contamination of water systems, and infection control procedures that will minimize the risk of transmission from water system to patients. Where possible, such studies should be designed prospectively and include baseline and ongoing surveillance/clinical cultures, repeated cultures from multiple water outlets, molecular typing of more than one colony and methods that allow temporal relationships between plumbing system and infection/colonization in patients to be identified.

Conflict of interest statement

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