J Antimicrob Chemother 2013; **68**: 2718–2732
doi:10.1093/jac/dkt281 Advance Access publication 18 July 2013

Journal of Antimicrobial Chemotherapy

Current and emergent strategies for disinfection of hospital environments

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A significant number of hospital-acquired infections occur due to inefficient disinfection of hospital surfaces, instruments and rooms. The emergence and wide spread of multiresistant forms of several microorganisms has led to a situation where few compounds are able to inhibit or kill the infectious agents. Several strategies to disinfect both clinical equipment and the environment are available, often involving the use of antimicrobial chemicals. More recently, investigations into gas plasma, antimicrobial surfaces and vapour systems have gained interest as promising alternatives to conventional disinfectants. This review provides updated information on the current and emergent disinfection strategies for clinical environments.

Keywords: antimicrobial resistance, cross-contamination, disinfection, hospital-acquired infections

Introduction

The number of hospital-acquired infections (HAIs) has been growing exponentially worldwide since 1980, especially due to the emergence and wide spread of multidrug-resistant (MDR) bacteria. Multidrug resistance is an intrinsic and inevitable aspect of microbial survival and has been a major problem in the treatment of bacterial infections.[1–4] The evolution of bacterial resistance is a consequence of the indiscriminate use of antibiotics and of the transmission of resistance within and between individuals.[5–8] Also, the lack of new clinically relevant classes of antibiotics constitutes a major threat to public health.

HAIs are among the major causes of death and increased morbidity among hospitalized patients, with a minimum of 175 000 deaths every year in industrialized countries.[9–12] Several investigations showed that >60% of worldwide HAIs have been linked to the attachment of different pathogens to medical implants and devices, such as venous and urinary catheters, arthroprostheses, fracture-fixation devices and heart valves.[13–18] As a direct consequence, the replacement of implants, which entails significant costs and suffering for patients, often remains the only efficient therapy.[19] Additionally, it has been demonstrated that the increased incidence of HAIs is related to cross-infections from patient to patient or hospital staff to patient and to the presence of pathogenic microorganisms that are selected and maintained within the hospital environment (including equipment).[1,11,20–23] Poor infection control practices may facilitate patient-to-patient transmission of pathogens; for instance, in the accommodation of multiple patients in the same room. However, failure of the immune system due to illness and/or the use of immunosupressors and other therapeutic drugs can increase the patient's susceptibility to infections. Moreover, the use of antibiotics can inadvertently select antibiotic-resistant microorganisms.[21]

Since the environment serves as an important reservoir for infectious organisms, the control of hospital infections is a matter of great concern and a major challenge. The introduction of optimized disinfection products and processes is critical to control and prevent the spread of nosocomial infections, cross-resistance and persister cells.[24] Within recent decades, requirements regarding the antimicrobial activity of disinfectants in the medical field have been defined in various European standards.[25] Also, guidelines have been developed by the CDC, which recommend hospitals to thoroughly clean and disinfect environmental and medical equipment surfaces on a regular basis.[26] However, there is a variety of products available on the market with moderate or even insufficient antimicrobial action.[25] New products and technologies with 'permanent' antimicrobial activity without the risk of generating resistant microorganisms are needed.[12] Hence, this manuscript provides information on the main pathogens causing HAI and the relevant in-use and emergent strategies for their control.

Main hospital pathogens

The increase in HAI is associated with the higher capacity of bacteria to resist and adapt to harsh environmental conditions, including the presence of antimicrobial agents. Deadly pathogens can survive for long periods of time on hospital surfaces, making the environment a continuous reservoir of infectious agents. The adhesion of pathogens to a surface followed by biofilm formation in <24 h is a critical microbiological problem for healthcare

services.[10] In fact, the concentration of disinfectants required to kill sessile bacteria may be 1000-fold higher than that required to kill planktonic bacteria of the same strain. Thus, antimicrobial therapies fail to kill biofilms most of the time.[27–30] Furthermore, there are few prevention techniques to control biofilm formation without causing side effects.[31]

Some of the most important pathogens involved in HAIs include methicillin-resistant *Staphylococcus aureus* (MRSA), *Clostridium difficile*, *Pseudomonas aeruginosa*, vancomycin-resistant *Enterococcus* spp. (VRE), *Acinetobacter baumannii* and some Enterobacteriaceae strains.[1,21,32,33] To a lesser extent, pathogens such as *Candida* species, viruses [adenoviruses, noroviruses, rotaviruses, influenza, parainfluenza, hepatitis B viruses and severe acute respiratory syndrome (SARS)-associated coronaviruses] can also survive on surfaces and medical equipment, although there is little evidence of possible survival.[2,32–34] Most of these pathogens can survive for months on surfaces.[32,35] Some examples of the most persistent hospital pathogens are summarized in Table 1 along with some of their characteristics. Some investigations have proposed that Gram-negative bacteria persist longer than Gram-positive bacteria and, although it has been suggested that the type of surface does not influence the period of persistence, it has also been shown that longer persistence may occur on plastic or even on steel.[32,36] In terms of environmental conditions, lower temperatures (4–6°C) and high humidity (>70%) improved the persistence of several bacteria, fungi and viruses.[32] Moreover, the frequency of contamination has been shown to vary depending on the body sites at which patients are colonized or infected. It was demonstrated that 36% of surfaces sampled in the rooms of patients with MRSA in a wound or urine were contaminated, compared with 6% of surfaces in the rooms of patients infected with MRSA at other body sites.[37]

Influence of clinical environment on HAI propagation

Pathogens can spread from patient to patient through contact with inanimate surfaces, including medical equipment and the immediate patient environment.[38] There is clinical evidence suggesting an association between poor environmental hygiene and the transmission of microorganisms causing HAIs.[39] Cheng *et al.*[40] found a strong correlation between environmental contamination by MRSA and hospital infection rates. Drees *et al.*[41] demonstrated an increase in VRE infection risk for an occupant of a room where a patient with this infection was previously treated. It was also demonstrated that nosocomial transmission of norovirus, *C. difficile* and *Acinetobacter* spp. was correlated with contaminated environmental surfaces.[15] In another study, a positive and measurable effect on the clinical environment was demonstrated with the introduction of one extra cleaner, which apparently protected the patients against MRSA infection.[42] The potential for contaminated environmental surfaces to contribute to pathogen transmission depends on two important factors: the pathogens must survive on dry surfaces and the contamination has to occur on surfaces commonly touched by patients and healthcare staff at a sufficiently high level to enable transmission to patients.[35] Moreover, pathogen transmission will also depend on the infectious dose and route of transmission, along with host susceptibility.

Shared clinical equipment that comes into contact with intact skin, despite being unlikely to introduce infection, can also promote the transfer of microorganisms between patients.[43] The most frequently contaminated surfaces are floors, doorknobs, television remote control devices, bed-frame lockers, mattresses, bedside tables and toilet seats in rooms previously occupied by an infected patient.[1,12,35,44] Wilcox *et al.*[45] found that ~50% of commodes, toilet floors and bed frames sampled at a hospital were contaminated with *C. difficile*. Medical devices, including stethoscopes and otoscopes, are highly prone to be contaminated with bacteria and have been implicated as potential vectors of cross-transmission.[46] Moreover, bacteria were found on various plastic items in the hospital, including pagers and cell phones.[47] Cotterill *et al.*[48] provided suggestive evidence that contaminated ventilation grills were sources of MRSA outbreaks in hospitals. Additionally, an estimated 20%–40% of HAIs have been attributed to cross-infection via the hands of healthcare personnel, who have become contaminated from direct contact with the patient or indirectly by touching contaminated environmental surfaces.[15,38] In fact, hand hygiene is a major contributing factor to the current infection threats to hospital inpatients.[49] Barker *et al.*[50] showed that norovirus is consistently transferred via the fingers to melamine surfaces and from there to other typical hand-contact surfaces, such as taps, door handles and telephone receivers. Pessoa-Silva *et al.*[51] demonstrated that hands become increasingly contaminated with commensal flora and potential pathogens during neonatal care and that gloves do not fully protect the workers' hands from contamination. Pittet *et al.*[52] concluded that bacterial contamination increased linearly with time on ungloved hands during patient care. This demonstrates the importance of decontaminating hands before every patient contact. Fendler *et al.*[53] concluded that the use of an alcohol gel hand sanitizer decreased infection rates during a 34 month period and can provide an additional tool for an effective infection control programme. The same conclusion was reached by Hilburn *et al.*[54] The gloves of medical staff are also easily infected from direct contact with an infected patient or, indirectly, by touching contaminated surfaces, which serve as a carrier for pathogenic microorganisms.[11] In a study focused on MRSA infection, 42% of personnel gloves that contacted the furniture/surfaces of a patient room but had no direct contact with infected patients were contaminated.[37,44] More significantly, it was found that 65% of the nursing staff that had directly treated an infected individual contaminated their gowns/uniforms with the organism.[55] The white coats, shirts and ties of doctors have also been found to contain potentially pathogenic flora.[56]

Disinfectant selection

Maintenance of a good hospital environment requires the implementation of adequate strategies. Such strategies are described in guidelines proposed by several committees, particularly the Healthcare Infection Control Practice Advisory Committee.[57] For instance, in the case of surfaces with blood contamination, a disinfectant with activity against tuberculosis and hepatitis B virus (HBV)/HIV or a 5.25% bleach solution, at a final dilution of 1:10, can be used.[11] These documents describe procedures to be implemented in healthcare facilities in order to achieve efficient cleaning and disinfection and also review the main uses of

Table 1. Examples of clinically relevant nosocomial pathogens

Microorganisms	Mode of transmission	Length of survival	Disease/symptoms
Bacteria			
Acinetobacter baumannii	extensive environmental contamination[33]	33 days on plastic laminate surface;[33] 3 days to 5 months on dry inanimate surfaces[32]	pneumonia and bloodstream infection[33]
Bordetella pertussis	airborne droplet infection (person-to-person transmission)[109]	3–5 days on dry inanimate surfaces[32]	mild whooping cough syndrome[110]
Clostridium difficile	extensive environmental contamination[33]	5 months on dry inanimate surfaces and hospital floors[32,33]	diarrhoea and colitis[111]
Chlamydia pneumoniae	transmission from asymptomatic carriers[112]	≤30 h on dry inanimate surfaces[32]	acute respiratory disease, bronchitis, sinusitis, pneumonia, otitis media and chronic obstructive pulmonary disease, asthma, reactive airway disease, Reiter's syndrome and sarcoidosis[113]
Corynebacterium diphtheriae	mainly by infected droplet spread through contact with an infected person[114]	7 days to 6 months on dry inanimate surfaces[32]	diphtheria[115]
Escherichia coli	ingestion of contaminated food, water or milk; person-to-person transmission[21]	1.5 h to 16 months on dry inanimate surfaces[32]	blood and urinary tract infection[30]
Enterococcus spp., including VRE	nosocomial and person-to-person transmission; also by transmission on food products[116]	5 days to 4 months on dry inanimate surfaces;[32] ≤58 days on counter tops[33]	blood, skin and respiratory tract infection[30]
Haemophilus influenzae	person-to-person transmission through contact with discharges or droplets from the nose or throat of an infected person[21]	12 days on dry inanimate surfaces[32]	acute and chronic respiratory tract infections, meningitis[117]
Klebsiella pneumoniae	contact with contaminated surfaces and objects, medical equipment and blood products[118]	2 h to >30 months on dry inanimate surfaces[32]	urinary tract infections, pneumonia, septicaemias and soft tissue infections[118]
Mycobacterium tuberculosis	sputum droplets (exhaled through a cough or sneeze) of a person with active disease[21]	1 day to 4 months on dry inanimate surfaces[32]	lung infection[30]
Pseudomonas aeruginosa	contamination from tap water and different medical devices[119]	6 h to 16 months on dry inanimate surface; 5 weeks on dry floor;[32] 7 h on glass slides[33]	lung and urinary tract infection[30]
Serratia marcescens	direct hand-to-hand transmission; with contaminated invasive medical devices, work surfaces, intravenous and topical solutions[120]	3 days—2 months on dry inanimate surfaces; 5 weeks on dry floor[32]	urinary tract infections and pneumonia[121]
Staphylococcus aureus, including MRSA	contact with the organism in a purulent lesion or on the hands; burn units extensively contaminated[21,33]	*S. aureus* can remain virulent for 10 days on dry surfaces;[122] MRSA can survive for 7 days to 9 weeks on dry inanimate surfaces and 2 days on plastic laminate surfaces[32,33]	blood, skin and respiratory tract infection, septicaemia and death[23]
Streptococcus pneumoniae	person to person through close contact via respiratory droplets; illness among casual contacts and attendants is infrequent[123]	1–20 days on dry inanimate surfaces[32]	blood, lung and ear infections[30]
Streptococcus pyogenes	respiratory droplets and skin contact with impetigo lesions[124]	3 days to 6.5 months on dry inanimate surfaces[32]	rheumatic fever, sepsis, severe soft-tissue invasion and toxic-shock-like syndrome (TSLS)[125]

Continued

Table 1. *Continued*

Microorganisms	Mode of transmission	Length of survival	Disease/symptoms
Fungi			
Candida spp.	via contaminated medical devices;[126] contact with secretions or excretions from infected persons[21]	1–120 days on dry inanimate surfaces[32]	infections of the gastrointestinal tract, vagina and oral cavity[21]
Viruses			
HBV	percutaneous or permucosal exposure to blood or secretions via abrasions, sharing needles/syringes, sexual contact[127]	> 1 week on dry inanimate surfaces[32]	nausea, vomiting, jaundice; chronic infection leads to hepatocellular carcinoma and cirrhosis[21]
influenza virus	respiratory droplet or direct contact;[127] aerosolization after sweeping; survival on fomites[33]	24–48 h on non-porous surfaces[33]	influenza[21]
SARS-associated coronavirus	spread person to person via infected droplets[21]	24–72 h on fomites and in stool samples;[33] 72–96 h on dry inanimate surfaces[32]	respiratory infection and pneumonia[21]
norovirus	faecal contaminated vehicle (food or water); person-to-person transmission[128]	8 h to 7 days on dry inanimate surfaces[32]	abdominal pain, nausea, vomiting, headache and chills[128]
rotavirus	primarily faecal–oral transmission; faecal–respiratory transmission can also occur[21]	6–60 weeks on dry inanimate surfaces[32]	enteritis: diarrhoea, vomiting, dehydration and low-grade fever[21]

Table 2. Characterization of disinfectants according to their class[11,59,65,68,83]

Disinfectant	Spectrum of action	Required for	Examples
Sterilants	all microorganisms, including bacterial spores[65]	critical instruments that penetrate tissue or present a high risk if non-sterile (e.g. implants, needles and other surgical instruments)	heat, steam, higher concentrations of hydrogen peroxide and peracetic acid, glutaraldehyde (in 6–10 h)
High-level disinfectants	almost all microorganisms, but not spores	semi-critical items that do not penetrate tissues or contact mucous membranes (except dental) (such as endoscopes, respiratory therapy equipment and diaphragms)	hydrogen peroxide, glutaraldehyde, formaldehyde, *ortho*-phthalaldehyde, peracetic acid
Intermediate-level disinfectants	almost all vegetative bacteria, fungi, tubercle bacilli and enveloped and lipid viruses	non-critical items that touch intact skin (e.g. thermometers and hydrotherapy tanks)	alcohols, hypochlorites, iodine and iodophor disinfectants
Low-level disinfectants	not efficient for most bacteria, tubercle bacilli, spores, fungi and viruses	non-critical items: items such as stethoscopes bedpans, blood pressure cuffs and bedside tables	phenolics, quaternary ammonium compounds

disinfectants as well as their mechanism of action and activity. Rutala and Weber[58] developed a set of guidelines for hospital environment cleaning.

Cleaning is related to the clearance of foreign material from a surface or equipment, allowing the removal of some organic material and microorganisms by detergents.[11,33] However, this process does not kill bacteria, which, under favourable conditions, can redeposit elsewhere and form biofilms.[31] Consequently, cleaning must always precede disinfection and sterilization in order to eliminate infectious microorganisms.[59] A significant amount of microorganisms is destroyed by the disinfection process, which involves the use of chemical agents such as quaternary ammonium compounds, aldehydes, alcohols and halogens, or radiation and heat.[11,31,33,60] The control of hospital infection must involve both disinfection and sterilization processes and sometimes the use of aerosols to clean the air.[11,33]

A biocide can target different locations on a cell as it may interact with the surface, the bacterial cell wall and the outer membrane, or it may penetrate the cell, where it can cause reversible or irreversible changes by interacting with nucleic acids, inhibiting enzymes and cell growth.[24,60] When choosing a disinfectant, several factors must be taken into account, such as its efficiency, compliance with regulations, user acceptability, instrument compatibility, the types of surfaces and medical equipment, and the pathogenicity, infection rates and persistence of the microorganisms.[61] A disinfectant must be safe, easy to use and effective against a wide range of pathogenic microorganisms and should not leave toxic residues.[31,61] The efficiency of the disinfectant depends on several factors, mainly surface characteristics (hydrophobicity, charge and roughness), the amount of organic and inorganic matter, temperature, pH, the chemical structure of the biocidal agent and the type of infection and pathogen.[11,24,31] The mode of action of the disinfectant and the route of entry into the cell (porin channels in the case of hydrophilic disinfectants and the hydrophobic path for hydrophobic disinfectants) also play significant roles.[24] The risk of infection of the room/surface/equipment must also be considered in the choice of the disinfectant, as well as its concentration and exposure time.[24,62] Hospital areas should be defined according to the risk of infection in order to establish and promote proper cleaning/disinfection. Areas where contamination is expected, e.g. laboratories, operating theatres, ambulatory surgical units, labour and delivery rooms, areas with blood or body fluid spills, and neonatal and burn units, must be cleaned and disinfected frequently (often several times per day).[1] Areas of low risk, such as administration and waiting rooms, only require a daily cleaning.

According to its efficiency and ability to kill bacterial spores, an antimicrobial product can belong to one of four distinct groups: sterilants or high-, intermediate- and low-level disinfectants (Table 2). Given the increased resistance to antimicrobial agents displayed by bacteria upon biofilm formation, this hierarchy is only a rough guide.[60,63,64] A disinfectant is almost never 100% effective due to the resistance of some bacteria to specific compounds and due to inefficient cleaning protocols.[1] Once a disinfectant is removed, the surviving bacterial population can potentially regrow. Moreover, viable spores still attached to various materials can remain undetected by current sporicidal tests, resulting in overestimation of the sporicidal activity of sterilizing agents.[65]

The efficacy of diverse chemical disinfectants in inhibiting and killing some of the most clinically relevant bacteria, pathogenic fungi and yeasts has been evaluated by several authors. The activity of a disinfectant is generally analysed in terms of its MIC and MBC. However, the most suitable measure is the $\log_{10}$ reduction of the number of cfu. The time taken to obtain a 5 $\log_{10}$ reduction is also a reference to assess disinfection efficacy.[61]

Traditional disinfection strategies

The use of biocides has evolved over time. Alcohols such as ethanol have a long history of antiseptic use; around the 19th and 20th centuries phenolics and hypochlorites started to be employed and, later, quaternary ammonium compounds.[66] More recently, the most common products have been chlorhexidine and silver salts, peroxygens, glutaraldehyde and *ortho*-phthalaldehyde.[66,67]

Alcohol disinfectants cause protein denaturation and are effective against vegetative bacteria, fungi and viruses, but have no effect on spores.[61,68] Chlorine-releasing agents can oxidize membrane proteins and are very effective in removing biofilms from surfaces, requiring short exposure times for growth inhibition.[57,61,68] However, these chemical agents are corrosive to metals and can be inactivated by the presence of organic matter.[57,61,69] Moreover, in the last few years the use of chlorine has been associated with the formation of carcinogenic compounds and some pathogens have been shown to be resistant to chlorine.[70] The aldehyde-based disinfectants disrupt proteins and nucleic acids by alkylation and have antimicrobial activity against spores, bacteria, viruses and fungi.[61,64] Quaternary ammonium compounds and phenols solubilize the membrane and the cell wall.[68] Hydrogen peroxide and peracetic acid promote protein denaturation, and are active against several groups of microorganisms and pathogens implicated in nosocomial infections.[38,57,61,64] The mechanism of action of different disinfectant categories has been presented elsewhere in greater detail.[64,71,72]

Countless studies have been performed regarding the antimicrobial action and efficacy of different disinfectants. Rutala and Weber[69] reviewed the use of inorganic hypochlorite (bleach) in healthcare facilities for disinfection of medical devices and environmental surfaces, and concluded that the many advantages of chlorine (e.g. fast microbiocidal activity, cost-effectiveness and good track record) are likely to support its continued use in healthcare settings. Griffiths *et al.*[73] evaluated the efficacy of several disinfectants (sodium dichloroisocyanurate, chlorine dioxide, 70% industrial methylated spirits, 2% alkaline glutaraldehyde, 10% succinedialdehyde and formaldehyde mixture, 0.35% peracetic acid and a peroxygen compound at 1% and 3%) against different strains of mycobacteria and showed that disinfectants based on sodium dichloroisocyanurate were more effective. Moreover, they concluded that clinical strains were more resistant to biocides than laboratory type strains.[73] Other studies have shown that chlorhexidine at 0.5% concentration is the best choice, among several antiseptics and surface disinfectants (including betadine, hydrogen peroxide, sodium hypochlorite, alcohol and ultraviolet radiation), to kill clinical yeast isolates, either in planktonic cultures or in biofilm.[74] Oie *et al.*[75] analysed the effects of four different chemical treatments (0.2% alkyldiaminoethyl glycine, 0.01% or 0.1% sodium hypochlorite and 80% ethyl alcohol) on the disinfection of porous and smooth surfaces contaminated by *S. aureus* in a university hospital. The results demonstrated that the disinfection of porous surfaces was more difficult and none of the disinfectants was effective, highlighting the need for more frequent disinfection and the use of high-level disinfectants on these surfaces.[75] More recently, Speight *et al.*[76] evaluated the effect of 32 disinfectants on spores of *C. difficile* by a suspension test and only eight products gave >3 $\log_{10}$ reduction in viability within 1 min (to have a more realistic simulation of probable real-life exposures) under dirty conditions (3% BSA). These results underscore the importance of carefully selecting the disinfectant to eliminate spores of this particular microorganism.[76] Kim *et al.*[77] analysed the effectiveness of 13 disinfectants used in hospitals, day-care centres and food service kitchens (ZEP FS Amine Z, ZEP DZ-7, Lemonex, ZEP Micronex, T.B.Q., ZEP FS Formula 386 L, Perosan Liquid Sanitizer, LpH se, Vesphene IIse, Coverage Spray HB Plus, Coverage Spray TB, ZEP Kitchen Surface Sanitizer and ZEP FS RTU-D2) against *Enterobacter sakazakii* in suspension, dried on stainless steel and in biofilm, and

concluded that not all biocides used in hospitals can kill this microorganism. Also, the efficacy of disinfectants was higher for planktonic cells (reduction to undetectable levels).[77] Bridier *et al.*[78] studied the effects of three common disinfectants (peracetic acid, benzalkonium chloride and *ortho*-phthalaldehyde) on 77 bacterial strains and found that mycobacteria demonstrated a marked resistance to all the biocides. Benzalkonium chloride was inefficient even at very high concentrations. Also, resistance was dependent on the strain within the same species.[78] Gutiérrez-Martín *et al.*[79] analysed the activity of 16 active compounds and 11 commercial disinfectants against *Campylobacter jejuni* by performing a suspension test in the presence and absence of serum. High levels of reduction (>6 $\log_{10}$) for some disinfectants [chloramine-T, povidone iodine (1% available iodine), cetylpiridinium chloride, ethanol, isopropanol, chlorhexidine digluconate, formaldehyde, phenol and 10 of the 11 commercial formulations, especially those based on quaternary ammonium compounds] were obtained, regardless of the presence or absence of organic material.[79] Table 3 compiles some of the available information regarding hospital disinfectants.

Disinfection methods employed in many intensive therapy units and other healthcare facilities include the use of antimicrobial wipes. Such products might be efficient in removing a microbial bioburden from a surface.[80] The use of alcohol wipes was also demonstrated to generally decrease the mean daily bacterial load on toilets where wipes were made available.[81] However, in most cases, antibacterial wipes used in hospitals were found to spread germs rather than eradicate them. Wipes can act as sources of cross-contamination when they are used on surfaces next to patients or on those commonly touched by staff and patients (e.g. tables, keypads).[82] Moreover, many hospital personnel use a single wipe several times to clean and disinfect multiple surfaces before discarding it. Instead, they should use a wipe on a single discrete surface that requires only low-level disinfection.

A description of methods for hospital equipment disinfection with an analysis of the exposure time and the type of disinfectant and a summary of advantages and disadvantages of some chemical sterilants can be found elsewhere.[11,57] Nevertheless, it has to be taken into account that some of these studies were performed with culture collection strains, whose responses to the presence of these disinfectants may differ from those of clinical isolates.[60] Furthermore, some studies evaluated only a single strain of the species. Therefore, the results obtained may not always be representative of what occurs in clinical practice. Most of the presented investigations were performed on a laboratory scale, which may not truly reflect the complexity of a hospital scenario.

Alternatives to traditional disinfection

The need for appropriate disinfection procedures is enhanced by the multitude of outbreaks that have resulted from improperly decontaminated patient-care items.[83] The disinfection processes previously described are executed by the application of chemical agents in solution. However, this kind of disinfection has some disadvantages: the application of disinfectants requires an exposure time of at least 5–10 min; the chemicals might react with acids; they might lose their activity in contact with organic substances; and some of them can cause skin, eye and respiratory tract irritation.[23]

In this context, new disinfection strategies must be developed and their efficiencies must be evaluated in terms of their potential applications in hospital settings. This need for novel control methods has been emphasized by the increased resistance of bacterial species to some disinfectants, mainly as a consequence of biofilm formation.[31]

One of these alternative strategies is steam vapour disinfection, which has been evaluated by different groups. Tanner[84] demonstrated a reduction of 7 $\log_{10}$ in MRSA, VRE and *P. aeruginosa* (to undetectable values) within 5 s of application of a steam vapour system. Sexton *et al.*[23] applied a steam vapour system to combat MRSA, total coliform bacteria and *C. difficile* cells, attaining a 90% reduction in bacterial levels. Hydrogen peroxide vapour (HPV) is also used for decontamination of clinical surfaces and equipment. Otter and French[85] found that vegetative bacteria and spores (6–7 $\log_{10}$ cfu) survived on surfaces for >5 weeks, but were inactivated within 90 min of exposure to HPV in a 100 m^3 test room. Initial inocula of *M. tuberculosis* (~3 $\log_{10}$) and *Geobacillus stearothermophilus* (6 $\log_{10}$) were exposed to HPV at 10 locations during room experiments and both microorganisms were inactivated in all locations within 90 min of HPV exposure.[86] Falagas *et al.*[38] reviewed other studies of disinfection with HPV against MRSA, *C. difficile* and other pathogens in several sampled hospital locations (including surgical wards, ward side rooms, single isolation rooms, multiple-bed ward bays and bathrooms); complete or almost complete disinfection of the sampled hospital sites was achieved with airborne hydrogen peroxide. HPV appears to have low toxicity and has good compatibility with most inanimate materials.[87]

UV light exposure has also been applied for room decontamination. It has been used in air-handling systems and upper-room air-purifying systems to destroy microorganisms and can also inactivate microorganisms on surfaces.[88] UV-C was demonstrated to be effective in eliminating vegetative bacteria on contaminated surfaces (both in the line of sight and behind objects) within 15 min and in eliminating *C. difficile* spores within 50 min.[89] In other study, a mobile UV-C light unit significantly reduced aerobic colony counts and spores of *C. difficile* on contaminated surfaces in patient rooms.[88] It was also demonstrated that ceiling-mounted UV germicidal irradiation lamps were effective in reducing the viability of both *Bacillus cereus* and *Bacillus anthracis* vegetative cells and spores after a minimum exposure time of 1 h at an intensity as low as 8 $\mu W/cm^2$.[90]

Both the HPV and UV light methods have demonstrated good results. However, they require the removal of patients and healthcare personnel from the room, have a high acquisition cost and increase room turnover time.[91] Moreover, they do not replace standard cleaning and disinfection.[92]

Bacterial adhesion to stainless steel surfaces (the most commonly used material in industry and hospitals) is one of the major reasons for cross-contamination in many scenarios.[93] Thus, more recently, different strategies for the production of antimicrobial surfaces with the purpose of reducing HAI have been extensively investigated and developed. Researchers have focused on the development of surfaces with antimicrobial coatings in order to inhibit biofilm formation by either killing the bacteria or preventing their adhesion. Bacterial growth control can then occur by three different modes of action: biocide leaching, which involves the release of a cytotoxic compound to kill attached microorganisms; adhesion prevention, which uses a super-hydrophobic

Table 3. Efficacy of several chemical agents in hospital disinfection

Disinfectant	Microorganism	Method/test	Efficiency
Nu-Cidex® (0.35% peracetic acid)	*Mycobacterium* (5 strains)	suspension and surface test	complete inactivation after 5 min of exposure[129]
Nu-Cidex® (0.35% peracetic acid)	*Bacillus subtilis* spores	suspension test	>5 $\log_{10}$ reduction in 5 min with 10% serum[130]
Cidex Long-Life® (2% glutaraldehyde)	*B. subtilis* spores	suspension test	>5 $\log_{10}$ reduction in 2 h with 4% blood[130]
Titan Sanitizer® (sodium dichloroisocyanurate with Cl content of 2.2%)	*B. subtilis* spores	suspension test	>5 $\log_{10}$ reduction (disinfectant at 5% in 3 h); no reduction in the presence of 2% blood[130]
Presept® disinfectant granules (sodium dichloroisocyanurate with Cl content of around 30%)	*B. subtilis* spores	suspension test	>5 $\log_{10}$ reduction (disinfectant at 1% in 1 h in the absence of blood and in 2 h in the presence of 2% blood)[130]
Haz-Tab® disinfectant granules (sodium dichloroisocyanurate with Cl content of around 60%)	*B. subtilis* spores	suspension test	>5 $\log_{10}$ reduction (disinfectant at 1% in 5 and 30 min in the presence of 2% blood)[130]
Virkon® (peroxygen)	*B. subtilis* spores	suspension test	5 $\log_{10}$ reduction (disinfectant at 1% in 2–3 h in the absence of blood, but little kill in 3 h in the presence of 2% blood)[130]
Sporicidin® (2% glutaraldehyde, 7.05% phenol, 1.2% sodium phenate)	*B. subtilis* spores	suspension test	4 $\log_{10}$ reduction in 10 h and 2 $\log_{10}$ reduction in 10 h in the presence of 2% blood[130]
Sterilox® (9:1 v/v) (hypochlorous acid at a concentration of 144 mg/L and free chlorine radicals)	*C. difficile* spores, *Helicobacter pylori*, VRE, *C. albicans* and 4 *Mycobacterium* species	suspension test	>5 $\log_{10}$ reduction in 2 min with 5% horse serum (except for *C. difficile* spores since the disinfectant activity diminished in the presence of organic load)[131]
10% Povidone iodine	10 MRSA, 10 methicillin-susceptible *S. aureus* (MSSA), 9 VRE and 10 vancomycin-susceptible *Enterococcus faecalis*	European surface test method[132]	3.14, 3.49, 3.47 and 3.78 $\log_{10}$ reduction, after 1.5 min for VRE, VSE, MRSA and MSSA, respectively[133]
Perasafe® (peroxygen system equivalent to peracetic acid at 0.26%)	*C. difficile* and *Bacillus atrophaeus* spores	surface test on stainless steel and polyvinyl chloride floor covering	5.5–6 $\log_{10}$ reduction in 10 min[134]
Perasafe®	*S. aureus* ATCC 25923, MRSA, MSSA, *E. faecalis*, *Enterobacter cloacae*, *K. pneumoniae*, *P. aeruginosa*, *Acinetobacter anitratus*, *C. albicans*, *Mycobacterium fortuitum* ATCC 609 and *B. subtilis* (spore strips).	suspension, surface, sporicidal, endoscope model test, capacity and corrosion tests	complete inactivation except for *Mycobacterium* and spores; resistance to inactivation after repeated inoculation; did not corrode clean instruments; when organic matter was added, it cleaned without corrosion[135]
2% Glutaraldehyde	*S. aureus* ATCC 25923, MRSA, MSSA, *E. faecalis*, *E. cloacae*, *K. pneumoniae*, *P. aeruginosa*, *A. anitratus*, *C. albicans*, *M. fortuitum* ATCC 609 and *B. subtilis* (spore strips)	suspension, surface, sporicidal, endoscope model test, capacity and corrosion tests	complete inactivation except for *Mycobacterium* and spores; resistance to inactivation after repeated inoculation; did not corrode clean instruments; when organic matter was added it fixed the matter to the scalpel, causing corrosion within 2 h[135]

Continued

Table 3. *Continued*

Disinfectant	Microorganism	Method/test	Efficiency
Sodium dichloroisocyanurate	*C. difficile* and *B. atrophaeus* spores	surface test on stainless steel and polyvinyl chloride floor covering	0.7–1.5 $\log_{10}$ reduction in 10 min[134]
Monopercitric acid (peroxy-acid-based disinfectant)	*Clostridium* spores	suspension test	0.5% disinfectant is sporicidal within 5 min[136]
0.2% Alkyl-diaminoethylglycine and 80% (v/v) ethyl alcohol	*S. aureus*, MRSA and MSSA	wiping and membrane filtration technique	reduction of bacteria to an undetectable level[75]
0.01% Sodium hypochlorite and 0.1% sodium hypochlorite	*S. aureus*, MRSA and MSSA	wiping and membrane filtration technique	reduction of bacteria to a minimal detectable level[75]
Ortho-phthalaldehyde	*Pseudomonas fluorescens* (planktonic)	respirometry; adenosine triphosphate release; outer membrane protein expression and bacterial colour changes	complete inactivation (MBC 0.5 mM)[137]
Ortho-phthalaldehyde	*P. fluorescens* (planktonic)	respiratory activity, membrane permeabilization and integrity, and physico-chemical characterization	MIC 1500 mg/L[24]
Ortho-phthalaldehyde	*S. aureus*, *E. coli*, *P. aeruginosa*	suspension and carrier tests	≥5 log reduction in viability within 1 min of exposure[138]
Ortho-phthalaldehyde	bacteria found in 100 endoscopes	surface test	5 $\log_{10}$ reduction of bacteria with an exposure time of 5 min[139]
Glutaraldehyde	*P. fluorescens* (planktonic)	respirometry; adenosine triphosphate release; outer membrane protein expression and bacterial colour changes	no bacterial inactivation was detected[137]
Cetyltrimethyl ammonium bromide	*P. fluorescens* (planktonic)	respirometry; adenosine triphosphate release; outer membrane protein expression and colony colour changes	complete inactivation (MBC 5 mM)[137]
Polyhexamethylene guanidine hydrochloride	*S. aureus*, *P. aeruginosa*, *Salmonella choleraesuis*, MRSA and *E. coli*	phenol coefficient (PC)[a] value (for *S. aureus*, *P. aeruginosa* and *S. choleraesuis*); MIC and MBC (for MRSA and *E. coli*)	PC values for *S. aureus*, *S. choleraesuis* and *P. aeruginosa* were 7.5, 6.1 and 5, respectively; the MIC value for MRSA and *E. coli* was 0.04% and 0.005% (w/v), respectively, in 1.5 min[140]
Allrent® (2-propanol: 1%–5% weight; tensides 1%–5% weight; 60%–100% weight water)	*B. subtilis*, *S. aureus*, *C. albicans*	colony counting in agar plates and bioluminescence detection of adenosine triphosphate	final residual cfu percentage of 35.7%[141]
Appeartex® (active polymer A-200, polyhexamethylene biguanide and a surfactant solution)	*S. aureus*, *Enterococcus hirae*	contact agar plates; direct agar inoculation using swabs; swab rinse technique (on a laboratory scale and in a hospital ward)	reduction in magnitude of $10–10^3$,[142]

Continued

Table 3. *Continued*

Disinfectant	Microorganism	Method/test	Efficiency
Aqueous chlorine dioxide solution	*B. anthracis* spores	quantitative bacteriological culture methods	8 $\log_{10}$ reduction in 3 min in sealed microfuge tubes and 1 $\log_{10}$ reduction for spraying or spreading the disinfectant onto surfaces (when using the solution in 5% bleach—0.3% sodium hypochlorite—its full activity is restored)[143]
Dismozon® pur; Kohrsolin® extra; Kohrsolin® FF	*C. difficile* ribotype 027	suspension test in different concentrations at various exposure times	≥4 $\log_{10}$ (Dismozon pur at 1.5% and 2 h exposure time; Kohrsolin extra at 2% and 4 h exposure time; and Kohrsolin FF at 2% and 6 h exposure time)[144]

[a]A measure of the bactericidal activity of a chemical compound in relation to phenol.

covering in order to prevent microbial adhesion; and contact killing, which consists of disruption of cell membranes in contact with the surface.[13] Many of these techniques consist of surface modification by introduction of antimicrobial substances such as antibiotics, metals (such as copper and silver) and antiseptics.[93–98] These surfaces can be obtained by different methods, including adsorption, ligand–receptor pairing and covalent binding.[94] Surfaces that release antimicrobial products can work quite efficiently, although they eventually become exhausted and the diffusible antimicrobials pose the potential problem of inducing microbial resistance, since the surfaces are continually releasing active compounds to the environment for a long period of time.[55,99] Alternatively, the design of surfaces that kill microbes on contact and do not release biocides may solve this problem. The covering of surfaces with transient metals, such as copper and silver as mentioned above, is a well-established strategy. Moreover, surfaces that catalytically produce biocides using externally applied chemical, electrical or optical energy are an interesting alternative.[99]

An example of biocide leaching is the use of Surfacine, which incorporates an antimicrobial compound (silver iodide) in a surface-immobilized coating (a modified polyhexamethylenebiguanide).[83] This compound interacts with the microorganism by electrostatic attraction, penetrates the cell and finally kills it.[83] Surfaces treated with silver iodide resulted in excellent elimination of VRE at challenge levels of 100 cfu/in^2 for at least 13 days.[11] Furthermore, these surfaces retained the antimicrobial effect even after cleaning.[11] Photocatalytic oxidation on surfaces coated with titanium dioxide (TiO_2) is also a possible alternative. In the presence of water and oxygen, highly reactive OH^- radicals generated by TiO_2 and mild UV-A are able to destroy bacteria, thus reducing bacterial contamination.[100] Another example of a product that releases an organic antimicrobial is Microban®, which contains triclosan [5-chloro-2-(2,4-dichlorophenoxy)-phenol] as the antimicrobial agent, making the surface resistant to the growth of microorganisms.[55] This antimicrobial technology can be found in hundreds of consumer, industrial and medical products around the world.

Covalent immobilization of bioactive compounds onto functionalized polymer surfaces has also seen rapid growth in the past decade in such industries as biomedical, textiles, microelectronics, bioprocessing and food packaging.[101] Table 4 presents some examples of the application of these surfaces.

Furthermore, other kinds of surface are stimulating intensive research and some of them are already used, while others are promising candidates for practical application.[102–104] Examples include materials for medical implants (such as catheters), devices and instruments that are in contact with patients, surgical gowns and other protective clothing (such as surgical masks, caps) and polymeric coatings on surfaces such as shower walls.[102,103] Antimicrobial polymers provide a very suitable strategy for achieving this objective since they can be applied to diverse objects. Polyelectrolyte multilayers (PEMs) have also been investigated extensively as biomaterials and biomaterial interfaces and also for bacterial contamination prevention.[104]

Gas plasma is another promising alternative to sterilization that can be applied in healthcare services, although it is mainly targeted to equipment rather than to surfaces. Plasma consists of a mixture of photons, electrons, ions, atoms and radicals (such as atomic oxygen, ozone, nitrogen oxides, hydroxyl and superoxide). As a result of air plasma discharges, the gas enters an ionized state (by energetic transfer) and exhibits antimicrobial properties.[9,20,105,106] Two types of plasma can be defined according to the conditions under which the plasma is formed: thermal and non-thermal plasmas. Compared with non-thermal plasmas, thermal plasmas require higher pressure and are characterized by higher temperatures and a local thermodynamic equilibrium.[105,106] These systems have many advantages over more conventional disinfection techniques as they enable the disinfection of the interior of some types of equipment and materials, such as needles, at low cost and with easy handling.[107,108] Furthermore, gas plasma does not require chemical products and it is not toxic to the skin.[20] Shimizu *et al.*[108] performed treatments with plasma using a surface micro-discharge device, under different temperature and humidity conditions. The antimicrobial effect

Table 4. Examples of several coatings for the development of antimicrobial surfaces

Surface coating	Method	Bacteria tested	Results
Nanoparticulate silver-coated titania thin films	sol-gel preparation	MRSA and *E. coli*	99.9% reduction due to the presence of the silver ion for *E. coli* and due to enhanced photocatalysis for MRSA[97]
Copolymer poly(butylmethacrylate)-co-poly(Boc-aminoethyl methacrylate) on silicon wafers and glass surfaces	atom transfer radical polymerization	*E. coli* and *S. aureus*	100% reduction in <5 min[22]
TiO_2 film on medical grade AISI 304 stainless steel	arc ion plating	*E. coli* and *S. aureus*	$\log_{10}$ reductions of 3.0 and 2.5 for *S. aureus* and *E. coli*, respectively, due to photocatalysis action[145]
Perfluorooctylated quaternary ammonium silane coupling agent in cotton fabrics	pad-dry-cure	*S. aureus*	97.3% reduction and 95.6% reduction after 10 laundering cycles[146]
Ag and CuO layers on glass	flame-assisted chemical vapour deposition (FACVD) and overlaid with TiO_2 using thermal CVD	*E. coli*, *S. aureus* and *P. aeruginosa*	95%–99.9% reduction for hospital-related pathogens[147]
Magainin I and nisin peptides on stainless steel	covalent binding via an intermediate chitosan layer	*Listeria ivanovii*	reduction of bacteria adhesion by a factor of 2–3[94]
Pseudo-polyelectrolytes (pPE) and poly(4-vinylphenol) (PVPh) into multilayer systems with poly(allylamine hydrochloride) (PAH) and poly(diallyldimethylammonium chloride) (PDADMAC)	layer by layer	*S. epidermidis*	60% and 70% growth inhibition for PAH/PVPh and PDADMAC/PVPh, respectively[13]
Molybdic acid (H_2MoO_4) and molybdenum trioxide (MoO_3)	sol-gel	*S. aureus* and *P. aeruginosa*	surfaces almost without microorganisms after 6 h[12]
Stainless steel surfaces with different copper content (with a maximum of 7.1 wt % for a gas pressure of 60 Pa)	plasma surface alloying technique at various gas pressures	*E. coli*	reduction of 98% of cells within 1 h[93]
Copper-containing titanium nitride films on commercial stainless steel	hybrid processes combining dual magnetron sputtering	*E. coli*	very effective in killing the bacteria; longer TiN deposition time may lead to superior antibacterial capability, corrosion and wear resistance[96]
Duplex-treated plasma alloyed AISI 304 stainless steel with Ni with plasma alloying with Cu	double-glow plasma surface alloying technique	*E. coli* and *S. aureus*	reduction of 99.9% and 100% for *E. coli* and *S. aureus*, respectively[148]
Surfaces of titanium, Ti6Al4 V alloy or TiN, modified with SiO_2–TiO_2 layer	glow-discharge nitriding, sol-gel and electrophoresis	*S. epidermidis*	formation of biofilms on polished and ground titanium and titanium alloy surfaces covered with TiN, but not on those modified with SiO_2–TiO_2 nanofilm[149]
Medical grade poly(vinyl chloride) (PVC) chemically modified with the incorporation of monovalent silver	radio frequency oxygen (RF-O_2) glow discharge pre-functionalization and two-step wet treatment in sodium hydroxide and silver nitrate solutions	*P. aeruginosa*	100% reduction in initial bacterial adhesion[98]
Copolymer soft block containing trifluorethoxy (89 mol %) and C-12 alkylammonium (11 mol %) side chains	cationic ring opening polymerization; nucleophilic substitution	*P. aeruginosa*, *E. coli* and *S. aureus*	100% kill and 3.6–4.4 log reduction in 30 min[150]
Silicon wafers and glass surfaces functionalized with poly(butylmethacrylate)-*co*-poly(Boc-aminoethyl methacrylate)	surface-initiated atom transfer radical polymerization	*S. aureus* and *E. coli*	100% kill in <5 min[22]
Polyelectrolyte multilayers of poly(allylamine hydrochloride) (PAH) and poly(sodium 4-styrene sulfonate) (SPS)	SPS/PAH PEMs assembled on plain glass slides with poly(sodium 4-styrene sulfonate)	*S. epidermidis*, *E. coli*	viability of bacteria was effectively reduced on SPS/PAH multilayers displaying accessible cationic charge[104]

was tested on *Escherichia coli* and *Enterococcus mundtii* with a reduction of 5 $\log_{10}$ after 15 and 30 s of plasma treatment for *E. mundtii* and *E. coli*, respectively.[108] Other researchers have developed a large-scale plasma dispenser and evaluated its effect on *E. coli* and *Candida albicans* in agar plates in the presence and absence of textiles.[107] Their results demonstrated that the system was not affected by the presence of the textile, and in both cases a 15 s treatment caused a 5 $\log_{10}$ reduction and, after treatment for 5 s, the fungi were reduced by 4 $\log_{10}$. Joshi *et al.*[10] studied the biocidal efficacy of non-thermal dielectric-barrier discharge plasma against *E. coli*, *S. aureus* and MRSA in biofilms and planktonic cells. The planktonic cells were completely eliminated after 120 s of treatment, whereas the MRSA growing in biofilms were killed by >60% within 15 s, suggesting that the effectiveness of a plasma system is highly dependent on exposure time and cell density.[10] Recent investigations evaluated the effect of non-thermal gas plasma on biofilms of *Staphylococcus epidermidis* and MRSA on glass surfaces; a $\log_{10}$ reduction of 4 and 4.5 was observed after 1 h of exposure, respectively, and greater reductions could be attained with more prolonged exposure times.[9] Burts *et al.*[20] tested an atmospheric non-thermal plasma as a disinfectant for hospital pagers by analysis of MRSA reduction, and found complete disinfection within 30 s. Different cell densities and exposure times were also evaluated and a 4–5 $\log_{10}$ reduction was obtained within 10 min. More information regarding this disinfection strategy has been reviewed by Moisan *et al.*[105,106] These novel disinfection techniques are important means of reducing the high numbers of nosocomial infections and are more efficient than conventional disinfection methods.

Conclusions

There is great concern about the growth and prevalence of HAI due to the increased incidence of resistant bacteria. Furthermore, the development of new antibiotics is a difficult task because of high research costs and regulatory issues. Conventional cleaning methods for the eradication of hospital environmental contamination seem to be inefficient. This manuscript reviews several new disinfection alternatives as attempts to overcome these problems. Most of the data currently available have been generated by the manufacturers and need to be validated by independent investigations. Moreover, studies concerning bacterial biology and physiology allied to genomics and computer analysis should be applied to identify and understand the pathogenesis associated with resistant bacteria and crucial targets for novel biocides. Thus, further evaluation and implementation of new measures and new disinfection methods are necessary, not forgetting their validation in terms of effectiveness, safety and disposal. Additionally, it is important always to evaluate the risk of emerging phenotypic resistance when developing new disinfection strategies.

Funding

This work was supported by Operational Programme for Competitiveness Factors—COMPETE, FCT/MEC (PIDDAC) and FEDER through Projects Bioresist—PTDC/EBB-EBI/105085/2008 and Phytodisinfectants—PTDC/DTP-SAP/1078/2012 (COMPETE: FCOMP-01–0124-FEDER-028765) and the PhD grants awarded to A. C. A. (SFRH/BD/84393/2012) and A. B. (SFRH/BD/63398/2009).

Transparency declarations

None to declare.

References

1 Talon D. The role of the hospital environment in the epidemiology of multi-resistant bacteria. *J Hosp Infect* 1999; **43**: 13–7.

2 Schelz Z, Hohmann J, Molnar J. Recent advances in research of antimicrobial effects of essential oils and plant derived compounds on bacteria. In: Chattopadhyay D, ed. *Ethnomedicine: A Source of Complementary Therapeutics*. Kerala: Research Signpost, 2010; 179–201.

3 Dötsch A, Becker T, Pommerenke C *et al*. Genomewide identification of genetic determinants of antimicrobial drug resistance in *Pseudomonas aeruginosa*. *Antimicrob Agents Chemother* 2009; **56**: 2522–31.

4 Guz NR, Stermitz FR, Johnson JB *et al*. Flavonolignan and flavone inhibitors of a *Staphylococcus aureus* multidrug resistance pump: structure-activity relationships. *J Med Chem* 2000; **44**: 261–8.

5 Andersson DI, Levin BR. The biological cost of antibiotic resistance. *Curr Opin Microbiol* 1999; **2**: 489–93.

6 Andersson DI. Persistence of antibiotic resistant bacteria. *Curr Opin Microbiol* 2003; **6**: 452–6.

7 Guillemot D. Antibiotic use in humans and bacterial resistance. *Curr Opin Microbiol* 1999; **2**: 494–8.

8 Monroe S, Polk R. Antimicrobial use and bacterial resistance. *Curr Opin Microbiol* 2000; **3**: 496–501.

9 Cotter JJ, Maguire P, Soberon F *et al*. Disinfection of meticillin-resistant *Staphylococcus aureus* and *Staphylococcus epidermidis* biofilms using a remote non-thermal gas plasma. *J Hosp Infect* 2011; **78**: 204–7.

10 Joshi SG, Paff M, Friedman G *et al*. Control of methicillin-resistant *Staphylococcus aureus* in planktonic form and biofilms: a biocidal efficacy study of nonthermal dielectric-barrier discharge plasma. *Am J Infect Control* 2010; **38**: 293–301.

11 Rutala WA, Weber DJ. Surface disinfection: should we do it? *J Hosp Infect* 2001; **48**: S64–8.

12 Zollfrank C, Gutbrod K, Wechsler P *et al*. Antimicrobial activity of transition metal acid MoO_3 prevents microbial growth on material surfaces. *Mater Sci Eng C Mater Biol Appl* 2012; **32**: 47–54.

13 Pinto MS, McGahan ME, Steiner WW *et al*. The use of the pseudo-polyelectrolyte, poly(4-vinylphenol), in multilayered films as an antimicrobial surface coating. *Colloids Surf A Physicochem Eng Asp* 2011; **377**: 182–6.

14 Griffith CJ, Cooper RA, Gilmore J *et al*. An evaluation of hospital cleaning regimes and standards. *J Hosp Infect* 2000; **45**: 19–28.

15 Weber DJ, Rutala WA, Miller MB *et al*. Role of hospital surfaces in the transmission of emerging health care-associated pathogens: norovirus, *Clostridium difficile*, and *Acinetobacter* species. *Am J Infect Control* 2010; **38** Suppl 1: S25–33.

16 Cozad A, Jones RD. Disinfection and the prevention of infectious disease. *Am J Infect Control* 2003; **31**: 243–54.

17 Otter JA, Yezli S, French GL. The role played by contaminated surfaces in the transmission of nosocomial pathogens. *Infect Control Hosp Epidemiol* 2011; **32**: 687–99.

18 Costerton JW, Montanaro L, Arciola CR. Biofilm in implant infections: its production and regulation. *Int J Artif Organs* 2005; **28**: 1062–8.

19 Wach J-Y, Bonazzi S, Gademann K. Antimicrobial surfaces through natural product hybrids. *Angew Chem Int Ed* 2008; **47**: 7123–6.

20 Burts ML, Alexeff I, Meek ET *et al*. Use of atmospheric non-thermal plasma as a disinfectant for objects contaminated with

methicillin-resistant *Staphylococcus aureus*. *Am J Infect Control* 2009; **37**: 729–33.

21 Madigan M, Martinko J, Parker J. *Brock Biology of Microorganisms*. São Paulo: Prentice Hall, 2004.

22 Madkour AE, Dabkowski JM, Nüsslein K *et al*. Fast disinfecting antimicrobial surfaces. *Langmuir* 2009; **25**: 1060–7.

23 Sexton JD, Tanner BD, Maxwell SL *et al*. Reduction in the microbial load on high-touch surfaces in hospital rooms by treatment with a portable saturated steam vapor disinfection system. *Am J Infect Control* 2011; **39**: 655–62.

24 Simões M, Simões LC, Cleto S *et al*. Antimicrobial mechanisms of *ortho*-phthalaldehyde action. *J Basic Microbiol* 2007; **47**: 230–42.

25 Pitten FA, Werner HP, Kramer A. A standardized test to assess the impact of different organic challenges on the antimicrobial activity of antiseptics. *J Hosp Infect* 2003; **55**: 108–15.

26 Carling PC, Von Beheren S, Kim P *et al*. Intensive care unit environmental cleaning: an evaluation in sixteen hospitals using a novel assessment tool. *J Hosp Infect* 2008; **68**: 39–44.

27 Costerton JW, Stewart PS, Greenberg EP. Bacterial biofilms: a common cause of persistent infections. *Science* 1999; **284**: 1318–22.

28 Olson M, Ceri H, Morck D *et al*. Biofilm bacteria: formation and comparative susceptibility to antibiotics. *Can J Vet Res* 2002; **66**: 86–92.

29 Toté K, Berghe DV, Deschacht M *et al*. Inhibitory efficacy of various antibiotics on matrix and viable mass of *Staphylococcus aureus* and *Pseudomonas aeruginosa* biofilms. *Int J Antimicrob Agents* 2009; **33**: 525–31.

30 Simões M. Antimicrobial strategies effective against infectious bacterial biofilms. *Curr Med Chem* 2011; **18**: 2129–45.

31 Simões M, Simões LC, Vieira MJ. A review of current and emergent biofilm control strategies. *Food Sci Technol* 2010; **43**: 573–83.

32 Kramer A, Schwebke I, Kampf G. How long do nosocomial pathogens persist on inanimate surfaces? A systematic review. *BMC Infect Dis* 2006; **6**: 130.

33 Hota B. Contamination, disinfection, and cross-colonization: are hospital surfaces reservoirs for nosocomial infection? *Clin Infect Dis* 2004; **39**: 1182–9.

34 Dancer SJ. How do we assess hospital cleaning? A proposal for microbiological standards for surface hygiene in hospitals. *J Hosp Infect* 2004; **56**: 10–5.

35 Boyce JM. Environmental contamination makes an important contribution to hospital infection. *J Hosp Infect* 2007; **65**: 50–4.

36 Hirai Y. Survival of bacteria under dry conditions; from a viewpoint of nosocomial infection. *J Hosp Infect* 1991; **19**: 191–200.

37 Boyce JM, Potter-Bynoe G, Chenevert C *et al*. Environmental contamination due to methicillin-resistant *Staphylococcus aureus*: possible infection control implications. *Infect Control Hosp Epidemiol* 1997; **18**: 622–7.

38 Falagas ME, Thomaidis PC, Kotsantis IK *et al*. Airborne hydrogen peroxide for disinfection of the hospital environment and infection control: a systematic review. *J Hosp Infect* 2011; **78**: 171–7.

39 Dancer SJ. Mopping up hospital infection. *J Hosp Infect* 1999; **43**: 85–100.

40 Cheng KL, Boost MV, Chung JWY. Study on the effectiveness of disinfection with wipes against methicillin-resistant *Staphylococcus aureus* and implications for hospital hygiene. *Am J Infect Control* 2011; **39**: 577–80.

41 Drees M, Snydman DR, Schmid CH *et al*. Prior environmental contamination increases the risk of acquisition of vancomycin-resistant enterococci. *Clin Infect Dis* 2008; **46**: 678–85.

42 Dancer SJ, White LF, Lamb J *et al*. Measuring the effect of enhanced cleaning in a UK hospital: a prospective cross-over study. *BMC Med* 2009; **7**: 28.

43 Microbiology Advisory Committee. *Decontamination of Equipment, Linen or Other Surfaces Contaminated with Hepatitis B and/or Human Immunodeficiency Viruses*. Department of Health, London, 1991.

44 Dancer SJ. The role of environmental cleaning in the control of hospital-acquired infection. *J Hosp Infect* 2009; **73**: 378–85.

45 Wilcox MH, Fawley WN, Wigglesworth N *et al*. Comparison of the effect of detergent versus hypochlorite cleaning on environmental contamination and incidence of *Clostridium difficile* infection. *J Hosp Infect* 2003; **54**: 109–14.

46 Wood MW, Lund RC, Stevenson KB. Bacterial contamination of stethoscopes with antimicrobial diaphragm covers. *Am J Infect Control* 2007; **35**: 263–6.

47 Berendt AE, Turnbull L, Spady D *et al*. Three swipes and you're out: how many swipes are needed to decontaminate plastic with disposable wipes?. *Am J Infect Control* 2011; **39**: 442–3.

48 Cotterill S, Evans R, Fraise AP. An unusual source for an outbreak of methicillin-resistant *Staphylococcus aureus* on an intensive therapy unit. *J Hosp Infect* 1996; **32**: 207–16.

49 Kampf G, Rudolf M, Labadie JC *et al*. Spectrum of antimicrobial activity and user acceptability of the hand disinfectant agent Sterillium® Gel. *J Hosp Infect* 2002; **52**: 141–7.

50 Barker J, Vipond IB, Bloomfield SF. Effects of cleaning and disinfection in reducing the spread of Norovirus contamination via environmental surfaces. *J Hosp Infect* 2004; **58**: 42–9.

51 Pessoa-Silva CLMD, Dharan SMT, Hugonnet SMDM *et al*. Dynamics of bacterial hand contamination during routine neonatal care. *Infect Control Hosp Epidemiol* 2004; **25**: 192–7.

52 Pittet D, Dharan S, Touveneau S *et al*. Bacterial contamination of the hands of hospital staff during routine patient care. *Arch Intern Med* 1999; **159**: 821–6.

53 Fendler EJ, Ali Y, Hammond BS *et al*. The impact of alcohol hand sanitizer use on infection rates in an extended care facility. *Am J Infect Control* 2002; **30**: 226–33.

54 Hilburn J, Hammond BS, Fendler EJ *et al*. Use of alcohol hand sanitizer as an infection control strategy in an acute care facility. *Am J Infect Control* 2003; **31**: 109–16.

55 Page K, Wilson M, Parkin IP. Antimicrobial surfaces and their potential in reducing the role of the inanimate environment in the incidence of hospital-acquired infections. *J Mater Chem* 2009; **19**: 3819–31.

56 Lopez P-J, Ron O, Parthasarathy P *et al*. Bacterial counts from hospital doctors' ties are higher than those from shirts. *Am J Infect Control* 2009; **37**: 79–80.

57 Rutala WA, Weber DJ. *Guideline for Disinfection and Sterilization in Healthcare Facilities, 2008*. Healthcare Infection Control Practices Advisory Committee (HICPAC). Atlanta, GA, USA: CDC.

58 Rutala WA, Weber DJ. Sterilization, high-level disinfection, and environmental cleaning. *Infect Dis Clin North Am* 2011; **25**: 45–76.

59 Rutala WA, Weber DJ. Disinfection and sterilization in health care facilities: what clinicians need to know. *Clin Infect Dis* 2004; **39**: 702–9.

60 Russell AD. Bacterial resistance to disinfectants: present knowledge and future problems. *J Hosp Infect* 1999; **43**: S57–68.

61 Fraise AP. Choosing disinfectants. *J Hosp Infect* 1999; **43**: 255–64.

62 Rutala WA, Weber DJ. Infection control: the role of disinfection and sterilization. *J Hosp Infect* 1999; **43**: S43–55.

63 McDonnell G, Burke P. Disinfection: is it time to reconsider Spaulding? *J Hosp Infect* 2011; **78**: 163–70.

64 McDonnell G, Russell AD. Antiseptics and disinfectants: activity, action, and resistance. *Clin Microbiol Rev* 1999; **12**: 147–79.

65 Sagripanti J-L, Bonifacino A. Bacterial spores survive treatment with commercial sterilants and disinfectants. *Appl Environ Microbiol* 1999; **65**: 4255–60.

66 Russell AD. Bacterial adaptation and resistance to antiseptics, disinfectants and preservatives is not a new phenomenon. *J Hosp Infect* 2004; **57**: 97–104.

67 Russell AD. Introduction of biocides into clinical practice and the impact on antibiotic-resistant bacteria. *J Appl Microbiol* 2002; **92** Suppl: 121S–35S.

68 Gilbert P, McBain AJ. Potential impact of increased use of biocides in consumer products on prevalence of antibiotic resistance. *Clin Microbiol Rev* 2003; **16**: 189–208.

69 Rutala WA, Weber DJ. Uses of inorganic hypochlorite (bleach) in health-care facilities. *Clin Microbiol Rev* 1997; **10**: 597–610.

70 Bermúdez-Aguirre D, Barbosa-Cánovas GV. Disinfection of selected vegetables under nonthermal treatments: chlorine, acid citric, ultraviolet light and ozone. *Food Control* 2013; **29**: 82–90.

71 Denyer SP, Stewart GSAB. Mechanisms of action of disinfectants. *Int Biodeter Biodegr* 1998; **41**: 261–8.

72 Russell AD. Similarities and differences in the responses of microorganisms to biocides. *J Antimicrob Chemother* 2003; **52**: 750–63.

73 Griffiths PA, Babb JR, Fraise AP. Mycobactericidal activity of selected disinfectants using a quantitative suspension test. *J Hosp Infect* 1999; **41**: 111–21.

74 Théraud M, Bédouin Y, Guiguen C *et al*. Efficacy of antiseptics and disinfectants on clinical and environmental yeast isolates in planktonic and biofilm conditions. *J Med Microbiol* 2004; **53**: 1013–8.

75 Oie S, Yanagi C, Matsui H *et al*. Contamination of environmental surfaces by *Staphylococcus aureus* in a dermatological ward and its preventive measures. *Biol Pharm Bull* 2005; **28**: 120–3.

76 Speight S, Moy A, Macken S *et al*. Evaluation of the sporicidal activity of different chemical disinfectants used in hospitals against *Clostridium difficile*. *J Hosp Infect* 2011; **79**: 18–22.

77 Kim H, Ryu J-H, Beuchat LR. Effectiveness of disinfectants in killing *Enterobacter sakazakii* in suspension, dried on the surface of stainless steel, and in a biofilm. *Appl Environ Microbiol* 2007; **73**: 1256–65.

78 Bridier A, Briandet R, Thomas V *et al*. Comparative biocidal activity of peracetic acid, benzalkonium chloride and *ortho*-phthalaldehyde on 77 bacterial strains. *J Hosp Infect* 2011; **78**: 208–13.

79 Gutiérrez-Martín CB, Yubero S, Martínez S *et al*. Evaluation of efficacy of several disinfectants against *Campylobacter jejuni* strains by a suspension test. *Res Vet Sci* 2011; **91**: e44–7.

80 Siani H, Cooper C, Maillard J-Y. Efficacy of 'sporicidal' wipes against *Clostridium difficile*. *Am J Infect Control* 2011; **39**: 212–8.

81 Giannini MA, Nance D, McCullers JA. Are toilet seats a vector for transmission of methicillin-resistant *Staphylococcus aureus*? *Am J Infect Control* 2009; **37**: 505–6.

82 Williams GJ, Denyer SP, Hosein IK *et al*. The development of a new three-step protocol to determine the efficacy of disinfectant wipes on surfaces contaminated with *Staphylococcus aureus*. *J Hosp Infect* 2007; **67**: 329–35.

83 Rutala WA, Weber DJ. New disinfection and sterilization methods. *Emerging Infect Dis* 2001; **7**: 348–53.

84 Tanner BD. Reduction in infection risk through treatment of microbially contaminated surfaces with a novel, portable, saturated steam vapor disinfection system. *Am J Infect Control* 2009; **37**: 20–7.

85 Otter JA, French GL. Survival of nosocomial bacteria and spores on surfaces and inactivation by hydrogen peroxide vapor. *J Clin Microbiol* 2009; **47**: 205–7.

86 Hall L, Otter JA, Chewins J *et al*. Use of hydrogen peroxide vapor for deactivation of *Mycobacterium tuberculosis* in a biological safety cabinet and a room. *J Clin Microbiol* 2007; **45**: 810–5.

87 McDonnell G. Hydrogen peroxide fogging/fumigation. *J Hosp Infect* 2006; **62**: 385–6.

88 Boyce JM, Havill NL, Moore BA. Terminal decontamination of patient rooms using an automated mobile UV light unit. *Infect Control Hosp Epidemiol* 2011; **32**: 737–42.

89 Rutala WA, Gergen MF, Weber DJ. Room decontamination with UV radiation. *Infect Control Hosp Epidemiol* 2010; **31**: 1025–9.

90 Sambol AR, Iwen PC. Biological monitoring of ultraviolet germicidal irradiation in a biosafety level 3 laboratory. *Appl Biosaf* 2006; **11**: 81–7.

91 Weber DJ, Rutala WA. Self-disinfecting surfaces. *Infect Control Hosp Epidemiol* 2012; **33**: 10–3.

92 Rutala WA, Weber DJ. Are room decontamination units needed to prevent transmission of environmental pathogens? *Infect Control Hosp Epidemiol* 2011; **32**: 743–7.

93 Zhang X, Huang X, Jiang L *et al*. Surface microstructures and antimicrobial properties of copper plasma alloyed stainless steel. *Appl Surf Sci* 2011; **258**: 1399–404.

94 Héquet A, Humblot V, Berjeaud J-M *et al*. Optimized grafting of antimicrobial peptides on stainless steel surface and biofilm resistance tests. *Colloid Surface B* 2011; **84**: 301–9.

95 Tiller JC. Coatings for prevention or deactivation of biological contamination. In: Kohli R, Mittal KL, eds. *Developments in Surface Contamination and Cleaning*. Norwich, NY, USA: William Andrew, 2008; 1013–65.

96 Tian XB, Wang ZM, Yang SQ *et al*. Antibacterial copper-containing titanium nitride films produced by dual magnetron sputtering. *Surf Coat Technol* 2007; **201**: 8606–9.

97 Dunnill CW, Page K, Aiken ZA *et al*. Nanoparticulate silver coated-titania thin films - photo-oxidative destruction of stearic acid under different light sources and antimicrobial effects under hospital lighting conditions. *J Photochem Photobiol A* 2011; **220**: 113–23.

98 Balazs DJ, Triandafillu K, Wood P *et al*. Inhibition of bacterial adhesion on PVC endotracheal tubes by RF-oxygen glow discharge, sodium hydroxide and silver nitrate treatments. *Biomaterials* 2004; **25**: 2139–51.

99 Siedenbiedel F, Tiller JC. Antimicrobial polymers in solution and on surfaces: overview and functional principles. *Polymers* 2012; **4**: 46–71.

100 Kühn KP, Chaberny IF, Massholder K *et al*. Disinfection of surfaces by photocatalytic oxidation with titanium dioxide and UVA light. *Chemosphere* 2003; **53**: 71–7.

101 Goddard JM, Hotchkiss JH. Polymer surface modification for the attachment of bioactive compounds. *Prog Polym Sci* 2007; **32**: 698–725.

102 Kenawy E-R, Worley SD, Broughton R. The chemistry and applications of antimicrobial polymers: a state-of-the-art review. *Biomacromolecules* 2007; **8**: 1359–84.

103 Ristić T, Zemljič LF, Novak M *et al*. Antimicrobial efficiency of functionalized cellulose fibres as potential medical textiles. In: Méndez-Vilas A, ed. *Science Against Microbial Pathogens: Communicating Current Research and Technological Advances*. Badajoz, Spain: Formatex, 2011; 36–51.

104 Lichter JA, Rubner MF. Polyelectrolyte multilayers with intrinsic antimicrobial functionality: the importance of mobile polycations. *Langmuir* 2009; **25**: 7686–94.

105 Moisan M, Barbeau J, Moreau S *et al*. Low-temperature sterilization using gas plasmas: a review of the experiments and an analysis of the inactivation mechanisms. *Int J Pharm* 2001; **226**: 1–21.

106 Moreau M, Orange N, Feuilloley MGJ. Non-thermal plasma technologies: new tools for bio-decontamination. *Biotechnol Adv* 2008; **26**: 610–7.

107 Morfill GE, Shimizu T, Steffes B *et al*. Nosocomial infections - a new approach towards preventive medicine using plasmas. *New J Phys* 2009; **11**: 1–10.

108 Shimizu T, Zimmermann JL, Morfill GE. The bactericidal effect of surface micro-discharge plasma under different ambient conditions. *New J Phys* 2011; **13**: 1–7.

109 Gregory DS. Pertussis: a disease affecting all ages. *Am Fam Physician* 2006; **74**: 420–6.

110 Hanna HMD, Raad IMD, Gonzalez VBS *et al*. Control of nosocomial *Clostridium difficile* transmission in bone marrow transplant patients. *Infect Control Hosp Epidemiol* 2000; **21**: 226–8.

111 Sinh P, Barrett TA, Yun L. *Clostridium difficile* infection and inflammatory bowel disease: a review. *Gastroenterol Res Pract* 2011; **2011**: 136064.

112 Kuo CC, Jackson LA, Campbell LA *et al*. *Chlamydia pneumoniae* (TWAR). *Clin Microbiol Rev* 1995; **8**: 451–61.

113 Campbell LA, Kuo CC. *Chlamydia pneumoniae* pathogenesis. *J Med Microbiol* 2002; **51**: 623–5.

114 Bonnet JM, Begg NT. Control of diphtheria: guidance for consultants in communicable disease control. *Commun Dis Public Health* 1999; **2**: 242–9.

115 Murphy JR. *Corynebacterium diphtheriae*. In: Baron S, ed. *Medical Microbiology*. Galveston, TX: University of Texas Medical Branch at Galveston, 1996; Chapter 32.

116 Oprea SF, Zervos MJ. *Enterococcus* and its association with foodborne illness. In: Simjee S, ed. *Foodborne Disease*. Totowa, NJ: Humana Press, 2007; 157–74.

117 Foxwell AR, Kyd JM, Cripps AW. Nontypeable *Haemophilus influenzae*: pathogenesis and prevention. *Microbiol Mol Biol Rev* 1998; **62**: 294–308.

118 Podschun R, Ullmann U. *Klebsiella* spp. as nosocomial pathogens: epidemiology, taxonomy, typing methods, and pathogenicity factors. *Clin Microbiol Rev* 1998; **11**: 589–603.

119 Engelhart S, Krizek L, Glasmacher A *et al*. *Pseudomonas aeruginosa* outbreak in a haematology–oncology unit associated with contaminated surface cleaning equipment. *J Hosp Infect* 2002; **52**: 93–8.

120 Manning ML, Archibald LK, Bell LM *et al*. *Serratia marcescens* transmission in a pediatric intensive care unit: a multifactorial occurrence. *Am J Infect Control* 2001; **29**: 115–9.

121 Passaro DJ, Waring L, Armstrong R *et al*. Postoperative *Serratia marcescens* wound infections traced to an out-of-hospital source. *J Infect Dis* 1997; **175**: 992–5.

122 Colbeck JC. Environmental aspects of staphylococcal infections acquired in hospitals. *Am J Public Health* 1960; **50**: 468–73.

123 Nuorti JP. Pneumococcal disease (*Streptococcus pneumoniae*). In: Brunette GW, Kozarsky PE, Magill AJ *et al*., eds. *CDC Health Information for International Travel*. New York: Oxford University Press, 2012; Chapter 3.

124 Bessen DE. Population biology of the human restricted pathogen, *Streptococcus pyogenes*. *Infect Genet Evol* 2009; **9**: 581–93.

125 Cleary PP, Schlievert PM, Handley JP *et al*. Clonal basis for resurgence of serious *Streptococcus pyogenes* disease in the 1980s. *Lancet* 1992; **339**: 518–21.

126 Pfaller MA. Nosocomial candidiasis: emerging species, reservoirs, and modes of transmission. *Clin Infect Dis* 1996; **22** Suppl 2: S89–94.

127 Queensland Health. *Communicable Diseases Control Manual*. 5th edn. 2011. Brisbane, Queensland, Australia.

128 Mattner F, Sohr D, Heim A *et al*. Risk groups for clinical complications of norovirus infections: an outbreak investigation. *Clin Microbiol Infect* 2006; **12**: 69–74.

129 Holton J, Shetty N, McDonald V. Efficacy of 'Nu-Cidex' (0.35% peracetic acid) against mycobacteria and cryptosporidia. *J Hosp Infect* 1995; **31**: 235–7.

130 Coates D. Sporicidal activity of sodium dichloroisocyanurate, peroxygen and glutaraldehyde disinfectants against *Bacillus subtilis*. *J Hosp Infect* 1996; **32**: 283–94.

131 Shetty N, Srinivasan S, Holton J *et al*. Evaluation of microbicidal activity of a new disinfectant: Sterilox 2500 against *Clostridium difficile* spores, *Helicobacter pylori*, vancomycin resistant *Enterococcus* species, *Candida albicans* and several *Mycobacterium* species. *J Hosp Infect* 1999; **41**: 101–5.

132 Vintov J, Aarestrup FM, Zinn CE *et al*. Association between phage types and antimicrobial resistance among bovine *Staphylococcus aureus* from 10 countries. *Vet Microbiol* 2003; **95**: 133–47.

133 Block C, Robenshtok E, Simhon A *et al*. Evaluation of chlorhexidine and povidone iodine activity against methicillin-resistant *Staphylococcus aureus* and vancomycin-resistant *Enterococcus faecalis* using a surface test. *J Hosp Infect* 2000; **46**: 147–52.

134 Block C. The effect of Perasafe® and sodium dichloroisocyanurate (NaDCC) against spores of *Clostridium difficile* and *Bacillus atrophaeus* on stainless steel and polyvinyl chloride surfaces. *J Hosp Infect* 2004; **57**: 144–8.

135 Vizcaino-Alcaide MJ, Herruzo-Cabrera R, Fernandez-Aceñero MJ. Comparison of the disinfectant efficacy of Perasafe® and 2% glutaraldehyde in *in vitro* tests. *J Hosp Infect* 2003; **53**: 124–8.

136 Wutzler P, Sauerbrei A, Schau HP. Monopercitric acid - a new disinfectant with excellent activity towards clostridial spores. *J Hosp Infect* 2005; **59**: 75–6.

137 Simões M, Pereira MO, Machado I *et al*. Comparative antibacterial potential of selected aldehyde-based biocides and surfactants against planktonic *Pseudomonas fluorescens*. *J Ind Microbiol Biotechnol* 2006; **33**: 741–9.

138 Walsh SE, Maillard JY, Russell AD. *Ortho*-phthalaldehyde: a possible alternative to glutaraldehyde for high level disinfection. *J Appl Microbiol* 1999; **86**: 1039–46.

139 Alfa MJ, Sitter DL. In-hospital evaluation of orthophthalaldehyde as a high level disinfectant for flexible endoscopes. *J Hosp Infect* 1994; **26**: 15–26.

140 Oulé MK, Azinwi R, Bernier A-M *et al*. Polyhexamethylene guanidine hydrochloride-based disinfectant: a novel tool to fight meticillin-resistant *Staphylococcus aureus* and nosocomial infections. *J Med Microbiol* 2008; **57**: 1523–8.

141 Andersen BM, Rasch M, Kvist J *et al*. Floor cleaning: effect on bacteria and organic materials in hospital rooms. *J Hosp Infect* 2009; **71**: 57–65.

142 Hedin G, Rynbäck J, Loré B. Reduction of bacterial surface contamination in the hospital environment by application of a new product with persistent effect. *J Hosp Infect* 2010; **75**: 112–5.

143 Chatuev BM, Peterson JW. Analysis of the sporicidal activity of chlorine dioxide disinfectant against *Bacillus anthracis* (Sterne strain). *J Hosp Infect* 2010; **74**: 178–83.

144 Horejsh D, Kampf G. Efficacy of three surface disinfectants against spores of *Clostridium difficile* ribotype 027. *Int J Hyg Environ Health* 2011; **214**: 172–4.

145 Chung C-J, Lin H-I, Tsou H-K *et al*. An antimicrobial TiO_2 coating for reducing hospital-acquired infection. *J Biomed Mater Res* 2008; **85B**: 220–4.

146 Shao H, Meng W-D, Qing F-L. Synthesis and surface antimicrobial activity of a novel perfluorooctylated quaternary ammonium silane coupling agent. *J Fluorine Chem* 2004; **125**: 721–4.

147 Foster HA, Sheel DW, Sheel P *et al*. Antimicrobial activity of titania/silver and titania/copper films prepared by CVD. *J Photochem Photobiol A* 2010; **216**: 283–9.

148 Xiangyu Z, Ailan F, Ruihua Z *et al*. Antibacterial property and tribological behavior of duplex-surface-treated AISI 304 stainless steel. *IEEE Trans Plasma Sci* 2011; **39**: 1598–605.

149 Belcarz A, Bieniaś J, Surowska B *et al*. Studies of bacterial adhesion on TiN, SiO2–TiO2 and hydroxyapatite thin layers deposited on titanium and Ti6Al4 V alloy for medical applications. *Thin Solid Films* 2010; **519**: 797–803.

150 Kurt P, Wood L, Ohman DE *et al*. Highly effective contact antimicrobial surfaces via polymer surface modifiers. *Langmuir* 2007; **23**: 4719–23.