American Journal of Infection Control 41 (2013) S6-S11

Contents lists available at ScienceDirect

American Journal of Infection Control

journal homepage: www.ajicjournal.org

Original research article

Evidence that contaminated surfaces contribute to the transmission of hospital pathogens and an overview of strategies to address contaminated surfaces in hospital settings

Jonathan A. Otter PhD [a,b,*], Saber Yezli PhD [b], James A.G. Salkeld BSc [b], Gary L. French MD, FRCPath [a]

[a] Centre for Clinical Infection and Diagnostics Research (CIDR), Department of Infectious Diseases, King's College London & Guy's and St. Thomas' NHS Foundation Trust, London, UK
[b] Bioquell, Andover, Hampshire, UK

Key Words:
Disinfection
Cleaning
MRSA
VRE
Acinetobacter
Clostridium difficile
Norovirus

Evidence that contaminated surfaces contribute to the transmission of hospital pathogens comes from studies modeling transmission routes, microbiologic studies, observational epidemiologic studies, intervention studies, and outbreak reports. This review presents evidence that contaminated surfaces contribute to transmission and discusses the various strategies currently available to address environmental contamination in hospitals.

Environmental surfaces were once thought to play a negligible role in the endemic transmission of nosocomial pathogens.[1] However, recent data indicate that contaminated surfaces play an important role in the endemic and epidemic transmission of certain pathogens that cause health care-associated infections.[2] *Clostridium difficile*, methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant enterococci (VRE), norovirus, and multidrug-resistant (MDR) gram-negative rods including *Acinetobacter baumannii* share the ability to be shed from infected or colonized patients, survive on dry surfaces for extend periods, and are difficult to eradicate by cleaning and disinfection.[2] Whereas the role of contaminated surfaces in the transmission of some pathogens such as the spore-forming *C difficile* has been recognized for some time,[3] the importance of contaminated surfaces in the transmission of other pathogens such as MDR *A baumannii* has come to light only in recent years.[4] The continued emergence of antimicrobial resistance in gram-negative bacteria in particular means that effective prevention and control strategies are required urgently.[5]

The transmission routes of pathogens are complicated and difficult to investigate, so studies focused on the role of surfaces in transmission have been rare until relatively recently.[2] Data suggesting that contaminated surfaces play a role in transmission come from studies modeling transmission,[6-8] microbiologic studies in vitro and in situ,[9-12] observational epidemiologic studies,[3,4,13-16] intervention studies aimed at improving the efficacy of cleaning and disinfection,[17-22] and outbreak reports.[23-25] The role played by contaminated environmental surfaces in the transmission of nosocomial pathogens was recently reviewed.[2] Here, we present the latest data evaluating the role of contaminated surfaces in transmission and discuss the various strategies available to address environmental contamination in hospitals.

EVIDENCE THAT CONTAMINATED SURFACES CONTRIBUTE TO TRANSMISSION

Modeling transmission

Modeling transmission routes can provide "proof of principle" that contaminated surfaces are involved in transmission: for example, monitoring the spread of nonmicrobial markers,[8] the use of animal models,[7] and mathematical modelling.[6] One study evaluated the spread of a nonmicrobial marker (plant DNA) designed to model the spread of pathogens from hospitals surfaces. The marker was inoculated onto a single telephone handle in one of six 8-cot "pods" in a neonatal intensive care unit (ICU). The spread of the marker was remarkable: within 4 hours, it was identified from environmental surfaces and staff hands across the unit including all 6 pods. Whereas the spread of plant DNA does not necessarily

* Address correspondence to Jonathan A. Otter, PhD, Centre for Clinical Infection and Diagnostics Research (CIDR), Department of Infectious Diseases, King's College London & Guy's and St. Thomas' NHS Foundation Trust, 5th Floor, North Wing, St. Thomas' Hospital, London, SE1 7EH, UK.
E-mail address: jonathan.otter@kcl.ac.uk (J.A. Otter).

Publication of this article was supported by Advanced Sterilization Products (ASP).
Conflicts of interest: None to report.

http://dx.doi.org/10.1016/j.ajic.2012.12.004

accurately represent the spread of a pathogenic micro-organism, it does present a picture of dynamic and rapid transmission involving both environmental surfaces and staff hands.

Another approach to modeling transmission is the use of animal models. For example, Lawley et al used a murine model to evaluate the transmission of *C difficile*.[7] The model established that *C difficile* could be spread through experimentally contaminated cages in a dose-dependent manner. Furthermore, the model also demonstrated that disinfection of the cages using a range of disinfectants interrupted transmission proportionally to the level of spore reduction achieved.

Mathematical modeling can also provide some insight into transmission routes. Mathematical models including the role of contaminated surfaces are rare, but one study evaluated the likely economic impact of various control strategies for norovirus including improved disinfection.[6] The model found that increased disinfection alone or in combination with increased hand hygiene and using protective apparel were most useful for the control and containment of norovirus outbreaks.

Microbiologic studies

Environmental sampling of the surfaces surrounding patients in hospitals has established that certain pathogens are shed into the hospital environment. Wide variation in the reported frequency of environmental contamination can be explained by several factors, including the culturability of the organism, the degree of shedding by the patient, the sampling methodology, the ease of contamination (or difficulty of cleaning) of the particular environment, and whether there is an ongoing outbreak at the time of sampling.

Surfaces in the vicinity of patients have a higher frequency of contamination than other sites.[10,26] Infected patients shed more pathogens than those who are only colonized, and diarrhea results in widespread contamination.[27,28]

Although the presence of a pathogen on a surface does not necessarily represent a risk for transmission,[1] studies have demonstrated that the infectious dose of some pathogens is low. For example, a small number of *C difficile* spores or norovirus particles are sufficient to initiate an infection.[7,29,30]

Microbiologic studies have established that certain hospital pathogens can survive on dry hospital surfaces for extend periods (Table 1).[31] The survival of hospital pathogens on dry hospital surfaces in vitro varies according to experimental conditions, but some strains of vegetative bacteria have the capacity to survive for months on dry hospital surfaces. VRE in particular seems to have remarkable survival properties, with a recent study showing that VRE can remain viable on dry surfaces for almost 4 years.[32] The mechanisms underlying this surprising survival capacity of certain vegetative bacteria are unknown, but the recent discovery of biofilms on dry hospital surfaces may provide a mechanism through which vegetative bacteria could survive on dry surfaces for such extend periods without a nutrient source.[33,34]

In vitro studies of the spread of DNA or other markers, model organisms, or pathogens show that transfer can occur from environmental surfaces to hands and vice versa.[35-38] Several microbiologic studies have investigated the transfer of pathogens from surfaces to the hands or gloves of health care personnel in the absence of direct patient contact (Table 2). Contact with an environmental surface carries approximately the same risk of acquiring MRSA,[39] VRE,[10] and *C difficile*[40] hand or glove contamination as touching an infected or colonized patient. One study estimated that VRE hand contamination was acquired through approximately 10% of contacts with either the patient or the surfaces surrounding the patient.[10] Importantly, hand hygiene compliance was significantly more likely following direct patient contact compared with contact with the patient environment, meaning that contamination acquired from the environment is likely to persist for longer and hence could be relatively more important for onward transmission.[41]

Table 1
Survival of hospital pathogens on dry hospital surfaces

Organism	Survival time
Clostridium difficile (spores)	>5 Months
Acinetobacter spp	3 Days to 11 months[79]
Enterococcus spp including VRE	5 Days to >46 months[32]
Pseudomonas aeruginosa	6 Hours to 16 months
Klebsiella spp	2 Hours to >30 months
Staphylococcus aureus, including MRSA	7 Days to >12 months[80]
Norovirus (and feline calicivirus)	8 Hours to >2 weeks[81]

NOTE. Adapted from Kramer et al.[31]

Table 2
Transfer of pathogens from surfaces to the hands of health care personnel

Direct patient contact	Contact with environmental surfaces only
	52% of 44 HCP acquired VRE on their hands or gloves[10]
45% of 50 HCP acquired MRSA on their gloved hands[39]	40% of 50 HCP acquired MRSA on their gloved hands[39]
50% of 30 HCP acquired *Clostridium difficile* on their gloved hands[40]	50% of 30 HCP acquired *C difficile* on their gloved hands[40]
Compliance with hand hygiene: 80%[41]	Compliance with hand hygiene: 50%[41]

HCP, Health care personnel.

Cleaning and/or disinfection is usually performed daily (or several times daily) to reduce the environmental burden and ensure that the patient environment remains visibly clean. More stringent cleaning and/or disinfection is performed at patient discharge (sometimes called "terminal" cleaning/disinfection) to ensure that the clinical area is properly disinfected and safe for the next occupant. Many studies have been performed to investigate the efficacy of cleaning and disinfection, and most focus on the efficacy of terminal cleaning/disinfection. Environmental sampling performed after terminal disinfection often identifies surfaces contaminated with the pathogen that the process is aiming to eliminate.[18,42-47] Even multiple "rounds" of bleach disinfection may not be sufficient to eliminate some pathogens.[11,42,46] For example, a recent study found that 27% of rooms remained contaminated with *A baumannii* or MRSA following 4 rounds of bleach disinfection.[11] Similarly, 43% of surfaces were contaminated with norovirus RNA after 1 round of bleach disinfection, and 16% of surfaces were contaminated after 2 rounds of bleach disinfection. Bleach and other disinfectants are effective against these and other pathogens in vitro, and, in theory, cleaning using a detergent alone would remove contamination with these pathogens. Thus, the failure of cleaning and disinfection to consistently eliminate surface contamination with pathogens is most likely explained by the challenge of repeatedly achieving adequate distribution and contact time of the agent.

Observational epidemiologic studies

Carefully performed observational epidemiologic studies have established that contaminated surfaces are involved in the transmission of certain pathogens.[3,16,48] For example, one study concluded that at least 3 of 26 patients acquired MRSA directly from contaminated environmental surfaces.[16] However, it is difficult to determine the independent role of contaminated surfaces in these studies.

A useful way to elucidate the role of contaminated surfaces in transmission is to evaluate the risk of acquiring certain

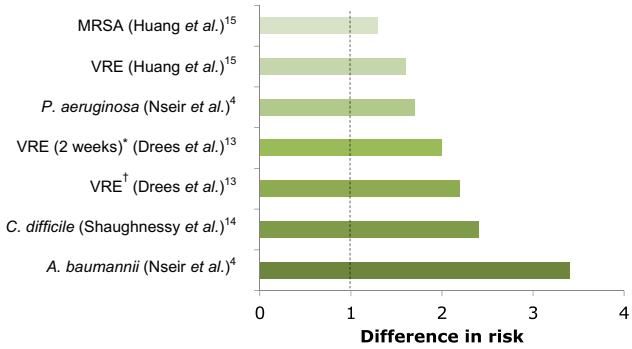

Fig 1. Chart showing the increased risk associated with the prior room occupant. The figures of difference in risk are unadjusted based on raw data. Several of the studies included adjusted measures of risk, but these were not included because of differences in study design. * Any patient infected or colonized with VRE in the two weeks prior to admission. † The immediate prior room occupant was known to be infected or colonized with VRE.

pathogens in patients admitted to rooms where the prior occupant was known to be infected or colonized with the pathogen. If environmental surfaces are an important factor in transmission because of inadequate disinfection after discharge of an infected or colonized patient, there will be an increased risk of acquisition of the same pathogen in the subsequent room occupant. This has been shown to be the case for a range of organisms, including *C difficile*, MRSA, VRE, and MDR gram-negative rods, including *A baumannii* (Fig 1).[4,13-15] For example, during a 14-month study performed on 2 ICUs in the United States, all patients were screened for VRE on admission and twice weekly, and the environment was screened weekly[13]; the 50 patients who acquired VRE were compared with the 588 who did not. Admission to a room from which a previous positive VRE culture had been obtained had the greatest increased risk of acquisition (hazard ratio [HR], 4.3); admission to a room where the immediate room occupant was infected or colonized with VRE had intermediate increased risk (HR, 3.8); and admission to a room that had been occupied by a VRE-infected or -colonized patient in the prior 2 weeks had the lowest increased risk (HR, 2.7).

The fact that terminal cleaning and disinfection does not reliably eliminate pathogens supports the findings of these "prior room occupancy" studies. Inadequate terminal disinfection may also result in a room becoming contaminated with more than 1 strain of a particular pathogen because of a "build up" over time. For example, MRSA with an average of 2.3 antibiograms were found in each patient room in one study where there was suboptimal terminal cleaning.[45] Similarly, in other studies, approximately 30% of MRSA environmental types were not closely related to the MRSA type affecting the patient in the room.[49,50] Also, pathogens can be identified in empty rooms[13,17] and can be transferred to the hands of health care personnel from surfaces in empty rooms.[51]

These "prior room occupancy" studies allow the assessment of the risks associated with environmental contamination independent of common confounding variables of hospital infection, such as patient age, comorbidities, and length of stay. In addition, because the source patients were already discharged, in these studies patient acquisition directly from surfaces or via hand transfer from health care personnel is most likely to have come from contaminated surfaces.

Intervention studies

The findings of the prior room occupancy studies are supported by evidence that improved terminal cleaning and disinfection can reduce the risk of infection for the next occupant.[17,20] Datta et al performed a retrospective cohort intervention study on 10 ICUs at a US hospital to evaluate the impact of improved cleaning and disinfection.[20] The intervention consisted of targeted feedback using a black-light marker, the introduction of a "bucket method" for wetting cleaning cloths, and increased education of housekeeping staff. Patient acquisition was compared during 20-month baseline and intervention periods separated by 16 months. The acquisition of both MRSA and VRE fell significantly during the intervention periods, by 50% and 27%, respectively. The risk associated with the prior room occupant was successfully mitigated for MRSA but not for VRE.

Passaretti et al performed a prospective 30-month cohort intervention study on 6 high-risk units in a US hospital to evaluate the impact of introducing hydrogen peroxide vapor (HPV) for the terminal disinfection of select patient rooms. HPV was introduced to disinfect the rooms of patients known to be infected or colonized with multidrug-resistant organisms (MDROs) on 3 units following a 12-month preintervention phase. Patients admitted to rooms decontaminated using HPV were significantly less likely to acquire any MDRO (64% reduction) and VRE (80% reduction). HPV decontamination significantly reduced the proportion of rooms environmentally contaminated with MDROs by 35%. In particular, rooms contaminated with multiple MDROs, MDROs cultured from a room that differed from the room occupant's known MDRO, and MDROs cultured from empty rooms were less frequent on HPV units during the intervention phase. These environmental findings can be explained by the improved terminal disinfection by HPV.

Several prospective studies have demonstrated that interventions aimed at reducing surface contamination reduce the transmission of hospital pathogens. These can be broadly divided into studies of a change in disinfection agent[18,22,52,53] or educational improvements using existing agents.[19,21] These studies have been reviewed in detail by Otter et al.[2] Since the publication of that review, a 4-year before-and-after Brazilian study evaluated the impact of an intervention aimed at reducing VRE environmental contamination.[54] The intervention comprised an educational program for housekeepers and health care personnel and observation of compliance with several infection prevention and control procedures. Following the intervention, there was a significant reduction in the frequency of VRE contamination of equipment and surfaces from 23% to 8.2% and an associated reduction in VRE prevalence from 7.7 to 1.9 cases per 1,000 patient-days. Although the multifaceted intervention makes it difficult to be certain that the reduction in environmental contamination is wholly responsible for the reduction in VRE cases, it provides further evidence that reducing the environmental burden can help to reduce the transmission of VRE.

Outbreak reports

Findings derived from outbreaks are often limited by lack of controls, multiple interventions and the potential for regression to the mean. However, many outbreak reports implicate contaminated surfaces in the transmission of *C difficile*,[55,56] MRSA,[57,58] VRE,[59,60] MDR gram-negative rods[23,24] and norovirus.[25,61]

Data supporting the role of contaminated surfaces in the transmission of norovirus come from outbreak reports, mostly in community settings. For example, a recent study from New Zealand provides compelling data that environmental contamination contributes to the transmission of norovirus through a remarkable outbreak of norovirus affecting successive flights of the same plane with distinct crews and passengers, associated with an episode of vomiting.[25] The attack rate among staff decreased sequentially with subsequent flights, presumably as the environmental reservoir diminished. The attack rate in passengers could

not be determined because follow-up of each passenger was not feasible. The outbreak only ceased once the plane was refitted with new carpet in the affected area. Health care facilities do not have epidemiologically distinct cohorts of patients and staff, so it is more difficult to establish the role of contaminated surfaces in the transmission of norovirus. However, the finding of norovirus RNA contamination on surfaces in the immediate vicinity of patients and the general association between improved disinfection and the containment of outbreaks provides convincing evidence that contaminated surfaces are an important factor in the transmission of norovirus.[6,46,62]

STRATEGIES TO ADDRESS ENVIRONMENTAL CONTAMINATION

It is now clear that contaminated surfaces contribute to the transmission of some pathogens in some settings. However, the importance of contaminated surfaces relative to other transmission routes is not well understood. Indeed, when 6 experts speaking at an environmental session at APIC 2012 were asked to estimate the "percentage of all *C difficile* transmission in hospitals that is mediated, directly or indirectly, by contamination of the inanimate environment," the responses ranged from 25% to 75% (unpublished data). Modeling, prior room occupancy studies, and intervention studies give a general indication of the contribution of contaminated surfaces to transmission, but carefully designed studies are required to provide more definitive data.

Despite the limitations of the evidence base, more needs to be done to address environmental contamination in hospitals to deliver the safest possible health care. Strategies to address environmental contamination can be divided into reducing and containing the shedding of pathogens and improved cleaning and disinfection.

Reducing and containing shedding

Improving compliance with hand hygiene following contact with a patient's surroundings will reduce the chances of indirect spread of pathogens acquired on the hands of health care personnel following contact with their surroundings (Table 2).[41] Also, improved compliance with hand hygiene before and after direct contact with patients will reduce the spread of contamination into the health care environment on the hands of health care personnel.

The rapid identification and isolation of infected or colonized patients is crucial for containing contamination. There is uncertainty surrounding the length of time patients should be isolated, and further work is required on this. Whereas hospitals in the United States generally have a high proportion of single rooms, hospitals in other countries typically have a much lower proportion of single rooms.[63] The lack of single rooms hampers effective isolation of patients known to be infected or colonized with pathogens. Where single rooms are not available, cohorting of patients affected with the same pathogen within a multioccupancy area is often practiced.[64,65] However, increasing the number of single rooms has been associated with reduced transmission.[66] Thus, hospitals and health care administrators should ensure the adequate provision of isolation facilities through building hospitals with a high proportion of single occupancy rooms or modifying existing facilities to increase the proportion of single occupancy rooms.[63,65-67]

"Source control" through daily bathing with chlorhexidine is another approach to reducing the shedding of pathogens, and this has been shown to reduce the transmission of MRSA and VRE.[68,69] However, most studies of the effectiveness of this intervention have been performed in ICU settings, so studies are required outside of the ICU.

Improved cleaning and disinfection

Effective cleaning and disinfection relies on the operator to repeatedly ensure adequate selection, formulation, distribution, and contact time of the agents used. Educational improvements designed to modify human behavior can be attempted with the support of various tools including fluorescent markers or adenosine triphosphate assays, and monitoring and feedback can improve the frequency of surface cleaning,[70] reduce the level of environmental contamination,[54,71] and reduce the acquisition of pathogens.[19,20] However, no studies have evaluated the sustainability of such systematic improvements. Indeed, recent evidence indicates that altering the location of florescent dye spots reduced the proportion of objects that were cleaned from 90% to approximately 60%.[72]

Improvements in hospital design and materials, novel disinfectants, and cleaning/disinfection technologies should be evaluated to determine their effectiveness in improving cleaning and disinfection. For example, there has been recent discussion on "no-touch" automated room disinfection (NTD) systems, which remove or reduce the reliance on the operator to achieve adequate distribution and contact time of the active agents.[72,73] HPV, aerosolized hydrogen peroxide, ultraviolet C, and pulsed-xenon ultraviolet radiation NTD systems have all shown promise and improved efficacy when compared with conventional methods.[11,45,74-76] HPV has been associated with reductions in patient acquisition and evaluations of other NTD systems with a clinical outcome are eagerly awaited.[17,18] NTD systems are only appropriate for certain applications and should be introduced in parallel with an educational campaign to improve conventional methods.

Antimicrobial or "self-disinfecting" surfaces and air disinfection units have shown some promise in reducing the environmental bioburden, but further evaluations with clinical outcomes are required.[77,78] The most appropriate strategies to address surface contamination will depend on the setting and on local epidemiology.

CONCLUSION

There is now compelling evidence from modeling of transmission routes, microbiologic studies, observational epidemiology studies, intervention studies, and outbreak reports that contaminated surfaces contribute to the transmission of hospital pathogens. The finding that admission to a room previously occupied by a patient with a hospital pathogen increases the risk of acquiring that pathogen, combined with intervention studies showing that this increased risk can be mitigated by improved environmental decontamination, provides the most powerful evidence that contaminated surfaces contribute to transmission and that more needs to be done to improve surface decontamination. Improvement strategies include interventions to reduce and contain the shedding of pathogens into the environment and interventions to improve the efficacy of cleaning and disinfection. The most appropriate strategies to address surface contamination will depend on the setting and on local epidemiology.

References

1. Rhame FS. The inanimate environment. In: Bennett JV, Brachmann PS, editors. Hospital infection. 4th ed. Philadelphia [PA]: Lipincott-Raven; 1998. p. 299-324.
2. 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.
3. Samore MH, Venkataraman L, DeGirolami PC, Arbeit RD, Karchmer AW. Clinical and molecular epidemiology of sporadic and clustered cases of nosocomial *Clostridium difficile* diarrhea. Am J Med 1996;100:32-40.
4. Nseir S, Blazejewski C, Lubret R, Wallet F, Courcol R, Durocher A. Risk of acquiring multidrug-resistant gram-negative bacilli from prior room occupants in the ICU. Clin Microbiol Infect 2011;17:1201-8.

5. Peleg AY, Hooper DC. Hospital-acquired infections due to gram-negative bacteria. N Engl J Med 2010;362:1804-13.
6. Lee BY, Wettstein ZS, McGlone SM, Bailey RR, Umscheid CA, Smith KJ, et al. Economic value of norovirus outbreak control measures in healthcare settings. Clin Microbiol Infect 2010;17:640-6.
7. Lawley TD, Clare S, Deakin LJ, Goulding D, Yen JL, Raisen C, et al. Use of purified *Clostridium difficile* spores to facilitate evaluation of health care disinfection regimens. Appl Environ Microbiol 2010;76:6895-900.
8. Oelberg DG, Joyner SE, Jiang X, Laborde D, Islam MP, Pickering LK. Detection of pathogen transmission in neonatal nurseries using DNA markers as surrogate indicators. Pediatrics 2000;105:311-5.
9. Boyce JM. Are the epidemiology and microbiology of methicillin-resistant *Staphylococcus aureus* changing? JAMA 1998;279:623-4.
10. Hayden MK, Blom DW, Lyle EA, Moore CG, Weinstein RA. Risk of hand or glove contamination after contact with patients colonized with vancomycin-resistant enterococcus or the colonized patients' environment. Infect Control Hosp Epidemiol 2008;29:149-54.
11. Manian FA, Griesenauer S, Senkel D, Setzer JM, Doll SA, Perry AM, et al. Isolation of *Acinetobacter baumannii* complex and methicillin-resistant *Staphylococcus aureus* from hospital rooms following terminal cleaning and disinfection: can we do better? Infect Control Hosp Epidemiol 2011;32:667-72.
12. 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.
13. Drees M, Snydman D, Schmid C, Barefoot L, Hansjosten K, Vue P, et al. Prior environmental contamination increases the risk of acquisition of vancomycin-resistant enterococci. Clin Infect Dis 2008;46:678-85.
14. Shaughnessy MK, Micielli RL, DePestel DD, Arndt J, Strachan CL, Welch KB, et al. Evaluation of hospital room assignment and acquisition of *Clostridium difficile* infection. Infect Control Hosp Epidemiol 2011;32:201-6.
15. Huang SS, Datta R, Platt R. Risk of acquiring antibiotic-resistant bacteria from prior room occupants. Arch Intern Med 2006;166:1945-51.
16. Hardy KJ, Oppenheim BA, Gossain S, Gao F, Hawkey PM. A study of the relationship between environmental contamination with methicillin-resistant *Staphylococcus aureus* (MRSA) and patients' acquisition of MRSA. Infect Control Hosp Epidemiol 2006;27:127-32.
17. Passaretti CL, Otter JA, Reich NG, Myers J, Shepard J, Ross T, et al. An evaluation of environmental decontamination with hydrogen peroxide vapor for reducing the risk of patient acquisition of multidrug-resistant organisms. Clin Infect Dis 2013;56:27-35.
18. Boyce JM, Havill NL, Otter JA, McDonald LC, Adams NM, Cooper T, et al. Impact of hydrogen peroxide vapor room decontamination on *Clostridium difficile* environmental contamination and transmission in a healthcare setting. Infect Control Hosp Epidemiol 2008;29:723-9.
19. Hayden MK, Bonten MJ, Blom DW, Lyle EA, van de Vijver DA, Weinstein RA. Reduction in acquisition of vancomycin-resistant enterococcus after enforcement of routine environmental cleaning measures. Clin Infect Dis 2006;42:1552-60.
20. Datta R, Platt R, Yokoe DS, Huang SS. Environmental cleaning intervention and risk of acquiring multidrug-resistant organisms from prior room occupants. Arch Intern Med 2011;171:491-4.
21. Dancer SJ, White LF, Lamb J, Girvan EK, Robertson C. Measuring the effect of enhanced cleaning in a UK hospital: a prospective cross-over study. BMC Med 2009;7:28.
22. Mayfield JL, Leet T, Miller J, Mundy LM. Environmental control to reduce transmission of *Clostridium difficile*. Clin Infect Dis 2000;31:995-1000.
23. Denton M, Wilcox MH, Parnell P, Green D, Keer V, Hawkey PM, et al. Role of environmental cleaning in controlling an outbreak of *Acinetobacter baumannii* on a neurosurgical intensive care unit. J Hosp Infect 2004;56:106-10.
24. Zanetti G, Blanc DS, Federli I, Raffoul W, Petignat C, Maravic P, et al. Importation of *Acinetobacter baumannii* into a burn unit: a recurrent outbreak of infection associated with widespread environmental contamination. Infect Control Hosp Epidemiol 2007;28:723-5.
25. Thornley CN, Emslie NA, Sprott TW, Greening GE, Rapana JP. Recurring norovirus transmission on an airplane. Clin Infect Dis 2011;53:515-20.
26. Huslage K, Rutala WA, Sickbert-Bennett E, Weber DJ. A quantitative approach to defining "high-touch" surfaces in hospitals. Infect Control Hosp Epidemiol 2010;31:850-3.
27. Boyce JM, Potter-Bynoe G, Chenevert C, King T. Environmental contamination due to methicillin-resistant *Staphylococcus aureus*: possible infection control implications. Infect Control Hosp Epidemiol 1997;18:622-7.
28. Boyce JM, Opal SM, Chow JW, Zervos MJ, Potter-Bynoe G, Sherman CB, et al. Outbreak of multidrug-resistant *Enterococcus faecium* with transferable *vanB* class vancomycin resistance. J Clin Microbiol 1994;32:1148-53.
29. Yezli S, Otter JA. Minimum infective dose of the major human respiratory and enteric viruses transmitted through food and the environment. Food Environ Microbiol 2011;3:1-30.
30. Larson HE, Borriello SP. Quantitative study of antibiotic-induced susceptibility to *Clostridium difficile* enterocecitis in hamsters. Antimicrob Agents Chemother 1990;34:1348-53.
31. Kramer A, Schwebke I, Kampf G. How long do nosocomial pathogens persist on inanimate surfaces? A systematic review. BMC Infect Dis 2006;6:130.
32. Wagenvoort JH, De Brauwer EI, Penders RJ, Willems RJ, Top J, Bonten MJ. Environmental survival of vancomycin-resistant *Enterococcus faecium*. J Hosp Infect 2011;77:282-3.
33. Vickery K, Deva A, Jacombs A, Allan J, Valente P, Gosbell IB. Presence of biofilm containing viable multiresistant organisms despite terminal cleaning on clinical surfaces in an intensive care unit. J Hosp Infect 2012;80:52-5.
34. Yezli S, Otter JA. Does the discovery of biofilms on dry hospital environmental surfaces change the way we think about hospital disinfection? J Hosp Infect 2012;81:293-4.
35. Winther B, McCue K, Ashe K, Rubino J, Hendley JO. Rhinovirus contamination of surfaces in homes of adults with natural colds: transfer of virus to fingertips during normal daily activities. J Med Virol 2011;83:906-9.
36. Rusin P, Maxwell S, Gerba C. Comparative surface-to-hand and fingertip-to-mouth transfer efficiency of gram-positive bacteria, gram-negative bacteria, and phage. J Appl Microbiol 2002;93:585-92.
37. 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.
38. Rheinbaben F, Schunemann S, Gross T, Wolff MH. Transmission of viruses via contact in a household setting: experiments using bacteriophage straight phiX174 as a model virus. J Hosp Infect 2000;46:61-6.
39. Stiefel U, Cadnum JL, Eckstein BC, Guerrero DM, Tima MA, Donskey CJ. Contamination of hands with methicillin-resistant *Staphylococcus aureus* after contact with environmental surfaces and after contact with the skin of colonized patients. Infect Control Hosp Epidemiol 2011;32:185-7.
40. Guerrero DM, Nerandzic MM, Jury LA, Jinno S, Chang S, Donskey CJ. Acquisition of spores on gloved hands after contact with the skin of patients with *Clostridium difficile* infection and with environmental surfaces in their rooms. Am J Infect Control 2012;40:556-8.
41. Randle J, Arthur A, Vaughan N. Twenty-four-hour observational study of hospital hand hygiene compliance. J Hosp Infect 2010;76:252-5.
42. Byers KE, Durbin LJ, Simonton BM, Anglim AM, Adal KA, Farr BM. Disinfection of hospital rooms contaminated with vancomycin-resistant *Enterococcus faecium*. Infect Control Hosp Epidemiol 1998;19:261-4.
43. Verity P, Wilcox MH, Fawley W, Parnell P. Prospective evaluation of environmental contamination by *Clostridium difficile* in isolation side rooms. J Hosp Infect 2001;49:204-9.
44. Otter JA, Cummins M, Ahmad F, van Tonder C, Drabu YJ. Assessing the biological efficacy and rate of recontamination following hydrogen peroxide vapour decontamination. J Hosp Infect 2007;67:182-8.
45. French GL, Otter JA, Shannon KP, Adams NM, Watling D, Parks MJ. Tackling contamination of the hospital environment by methicillin-resistant *Staphylococcus aureus* (MRSA): a comparison between conventional terminal cleaning and hydrogen peroxide vapour decontamination. J Hosp Infect 2004;57:31-7.
46. Morter S, Bennet G, Fish J, Richards J, Allen DJ, Nawaz S, et al. Norovirus in the hospital setting: virus introduction and spread within the hospital environment. J Hosp Infect 2011;77:106-12.
47. Goldenberg SD, Patel A, Tucker D, French GL. Lack of enhanced effect of a chlorine dioxide-based cleaning regimen on environmental contamination with *Clostridium difficile* spores. J Hosp Infect 2012;82:64-7.
48. Bonten MJ, Hayden MK, Nathan C, van Voorhis J, Matushek M, Slaughter S, et al. Epidemiology of colonisation of patients and environment with vancomycin-resistant enterococci. Lancet 1996;348:1615-9.
49. Sexton T, Clarke P, O'Neill E, Dillane T, Humphreys H. Environmental reservoirs of methicillin-resistant *Staphylococcus aureus* in isolation rooms: correlation with patient isolates and implications for hospital hygiene. J Hosp Infect 2006;62:187-94.
50. Boyce JM, Havill NL, Otter JA, Adams NM. Widespread environmental contamination associated with patients with diarrhea and methicillin-resistant *Staphylococcus aureus* colonization of the gastrointestinal tract. Infect Control Hosp Epidemiol 2007;28:1142-7.
51. Bhalla A, Pultz NJ, Gries DM, Ray AJ, Eckstein EC, Aron DC, et al. Acquisition of nosocomial pathogens on hands after contact with environmental surfaces near hospitalized patients. Infect Control Hosp Epidemiol 2004;25:164-7.
52. Mahamat A, MacKenzie FM, Brooker K, Monnet DL, Daures JP, Gould IM. Impact of infection control interventions and antibiotic use on hospital MRSA: a multivariate interrupted time-series analysis. Int J Antimicrob Agents 2007;30:169-76.
53. Wilcox MH, Fawley WN, Wigglesworth N, Parnell P, Verity P, Freeman J. 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.
54. Perugini MR, Nomi SM, Lopes GK, Belei RA, van der Heijden IM, Mostachio AK, et al. Impact of the reduction of environmental and equipment contamination on vancomycin-resistant enterococcus rates. Infection 2011;39:587-93.
55. Walters BA, Stafford R, Roberts RK, Seneviratne E. Contamination and cross-infection with *Clostridium difficile* in an intensive care unit. Aust N Z J Med 1982;12:255-8.
56. Kaatz GW, Gitlin SD, Schaberg DR, Wilson KH, Kauffman CA, Seo SM, et al. Acquisition of *Clostridium difficile* from the hospital environment. Am J Epidemiol 1988;127:1289-94.
57. Layton MC, Perez M, Heald P, Patterson JE. An outbreak of mupirocin-resistant *Staphylococcus aureus* on a dermatology ward associated with an environmental reservoir. Infect Control Hosp Epidemiol 1993;14:369-75.
58. Rampling A, Wiseman S, Davis L, Hyett AP, Walbridge AN, Payne GC, et al. Evidence that hospital hygiene is important in the control of methicillin-resistant *Staphylococcus aureus*. J Hosp Infect 2001;49:109-16.

59. Nourse C, Murphy H, Byrne C, O'Meara A, Breatnach F, Kaufmann M, et al. Control of a nosocomial outbreak of vancomycin resistant *Enterococcus faecium* in a paediatric oncology unit: risk factors for colonisation. Eur J Pediatr 1998; 157:20-7.
60. Falk PS, Winnike J, Woodmansee C, Desai M, Mayhall CG. Outbreak of vancomycin-resistant enterococci in a burn unit. Infect Control Hosp Epidemiol 2000;21:575-82.
61. Green J, Wright PA, Gallimore CI, Mitchell O, Morgan-Capner P, Brown DW. The role of environmental contamination with small round structured viruses in a hospital outbreak investigated by reverse-transcriptase polymerase chain reaction assay. J Hosp Infect 1998;39:39-45.
62. Wu HM, Fornek M, Schwab KJ, Chapin AR, Gibson K, Schwab E, et al. A norovirus outbreak at a long-term-care facility: the role of environmental surface contamination. Infect Control Hosp Epidemiol 2005;26:802-10.
63. Moore G, Ali S, FitzGerald G, Muzslay M, Atkinson S, Smith S, et al. Ward assessment of SmartIdeas Project: bringing source isolation to the patient. J Hosp Infect 2010;76:103-7.
64. Yokoe DS, Mermel LA, Anderson DJ, Arias KM, Burstin H, Calfee DP, et al. A compendium of strategies to prevent healthcare-associated infections in acute care hospitals. Infect Control Hosp Epidemiol 2008;29(Suppl 1):S12-21.
65. MacCannell T, Umscheid CA, Agarwal RK, Lee I, Kuntz G, Stevenson KB. Guideline for the prevention and control of norovirus gastroenteritis outbreaks in healthcare settings. Infect Control Hosp Epidemiol 2011;32:939-69.
66. Teltsch DY, Hanley J, Loo V, Goldberg P, Gursahaney A, Buckeridge DL. Infection acquisition following intensive care unit room privatization. Arch Intern Med 2011;171:32-8.
67. Illingworth E, Taborn E, Fielding D, Cheesbrough J, Diggle PJ, Orr D. Is closure of entire wards necessary to control norovirus outbreaks in hospital? Comparing the effectiveness of two infection control strategies. J Hosp Infect 2011;79:32-7.
68. Vernon MO, Hayden MK, Trick WE, Hayes RA, Blom DW, Weinstein RA, et al. Chlorhexidine gluconate to cleanse patients in a medical intensive care unit: the effectiveness of source control to reduce the bioburden of vancomycin-resistant enterococci. Arch Intern Med 2006;166:306-12.
69. Climo MW, Sepkowitz KA, Zuccotti G, Fraser VJ, Warren DK, Perl TM, et al. The effect of daily bathing with chlorhexidine on the acquisition of methicillin-resistant *Staphylococcus aureus*, vancomycin-resistant *Enterococcus*, and healthcare-associated bloodstream infections: results of a quasi-experimental multicenter trial. Crit Care Med 2009;37:1858-65.
70. Carling PC, Parry MM, Rupp ME, Po JL, Dick B, Von Beheren S. Improving cleaning of the environment surrounding patients in 36 acute care hospitals. Infect Control Hosp Epidemiol 2008;29:1035-41.
71. Goodman ER, Platt R, Bass R, Onderdonk AB, Yokoe DS, Huang SS. Impact of an environmental cleaning intervention on the presence of methicillin-resistant *Staphylococcus aureus* and vancomycin-resistant enterococci on surfaces in intensive care unit rooms. Infect Control Hosp Epidemiol 2008;29:593-9.
72. Rutala WA, Weber DJ. Are room decontamination units needed to prevent transmission of environmental pathogens? Infect Control Hosp Epidemiol 2011;32:743-7.
73. Boyce JM. New approaches to decontamination of rooms after patients are discharged. Infect Control Hosp Epidemiol 2009;30:515-7.
74. Shapey S, Machin K, Levi K, Boswell TC. Activity of a dry mist hydrogen peroxide system against environmental *Clostridium difficile* contamination in elderly care wards. J Hosp Infect 2008;70:136-41.
75. Nerandzic MM, Cadnum JL, Pultz MJ, Donskey CJ. Evaluation of an automated ultraviolet radiation device for decontamination of *Clostridium difficile* and other healthcare-associated pathogens in hospital rooms. BMC Infect Dis 2010; 10:197.
76. Stibich M, Stachowiak J, Tanner B, Berkheiser M, Moore L, Raad I, et al. Evaluation of a pulsed-xenon ultraviolet room disinfection device for impact on hospital operations and microbial reduction. Infect Control Hosp Epidemiol 2011;32:286-8.
77. Boswell TC, Fox PC. Reduction in MRSA environmental contamination with a portable HEPA-filtration unit. J Hosp Infect 2006;63:47-54.
78. O'Gorman J, Humphreys H. Application of copper to prevent and control infection. Where are we now? J Hosp Infect 2012;81:217-23.
79. Wagenvoort JH, Joosten EJ. An outbreak *Acinetobacter baumannii* that mimics MRSA in its environmental longevity. J Hosp Infect 2002;52:226-7.
80. Wagenvoort JH, Sluijsmans W, Penders RJ. Better environmental survival of outbreak vs. sporadic MRSA isolates. J Hosp Infect 2000;45:231-4.
81. Doultree JC, Druce JD, Birch CJ, Bowden DS, Marshall JA. Inactivation of feline calicivirus, a Norwalk virus surrogate. J Hosp Infect 1999;41:51-7.