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Universal decontamination of hospital surfaces in an occupied inpatient room with a continuous 405 nm light source

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SUMMARY

Background: Previous work has shown that a ceiling-mounted, 405 nm high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS) reduces bacterial contamination of environmental surfaces in a burns unit by between 27% and 75%. Examination of the efficacy of the light over extended exposure times and its probable mode of action was performed.

Aim: To ascertain the correlation between bacterial kill achieved on sampled surface sites around the burns unit and both irradiance levels of the 405 nm light, and exposure time.

Methods: Seventy samples were taken using contact agar plates from surfaces within an occupied side-room in the burns unit before, during, and after a seven-day use of the HINS-light EDS. This was repeated in three separate studies. Statistical analysis determined whether there was significant decrease in environmental contamination during prolonged periods of HINS-light treatment, and whether there was an association between irradiance and bacterial kill.

Findings: A decrease of between 22% and 86% in the mean number of surface bacteria was shown during the use of the HINS-light EDS. When the light ceased to be used, increases of between 78% and 309% occurred. There was no correlation between bacterial kill and irradiance levels at each sampling site but strong correlation between bacterial kill and exposure time.

Conclusion: Prolonged exposure to the HINS-light EDS causes a cumulative decontamination of the surfaces within a burns unit. The importance of exposure time and possible airborne effect over irradiance levels is emphasized.

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Introduction

Burns patients are exceptional in their propensity to dissipate large numbers of bacteria into the environment and their susceptibility to infection. This renders the burns unit an area liable to facilitate cross-contamination of hospital-acquired infections. The spread of multidrug-resistant organisms has serious consequences for patients, units, and hospitals. The burns unit is a uniquely challenging environment in which to address infection control. Transmission may be direct or indirect, with staff, the air, and surfaces all acting as potential vectors of transmission.

As antimicrobials become ineffective against resistant strains of bacteria, a growing focus has become environmental decontamination, as desiccated bacteria may survive for weeks on hospital surfaces [1–4]. Frequent cleaning of surfaces and hands, and the use of personal protective equipment (PPE) remain essential. However, surfaces are cleaned sporadically or ineffectively, with contamination fluctuating throughout the day [5].

The high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS) uses a narrow bandwidth of 405 nm light, which has extensive bactericidal effect, yet is safe for continuous use in a clinical environment [6]. Its effectiveness has been demonstrated in the hospital setting during treatment periods of up to five days, with decontamination of between 27% and 75%, over and above that achieved by standard infection control methods [7–9].

The dose received at any one site is a function of the exposure time and irradiance at that site, and this study aimed to determine which was more important. Furthermore, a universal effect around the room may indicate a contribution of the decontamination of airborne bacteria. Particles released from burns patients have been shown to be relatively small, making them airborne for substantial periods of time [8]. It was hypothesized that if the decontamination effect of the HINS-light EDS took place only on surface-associated bacteria, the irradiance received on any one site would be directly related to the amount of kill achieved at that surface. However, if the decontamination effect occurred mainly on airborne bacteria, which were then precipitated at random, little correlation between the amount of kill and levels of irradiance received at that site would be shown.

Methods

Setting

The studies took place in the burns inpatient unit at Glasgow Royal Infirmary, a 13-bed adult burns ward. Ethical approval was granted by NHS Scotland (West of Scotland Research Ethics Service). Throughout the studies, standard isolation and cleaning protocols continued. These included the wearing of PPE, hand hygiene, and daily room cleaning, with additional periodic wiping down of visibly contaminated surfaces with disinfectant wipes. The rooms were maintained at a negative pressure and incoming air was passed through high-efficiency particulate air (HEPA) filters.

The HINS-light EDS is a ceiling-mounted light-based continuous decontamination system. It emits a blue–violet (405 nm) light, with white LEDs incorporated to produce a soft pale violet light in conjunction with normal room lighting. Safety analysis had previously demonstrated the light emitted to be well within safe levels set by the American Conference of Governmental Industrial Hygienists [10]. It is powered by mains electricity and was timed to be on between 08:00 and 22:00.

Bacterial sampling

Bacterial monitoring was based on a previously described protocol [7–9]. Samples were taken using Baird Parker with egg yolk–telurite agar (BPA) 25 cm^2 contact agar plates, inoculated by pressing the agar surface on to the environmental surface, and incubated for 48 h at 37°C. BPA is a selective growth medium for staphylococcal-type organisms and therefore a good indicator of human contamination.

Studies were carried out with one HINS-light EDS on for seven days. A different patient occupied the isolation room during each of the three studies. The same protocol was repeated: (i) before-use samples were collected from selected sites around the room; (ii) the HINS-light EDS was switched on for seven consecutive days, during which time between one and three sets of during-use samples were collected; and (iii) after-use samples were taken two or three days after the HINS-light EDS exposure had been discontinued.

Seventy selected sites around the patient's room were sampled for each of the three studies (Table I). Environmental sampling was always performed at 08:00, as previous work had shown this to be the most consistent time to carry

Table I
Sampling sites and mean irradiance and percentage reduction following seven-day use of a single HINS-light EDS

No. of samples	Mean irradiance (mW/cm^2)	Mean % reduction after 7 days
2	0.0030	89.4%
2	0.0023	93.5%
2	0.0070	−70.9%
4	0.0023	81.4%
4	0.0160	88.8%
6	0.0027	90.8%
6	0.0337	77.6%
4	0.0035	−200.0%
2	0.0096	93.2%
4	0.0562	94.7%
10	0.0160	77.1%
6	0.2310	79.4%
1	0.0072	87.8%
2	0.0025	97.9%
4	0.0885	84.2%
4	0.0805	94.8%
4	0.0850	77.7%
3	0.0560	56.1%
Mean % reduction		60.7%
Pearson correlation of mean irradiance and mean % reduction		0.171%[a]

HINS-light EDS, high-intensity narrow-spectrum light environmental decontamination system.
[a] Not statistically significant.

out environmental surface sampling in the burns isolation room setting [6].

Patients

Patient A was aged 48 years with a 12% total body surface area (TBSA) scald. He had had a protracted stay of two months due to respiratory infections. Patient B was aged 38 years with a 50% TBSA flame burn. At the time of study, 40% TBSA had been excised and covered with skin graft or synthetic substitute. Patient C was aged 65 years with a 19% TBSA flame burn. At the time of study ~11% TBSA remained unhealed. The study protocol for each patient is summarized in Figure 1.

Irradiance measures

A radiant power meter and photodiode detector (Oriel Instruments, Stratford, CT, USA) was used to measure the irradiance, in mW/cm^2, received at each of the sampling sites around the isolation room. Measurements were taken with the blue–violet 405 nm light of a single HINS-light EDS switched on, and other light eliminated.

Statistical analysis

Following enumeration of bacterial colony-forming units (cfu), the mean cfu per plate for each study was calculated. Percentage reduction in bacterial count during use and percentage increase after use were also calculated. Further analysis was performed on log-transformed counts using Minitab V16. Analysis of variance (ANOVA) and Dunnett's post-hoc comparisons were done to examine for significant differences between before-use and each of the during-use periods for each study, and between after-use and the final during-use period for each study. $P < 0.05$ was considered statistically significant.

The 70 contact-plate sample sites were grouped into 18 sample areas (e.g. bedside table, six samples; see Table II). For each area, the mean percentage reduction achieved following seven days' use of the HINS-light EDS was calculated. A scatter graph was produced to determine the relationship between irradiance and mean percentage reduction after seven days' exposure to each area. Pearson's correlation coefficients demonstrated the significance of any interaction between irradiance and percentage bacterial kill.

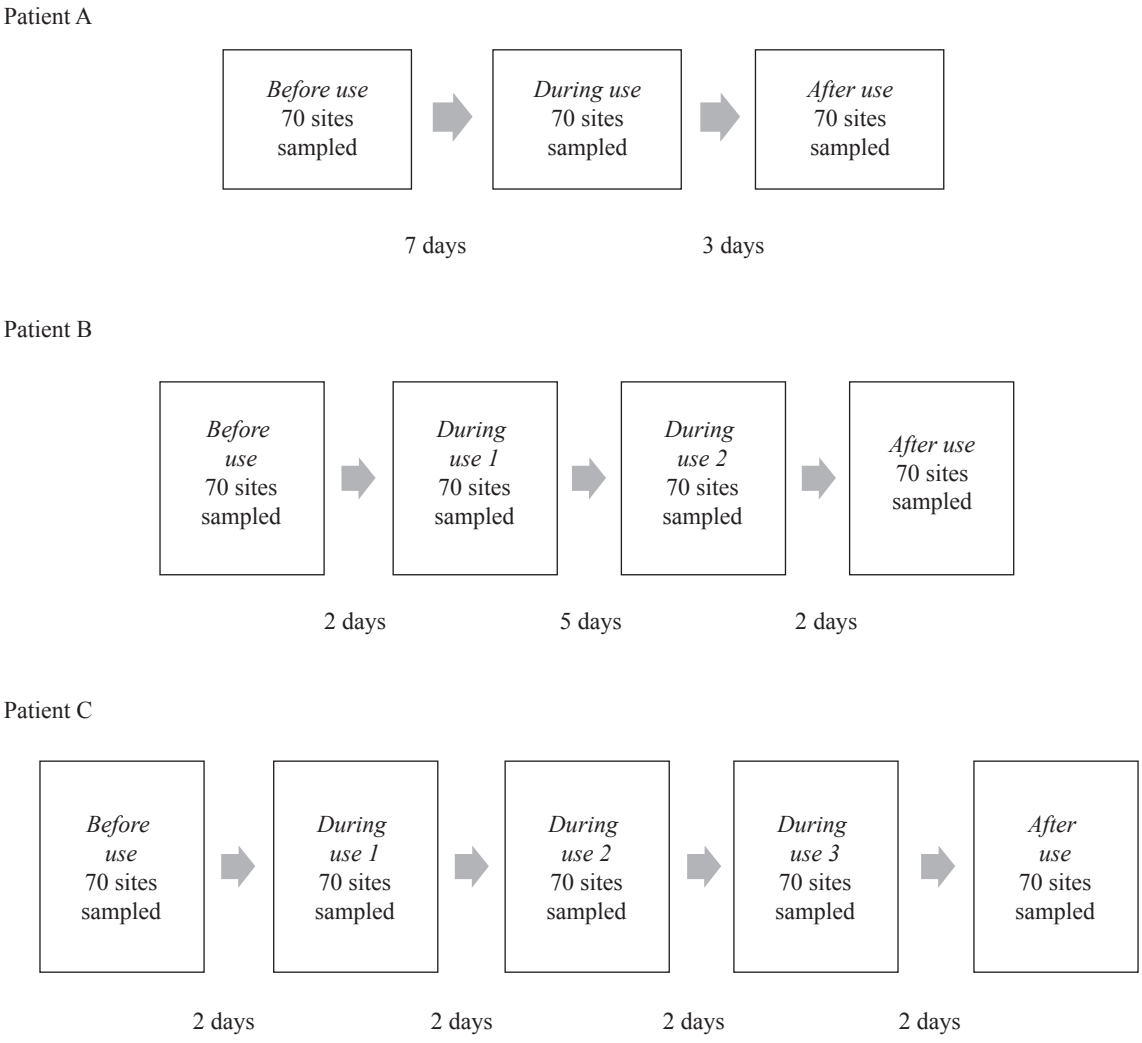

Figure 1. Protocols for three studies investigating the effect of a single high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS) in an occupied inpatient room.

Table II
Statistical analysis for the seven-day use of a single HINS-light EDS in three different patient rooms

% change	Patient A	Patient B	Patient C
% decrease in mean bacterial count			
during use 1	22% ($P = 0.999$)	34% ($P = 0.014$)	53% ($P < 0.001$)
during use 2	n/a	74% ($P < 0.001$)	69% ($P < 0.001$)
during use 3	n/a	n/a	86% ($P < 0.001$)
Significant reduction	No	Yes	Yes
% increase in mean bacterial count after use	120% ($P < 0.001$)	78% ($P = 0.036$)	309% ($P < 0.001$)
Significant increase	Yes	Yes	Yes

HINS-light EDS, high-intensity narrow-spectrum light environmental decontamination system; n/a, not applicable.
P-values are based on log-transformed data.

Results

Decontamination effect over different time-periods

A decrease was observed in the mean bacterial count when a single HINS-light EDS was used for any time between two and seven days. Subsequent increases in bacterial contamination were demonstrated in all three studies when the EDS was switched off again.

The studies, displayed as graphs, show the mean bacterial cfu/plate during each sampling session (Figure 2). Decontamination increases with increased exposure time: this is particularly apparent in the study in patient C's room. Statistically significant decreases in mean bacterial counts were produced during the studies of patients B and C, but not of patient A. Significant increases were demonstrated when EDS use was discontinued in all three studies (Table I).

Irradiance levels and decontamination effect

Mean percentage bacterial reduction in each area and correlation with the irradiance received at that area are summarized in Table I. Figure 3 is a scatter graph demonstrating poor correlation between irradiance and the mean percentage bacterial reduction at each sampling site. Statistical analysis confirmed no significant correlation (Pearson $r = 0.171$; $P = 0.497$). There is a consistent reduction of between 50% and 100% regardless of irradiance at that site with use of the HINS-light EDS.

Discussion

Burns units are a key area of focus for infection control as outbreaks of hospital-acquired infection are numerous and devastating, and burns patients are particularly susceptible to cross-contamination [11,12]. Technologies such as ultraviolet light, portable HEPA filters, and fogging with hydrogen peroxide vapour have attempted to tackle environmental decontamination [13–17]. Although effectively bactericidal, these methods are restricted to sporadic use in unoccupied, sealed rooms. This is time-consuming and costly, requiring an operator and period when the room is out of commission. Furthermore, bacterial load quickly returns to pre-treatment levels following cessation of use [18,19]. The HINS-light EDS uses visible light at a safe irradiance, and can thus be used continuously throughout the day. Another continuous technology under development is the release of essential oil vapour, although no clinical studies have been carried out to date [20]. Other technologies include products with antimicrobial coatings such as silver, but these do not achieve the universal decontamination effect seen with HINS-light EDS [21,22].

All three studies demonstrated a decrease in bacterial bio-burden following HINS-light EDS use of between two and seven days, with a cumulative effect clearly demonstrated in the study in patient C's room: 53% decrease after two days; 69% decrease after four days; and 86% after seven days. The bacterial kill achieved was comparable, in these studies where one HINS-light EDS was used, to that seen in previous studies where two were used in the same room [8,9]. This suggests that one HINS-light EDS may be as effective as two, provided it is used for a sufficient time-period. The mass effect of the HINS-light EDS over the whole room has previously been demonstrated in a study where an EDS was mounted in one-half of a room, and the relative decrease in bio-burden compared between the two sides of the room [7]. A similar effect was seen in both halves of the room, although it was greater in the half where the HINS-light EDS was sited.

The measurement of irradiance levels (a function of dose) in the current study supports this theory, and suggests a possible bactericidal effect on airborne bacteria. Simultaneous evaluation of percentage bacterial reduction and the irradiance at each sampling site demonstrated that no correlation was found between the two. The irradiance received on surfaces is small (between 0.0000023 and 0.000231 W/cm^2), whereas the exposure time (in seconds) is greater during several days of exposure. As dose is a function of both measures, the irradiance received at any one site is less important than the time of exposure. In a system designed to be used continuously, high doses can therefore be achieved at low irradiance levels. In addition, bacteria are suspended in the air almost indefinitely depending on size of the particles before being precipitated on to surfaces [23]. This puts them in closer proximity to the EDS than those bacteria on surfaces, and therefore exposed to higher doses of 405 nm light.

No attempt was made to isolate the bacteria in the environment, other than the use of BPA contact agar plates, which is an indicator of human-originating pathogens. Preliminary studies using broader-spectrum agars yielded too dense a population of bacterial cfu to count in many circumstances, as

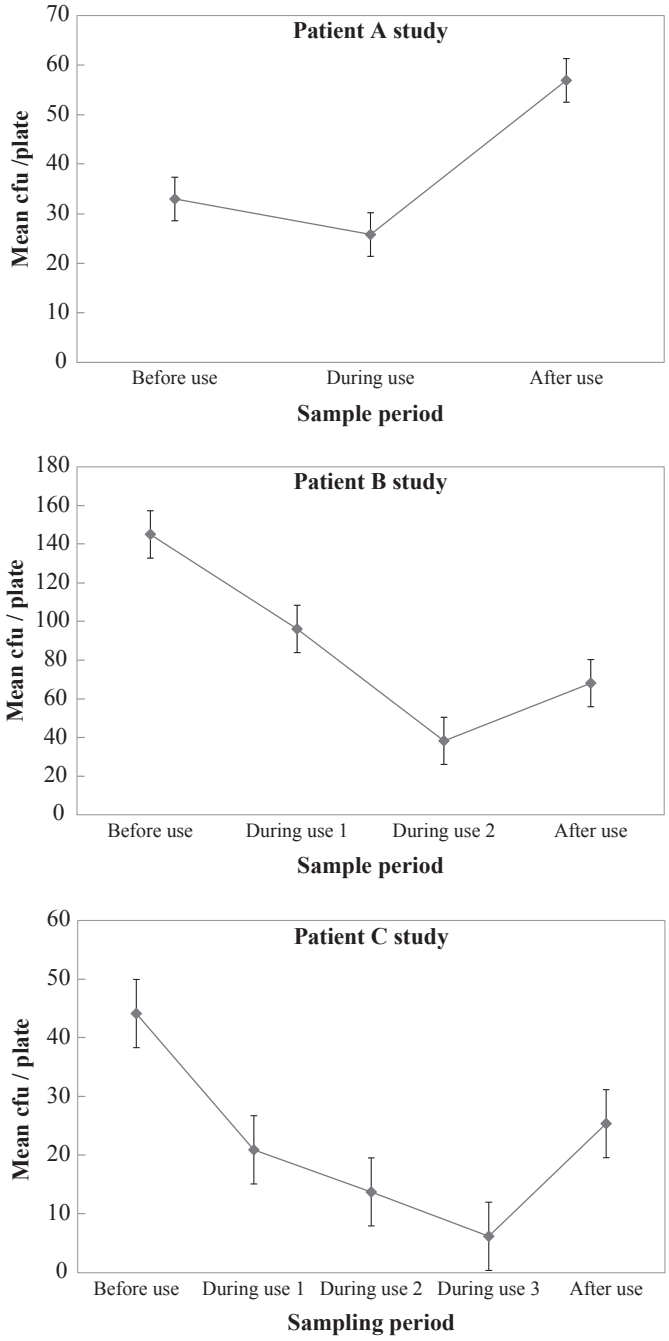

Figure 2. Mean bacterial counts on surfaces within the rooms of patients A, B and C before, during, and after use of the high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS) ($N = 70$). Error bars denote standard errors. cfu, colony-forming units.

well as a higher proportion of bacteria of unknown significance. Laboratory studies on bacteria pertinent to burns patients have demonstrated that Gram-positive bacteria (including multidrug-resistant *Staphylococcus aureus* and *Streptococcus pyogenes*) are inactivated by HINS-light at a faster rate than are Gram-negative bacteria (including *Acinetobacter baumannii* and *Pseudomonas aeruginosa*), although all bacteria tested demonstrated significant reductions after 2 h exposure and complete kill within <6 h exposure using the

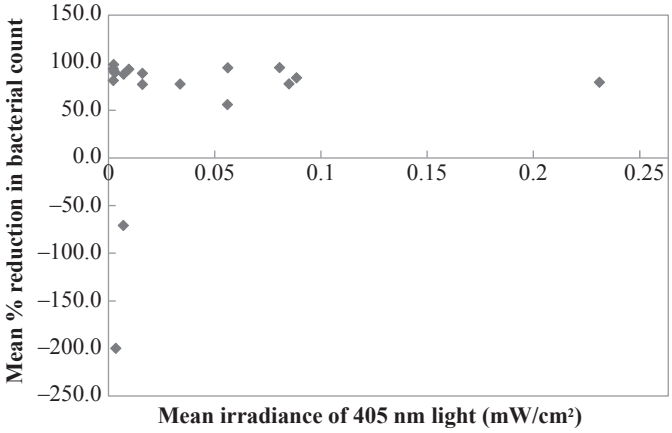

Figure 3. Mean percentage reduction in surface bacteria following seven days' exposure to the high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS) at each sampling site, correlated with the mean irradiance at each sampling site.

same ceiling-mounted HINS-light that was used in the current studies [6,24].

Comparisons between studies on different patients are difficult due to huge variability in bacterial dispersal between burns patients. However, the studies on patients B and C achieved similar reductions to those previously reported, although the study on patient A did not show a statistically significant reduction [7–9]. However, examination of the after-use bacterial counts from the study reveal them to be considerably higher than both the during-use and before-use counts: a 120% increase is shown following cessation of the EDS use. Considering the effect of the EDS that has been demonstrated repeatedly during previous inpatient studies, this suggests that the before-use bacterial counts were unusually low in this study. An explanation for this is not available from the contemporaneous information gathered. The most likely scenarios are that either an extra clean was performed prior to the before-use sample collection, or that the patient mobility and activity around the room increased significantly following before-use sample collection. Previous work showed that there is more variation of bacterial levels when samples are taken at times of increased activity within rooms, a factor that is almost impossible to control in a clinical environment, but which is mitigated against by examination of ANOVA plots for significant outliers [8].

In addition, at the time of sampling, much of patient A's burns had healed, with only 11% TBSA still unhealed, possibly contributing to lower than expected before-use samples. Furthermore, both patients B and C were receiving treatment for chest sepsis; therefore environmental contamination may also have been from a respiratory source. None had an active burn wound infection at the time of the study, although with burns of this size and age the wounds will likely be colonized with a range of Gram-positive and -negative bacteria, which are not routinely quantified or isolated unless clinically relevant. These differences between patients highlight why in the design of all our studies we have used patients as their own controls with a before, during and after model to avoid intra-patient comparisons. Although the studies were only carried out on rooms containing three patients, the significant

decreases in environmental contamination during use of the HINS-light EDS were comparable with multiple previous studies where use of the HINS-light EDS in the burns unit resulted in an average reduction in environmental bacterial load of between 27% and 86% [7—9]. The current study provides further evidence from several thousand contact plate samples that the use of the HINS-light EDS reduces environmental bacterial load over and above standard hospital cleaning protocols within the burns unit environment.

With the introduction of any novel technology such as the HINS-light EDS it is important to consider the possible impact on patient wellbeing and comfort. There has been an increasing awareness of the importance of lighting conditions on factors such as mood and awareness. Normal operation of the EDS, as applied during this study, involved synchronizing on—off timing with normal ward lighting so as not to disturb patient sleep. It is, however, also the case that lighting conditions experienced prior to sleeping are important and this is especially the case with exposure to blue light which can interfere with circadian rhythm, thereby increasing alertness and interfering with sleep onset. It is now known that the eye possesses photosensitive retinal ganglion cells (pRGCs) whose function is to modulate diverse physiological responses to light, including circadian physiology and pupil constriction [25]. The pRGCs have an absorption maximum (i.e. peak sensitivity) at ~480 nm. As HINS-light uses 405 nm violet light to achieve the bactericidal effect, this is far below the 480 nm blue light value; thus, HINS-light should have little effect on the pRGCs and their associated physiological effects.

In conclusion, a ceiling-mounted 405 nm wavelength light source is an effective method of environmental decontamination, as demonstrated in the challenging environment of the burns unit inpatient room. It is safe for continuous use in the presence of patients and staff, and the bactericidal effect increases with treatment time. A universal decrease in bioburden is seen on surfaces throughout the room, despite ongoing activities within the room and the variation in irradiance levels on the surfaces. This suggests either the variation in irradiance is outweighed by exposure time, or the possible airborne effect on suspended bacteria.

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Conflict of interest statement

The intellectual property rights of the HINS-light EDS belong to the University of Strathclyde. As co-inventors, M.M., S.J.M., and J.G.A. have a share of intellectual property rights. All HINS-light EDS made by the University are for research purposes only. However, since this work was carried out, there has subsequently been commercial uptake of this technology in the USA from which the University and the co-inventors will benefit.

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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] 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.
[3] Bonilla HF, Zervos MJ, Kauffman CA. Long-term survival of vancomycin-resistant Enterococcus faecium on a contaminated surface. Infect Control Hosp Epidemiol 1996;17:770—1.
[4] Hirai Y. Survival of bacteria under dry conditions; from a viewpoint of nosocomial infection. J Hops Infect 1991;19:191—200.
[5] Schabrun S, Chipchase L. Hospital equipment as a source of nosocomial infection: a systemic review. J Hosp Infect 2006;63:239—45.
[6] Maclean M, MacGregor SJ, Anderson JG, Wooley GA. Inactivation of bacterial pathogens following exposure to light from a 405-nm LED array. Applied Environ Microbiol 2009;75:1932—7.
[7] Maclean M, Booth MG, Anderson JG, MacGregor SJ, Woolsey GA, Coia JE, et al. Continuous decontamination of an intensive care isolation room during patient occupancy using 405 nm light technology. J Hosp Prevention 2013;14:176—81.
[8] Bache SE, Maclean M, MacGregor SJ, Anderson JG, Gettinby G, Coia JE, et al. Clinical studies of the high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS), for continuous disinfection in the burn unit inpatient and outpatient settings. Burns 2012;38:69—76.
[9] Maclean M, MacGregor SJ, Anderson JG, Woolsey GA, Coia JE, Hamilton K, et al. Environmental decontamination of a hospital isolation room using high-intensity narrow-spectrum light (HINS-light). J Hosp Infect 2010;76:247—51.
[10] American Conference of Governmental Industrial Hygienists (ACGIH). Threshold limit values (TLVs) & biological exposure indices. Cincinnati: Signature Publications; 2007.
[11] Rafla K, Tredget EE. Infection control in the burn unit. Burns 2011;37:5—15.
[12] Falagas ME, Thomaidis PC, Kotsantis IK, Sgouros K, Samonis G, Karageorgopoulos DE. Airborne hydrogen peroxide for disinfection of the hospital environment and infection control: a systematic review. J Hosp Infect 2011;78:171—7.
[13] Memarzadeh F, Olmsted RN, Bartley JM. Applications of ultraviolet germicidal irradiation disinfection in health care facilities: effective adjunct, but not stand-alone technology. Am J Infect Control 2010;38:S13—24.
[14] Otter JA, French GL. Survival of nosocomial bacteria and spores on surfaces and inactivation by hydrogen peroxide vapour. J Clin Microbiol 2009;47:205—7.
[15] Bartels MD, Kristoffersen K, Slotsberg T, Rohde SM, Lundgren B, Westh H. Environmental methicillin-resistant S. aureus (MRSA) disinfection using dry-mist-generated hydrogen peroxide. J Hosp Infect 2008;66:360—8.
[16] Taneja N, Biswal M, Kumar A, Edwin A, Sunita T, Emmanuel R, et al. Hydrogen peroxide vapour for decontaminating air-conditioning ducts and rooms of an emergency complex in northern India: time to move on. J Hosp Infect 2011;78:200—3.
[17] Boswell TC, Fox PC. Reduction in MRSA environmental contamination with a portable HEPA-filtration unit. J Hosp Infect 2006;63:47—54.
[18] Otter JA, Puchowicz M, Ryan D, Salkeld JA. Feasibility of routinely using hydrogen peroxide vapour to decontaminate rooms in a busy United States hospital. Infect Control Hosp Epidemiol 2009;30:574—7.
[19] Hardy KJ, Gossain S, Henderson N, Drugan C, Oppenheim BA, Gao F, et al. Rapid recontamination with MRSA of the environment of an intensive care unit after decontamination with hydrogen peroxide vapour. J Hosp Infect 2007;66:360—8.

[20] Edwards-Jones V, Buck R, Shawcross SG, Dawson MM, Dunn K. The effects of essential oils on methicillin-resistant Staphylococcus aureus using a dressing model. Burns 2004;30:772—7.
[21] Taylor L, Phillips P, Hastings R. Reduction of bacterial contamination in a healthcare environment by silver antimicrobial technology. J Infect Prevent 2009;10:6—11.
[22] Hedin G, Rynback J, Lore 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.
[23] Tang JW, Eames YLI, Chan PKS, Ridgway GL. Factors involved in the aerosol transmission of infection and control of the ventilation in healthcare premises. J Hosp Infect 2006;64:100—14.
[24] Bache SE, Maclean M, Anderson JG, Gettinby G, Coia JE, MacGregor SJ, et al. Laboratory inactivation of healthcare-associated isolates by a visible HINS-light source and its clinical application in the burns unit. Burns 2011;37(Suppl. 1):S6.
[25] Foster RG. The 'third' photoreceptor system of the eye — photosensitive retinal ganglion cells. Eur Ophthalmic Rev 2009;2:84—6.