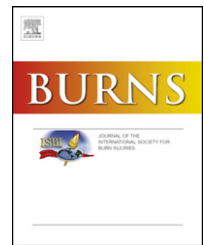


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# Clinical studies of the High-Intensity Narrow-Spectrum light Environmental Decontamination System (HINS-light EDS), for continuous disinfection in the burn unit inpatient and outpatient settings<sup>☆</sup>

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## ABSTRACT

Infections are the leading cause of morbidity and mortality in burn patients and prevention of contamination from exogenous sources including the hospital environment is becoming increasingly emphasised. The High-Intensity Narrow-Spectrum light Environmental Decontamination System (HINS-light EDS) is bactericidal yet safe for humans, allowing continuous disinfection of the environment surrounding burn patients. Environmental samples were collected from inpatient isolation rooms and the outpatient clinic in the burn unit, and comparisons were then made between the bacterial contamination levels observed with and without use of the HINS-light EDS. Over 1000 samples were taken. Inpatient studies, with sampling carried out at 0800 h, demonstrated a significant reduction in the average number of bacterial colonies following HINS-light EDS use of between 27% and 75%, ( $p < 0.05$ ). There was more variation when samples were taken at times of increased activity in the room. Outpatient studies during clinics demonstrated a 61% efficacy in the reduction of bacterial contamination on surfaces throughout the room during the course of a clinic ( $p = 0.02$ ). The results demonstrate that use of the HINS-light EDS allows efficacious bacterial reductions over and above that achieved by standard cleaning and infection control measures in both inpatient and outpatient settings in the burn unit.

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## 1. Introduction

The sequelae of burn wound infections can be devastating to the burn patient, causing progression of burn depth, graft loss,

increased scarring, and subsequent sepsis, leading to multi-organ failure, and death or a significantly prolonged hospital stay. Due to advances in resuscitation and early excision regimes, it is now estimated that 75% of deaths in patients

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with burns over 40% of the total body surface area (TBSA) are related to sepsis from burn wound infection or other infectious complications and/or inhalation injury [1,2]. Destruction of the skin barrier, a state of immunosuppression, and large wound areas of nutrient rich, bacteria harbouring eschar render burn patients unique in their tendency to disperse bacteria into the surrounding environment and their susceptibility to developing infections [3]. The spread of healthcare-associated infections (HAI) is an increasing worry as new strains of multi-drug resistant bacteria emerge, with a diminishing number of effective antimicrobials, leading to severe sepsis and outbreaks in burn units. Efforts to improve hand hygiene and limit the use of broad-spectrum antibiotics are important in reducing nosocomial infection rates on the burn unit, but the impact of environmental cleanliness is also becoming increasingly acknowledged [1]. The environment surrounding burn patients has been shown to be a reservoir for pathogens, and a potential source of cross-contamination between patients [4,5]. Bacteria surviving on inanimate surfaces for weeks or months can contaminate patients or healthcare workers, who become colonised, spreading HAI amongst patients [4–8].

Novel methods of cleaning and decontamination within hospitals have been developed, including hydrogen peroxide vapour (HPV), ultraviolet light (UV-light), and super-oxidised water [9–11]. These enable efficient temporary disinfection of the environment, but the effect is only transient and within a matter of hours the number of microorganisms begins to return to pre-decontamination levels [12]. Furthermore, they are time-consuming, requiring the removal of patients from the room, which limits their usefulness in a busy burn unit, and particularly in a burns outpatient clinic. The High-Intensity Narrow-Spectrum light Environmental Decontamination System (HINS-light EDS) is a ceiling-mounted lighting unit, which allows continuous decontamination of the clinical environment, killing bacteria through photodynamic inactivation while being safe to humans [13]. The decontamination technology uses a narrow bandwidth of visible blue-violet light, with a peak output at 405 nm. This has previously been demonstrated *in vitro* to kill a wide spectrum of pathogenic bacteria, including meticillin-resistant *Staphylococcus aureus* (MRSA), meticillin-sensitive *S. aureus* (MSSA), *Pseudomonas aeruginosa*, *Streptococcus pyogenes* and *Acinetobacter* sp. in a dose-dependent and species-dependent fashion [14,15].

The present study focused on assessing the use of the HINS-light EDS in two different burn unit environments: an isolation room housing a burn inpatient, and the burn outpatient clinic, through which several patients pass each day, so total decontamination of the room between patients is almost impossible to achieve. The propensity of burn patients to disperse pathogens into the environment means that environmental bacterial contamination is higher on the burn unit than most other hospital wards, which increases the risk of healthcare workers contaminating their hands and uniforms, and transmitting HAI to other patients in their care. This study assessed whether use of the HINS-light EDS had a significant effect on reducing the levels of environmental bacterial contamination in both the inpatient and outpatient settings, therefore potentially aiding in reducing the risk of

cross-contamination of infectious pathogens from the environment to patients.

## 2. Materials and methods

### 2.1. Setting

Glasgow Royal Infirmary (GRI) has a dedicated 13-bed burn unit, arranged as six single isolation rooms, one three-bed high dependency bay, one four-bed open bay and an outpatient clinic area. Intubated patients are treated in a separate general intensive care unit. Throughout all studies, GRI burn unit infection control and isolation policies were adhered to [16]. These state that disposable gloves and aprons are donned by staff on entering isolation rooms and hands are decontaminated before and after entering the room with alcohol gel or soap and water. Appropriate ethical approval was obtained.

All air-conditioning units in the ward contain High Efficiency Particulate Air (HEPA) filters and isolation rooms are maintained at a negative pressure. Domestic staff clean inpatient isolation rooms daily, usually around 1100 h, using chlorine-based detergents. Table tops and locker tops are wiped down periodically by nursing staff using hard surface disinfectant wipes. Following vacation of the room, a “terminal clean” is carried out. The outpatient clinic room is cleaned before the start of a clinic, around 0800 h by domestic staff, using chlorine-based detergents. The clinic nurse cleans the worktop, examination couch and any equipment used, using hard surface disinfection wipes between each patient.

### 2.2. HINS-light EDS

HINS-light EDS prototype units were installed in the burn unit. Two units were installed in the ceiling of two test inpatient isolation rooms and one unit in the ceiling of the smaller outpatient clinic room. Light was generated from a matrix of light-emitting diodes (LEDs), emitting a narrow bandwidth of blue-violet light centred on 405 nm wavelength. White LEDs are also incorporated into the HINS-light EDS such that the illumination effect is predominantly white. The HINS-light EDS units were connected to mains electricity and simply switched on and off at the wall. Minimal staff training was required and there was no disruption of the normal hospital routine. The HINS-light EDS is designed to treat an area of approximately 10 m<sup>2</sup>, with sufficient intensity to cause inactivation of exposed bacteria. Rigorous safety analysis has been carried out to standards set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the American Conference of Governmental Industrial Hygienists (ACGIH). It has shown that the intensity levels used in the hospital are well below the threshold limit for any adverse effects occurring, as established by ACGIH [17–19].

### 2.3. Bacteriological methods

Methods were based on previous work evaluating the efficacy of the HINS-light EDS in clinical environments [13]. Environmental bacterial samples were collected from surfaces in each

room using 25 cm<sup>2</sup> Baird Parker with egg yolk telurite contact agar plates (BPA plates; Cherwell Laboratories Ltd, Bicester, UK), by the same researcher (SEB). Contact plate sampling, which enables microorganisms to be directly collected on an agar surface, was selected as the most appropriate method of assessing bacterial counts on environmental surfaces. Sample collection using broad spectrum contact agar plates, such as tryptone soya or blood agar yielded plates with too many bacterial colony forming units (cfu) to accurately enumerate in preliminary studies. Therefore, Baird Parker agar, a selective agar for staphylococcal bacteria, and an accepted marker of hospital environmental contamination in studies of hospital cleanliness, was used in the present study [20]. Staphylococci are known to survive on environmental surfaces for significant periods of time and can be transmitted between patients, staff and the environment [20,23–25]. Studies have shown the association between levels of environmental contamination with *S. aureus* and the size of the burn wound [21]. Furthermore, analysis of GRI burn wound swabs from the previous two years showed that MSSA and MRSA accounted for approximately 50% of all positive routine admission and twice-weekly surveillance wound cultures. It was therefore felt that an agar that selected for the commonest pathogens was justified, using the most accurate environmental sampling technique available.

Between forty and fifty sites on frequently-touched surfaces were identified around each room being studied, and bacterial samples were collected by directly pressing the contact agar plates onto the sampling site, with samples being taken from the same sites each time. After collection, contact plates were incubated at 37 °C (98.6 °F) for 48 h and the number of bacterial cfu on each contact agar plate was enumerated. Raw counts were statistically analysed by a chartered statistician.

#### 2.4. Inpatient studies

The first part of the study was carried out in an inpatient isolation room containing a 49-year-old male, Patient A, with

45% TBSA full thickness (third degree) flame burns, one month after admission. Routine wound surveillance swabs had isolated MRSA and *P. aeruginosa*, and mixed coliforms immediately before and during the study. Forty sampling sites ( $n = 40$ ) were identified around the room (Table 1). For each study, contact plate samples were collected during three phases: before the HINS-light EDS was in use (*pre-HINS*); after the HINS-light EDS had been on for two days (*during-HINS*); and after the HINS-light EDS had been switched off for a further two days (*post-HINS*).

*Pre-HINS* sampling was first carried out at 0800 h. Immediately after this, the HINS-light EDS was switched on and remained on for 14 h during daylight hours, for two consecutive days. *During-HINS* samples were collected at 0800 h from the same 40 sites following this two-day use of HINS-light EDS. The HINS-light EDS was then switched off for two consecutive days, after which time *post-HINS* samples were collected at 0800 h, again from the same 40 sampling sites. This study was repeated over three consecutive weeks using identical methods with the same patient in the same room but with sample collection at 1500 h, and then 2200 h in order to assess the efficacy of the HINS-light EDS when samples were collected at differing times of day.

To address reproducibility, the 0800 h sampling protocol was repeated in rooms occupied with two further patients. Patient B was a 35-year-old female with 25% TBSA mixed deep dermal and full thickness (second and third degree) flame burn, housed in the same isolation room that Patient A had previously occupied. Her routine wound surveillance swabs had isolated MRSA and mixed coliforms. Patient C was a 55-year-old female with 40% TBSA full thickness (third degree) burn in a different room of the unit, with a mirror-image layout. Her routine wound surveillance swabs had isolated MRSA and *P. aeruginosa*. Ten extra sampling sites were included in the studies on Patients B and C, along both bed rails, as these two patients were bed-bound, and the bed rails were constantly upright, and an important potential site of contamination (Table 1) ( $n = 50$ ).

**Table 1 – Environmental sampling sites used in inpatient and outpatient rooms on the burn unit, with the number of samples taken from each site stated.**

Inpatient isolation rooms		Outpatient clinic room	
Sampling site	No. samples	Sampling site	No. samples
Bed sheet	4	Waste bin	4
Locker top	2	Apron dispenser	4
Ledge	6	Glove dispenser	2
Table	4	Sink area	6
Foot of bed rail	3	Dressings trolley	4
Drip stand	2	Dressings shelves	8
Patient chair	2	Worktop	6
Light switches	2	Lamp	2
Door handles	3	Examination couch	6
Air con supply	2	Patient chair	4
Waste bins	4	Power supply	2
Sink area	4	Light switch	1
Bed cot sides	10 (Studies B and C)	Door handle	1
Total	40 (50)	Total	50

## 2.5. Outpatient studies

Fifty sampling sites were identified on frequently touched surfaces around the outpatient clinic room ( $n = 50$ ) (Table 1). Before clinic samples were collected at 0830 h, shortly after the room had been cleaned. Clinics ran between 0900 h and 1600 h, and between seven and 12 burns patients were seen per clinic. After clinic samples were collected at 1630 h from the surfaces, immediately adjacent to where the 50 sites had been sampled before clinic. Samples were collected 30 min before and 30 min after two clinics when the HINS-light EDS was switched off (HINS off) and two clinics when the HINS-light EDS was switched on continually for 8 h during the clinic (HINS on).

## 2.6. Statistical analysis

The pre-HINS and post-HINS sampling periods in the inpatient room studies acted as controls for each during-HINS sampling period. A rise in the average number of bacterial cfu in the post-HINS samples indicated that reductions seen in during-HINS samples were not due to a general decrease in bacterial shedding by the patient over the two days, but the effect of the HINS-light EDS. For the outpatient clinic investigation, the study was repeated during two clinics in the absence of the HINS-light EDS. This acted as a control to show the expected increase in contamination levels usually seen throughout the course of a typical burns outpatient clinic. Statistical software (Minitab version 15) was used and a log-transformation was found to normalise data and equalise variances when analysing cfu data. For the inpatient studies, analysis of variance (ANOVA) and Tukey pair-wise comparisons were undertaken. The cfu counts per plate were compared between the three periods, pre-HINS, HINS and post-HINS. A 95% confidence interval (CI) was calculated for the differences obtained between the means of the three sampling periods. For the outpatient studies, the differences in cfu count before clinic and after clinic was compared with and without the use of the HINS-light EDS. Results were displayed using mean values and statistical testing was carried out at the 5% significance level ( $p \leq 0.05$ ).

## 3. Results

### 3.1. Inpatient studies

Results from the five inpatient studies are summarised in Table 2. Samples collected in Patient A's room at 0800 h demonstrated a statistically significant reduction of 43% in the average number of Baird Parker agar isolated bacterial cfu following two days of HINS-light EDS use ( $p = 0.043$ ). After the light had been switched off for two days, bacterial numbers recovered to pre-decontamination levels, a 48% rise, ( $p = 0.040$ ). Sample collection at 1500 h demonstrated a 45% reduction in bacterial contamination following two days of HINS-light EDS use, which was not statistically significant ( $p = 0.252$ ). The study with samples collected at 2200 h, produced a 39% reduction in the number of cfu

**Table 2 – Results and statistical analysis of the data on the effects of the HINS-light EDS on Baird Parker isolated bacterial contamination levels in a burns unit isolation room (i) occupied with three different patients (A–C) and (ii) when environmental samples are taken at three different times of day from the room occupied by Patient A.**

Time of sample collection	Patient	Sample number (n)	Mean plate counts [cfu/plate] (standard error, SE)			Mean cfu reduction by EDS use (95% CI)	% reduction by EDS use	Sig. reduction by EDS use (p < 0.05)	Mean cfu increase after EDS switched off (95% CI)	% increase after EDS switched off	Sig. increase after EDS switched off (p < 0.05)
			Pre-HINS	During-HINS	Post-HINS						
0800 h	A	40	206.7 (29.5)	117.8 (29.5)	173.8 (29.5)	88.9 (5.7, 183.5)	43	Yes (p = 0.043)	56.0 (–38.6, 150.6)	48	Yes (p = 0.040)
1500 h	A	40	165.4 (28.2)	90.6 (28.2)	107.8 (28.2)	74.8 (15.6, 165.2)	45	No (p = 0.252)	17.2 (–73.1, 107.6)	19	No (p = 0.149)
2200 h	A	40	132.1 (25.4)	80.9 (25.4)	129.6 (25.4)	51.2 (–30.1, 132.5)	39	No (p = 0.054)	48.7 (–32.6, 130.0)	60	Yes (p = 0.005)
0800 h	B	50 <sup>a</sup>	22.5 (3.4)	5.6 (3.4)	10.1 (3.4)	16.9 (6.4, 27.4)	75	Yes (p < 0.0001)	4.5 (–6.1, 15.0)	80	Yes (p < 0.0001)
0800 h	C	48 <sup>b</sup>	25.3 (8.1)	18.5 (8.1)	17.2 (8.1)	6.8 (–18.6, 32.1)	27	Yes (p = 0.022)	–1.3 (–24.0, 26.6)	–7	No (p = 0.692)

<sup>a</sup> Ten extra sampling sites on cot sides included in study with Patient B ( $n = 50$ ).

<sup>b</sup> Ten extra sampling sites on cot sides were included in study with Patient C, but two sites excluded on statistical grounds ( $n = 48$ ), see Section 3.



following two days of HINS-light EDS use, again not statistically significant ( $p = 0.054$ ). After the light had been switched off again for two days there was a statistically significant 60% rise in bacterial contamination ( $p = 0.005$ ).

The results from 0800 h sampling carried out in the room occupied by Patient B confirmed these findings. A significant 75% reduction in the average number of cfu was achieved following two days of HINS-light EDS use ( $p < 0.0001$ ). When the light was switched off again, the average number of cfu rose by 80% ( $p < 0.0001$ ). In the study involving Patient C, the average number of bacterial cfu increased slightly from 25.2 to 25.5 cfu following the use of the HINS-light EDS. However, the statistical analysis indicated an exceptionally unusual observation associated with the two samples from the sink site in the *during-HINS* sampling period. From the least squares fitted model, the standardised residual was estimated to be 8.1 and the pattern associated with the sink site was inconsistent with all other sites. A further analysis was undertaken excluding samples from the sink site ( $n = 48$ ) and this demonstrated a significant 27% reduction from 25.3 to 18.5 cfu ( $p = 0.022$ ). There was a small (7%) decrease in the average number of cfu when the light was switched off again for two days, but this was not statistically significant ( $p = 0.692$ ).

### 3.2. Outpatient studies

Results of the outpatient studies are summarised in Table 3. For studies both with and without HINS-light EDS intervention, 50 samples were collected at the start and end of two clinics. The combined results were analysed using a block design to take account of the findings from the two clinics. The difference between clinics with and without HINS-light EDS was then compared. The mean number of Baird Parker agar isolated bacterial cfu per plate before *HINS off* clinics was 8.1 cfu, and rose to 22.2 cfu during the course of the clinics. This increase in contamination levels was expected, due to the dispersal of bacteria into the air and onto environmental surfaces during dressing changes and wound care of between seven and 12 patients a day. During *HINS on* clinics, the mean number of bacterial colonies at the start of the clinic was 6.5 cfu, and only rose to 12.0 cfu by the end of the clinic. This indicated that the amount of additional contamination of the room, released throughout the course of a burn outpatient clinic, was reduced by an average of 8.6 cfu per plate by the HINS-light EDS. This was the equivalent of a significant 61% efficacy ( $p = 0.02$ ).

## 4. Discussion

The consequences of HAI for burn patients and the burn unit as a whole are serious and multiple. Prevention, identification and eradication of nosocomial infections is thus becoming an increasingly important area of burn care research [1]. The vital importance of infection control and isolating burn patients has been recognised for many decades [22]. More recently, the role of the burn unit environment in harbouring pathogens including MRSA that can survive on dry surfaces for weeks or months has been acknowledged [23–25]. A 42% transmission rate of MRSA to the hands of healthcare workers who had no direct patient contact, as a result of touching contaminated surfaces has previously been demonstrated [26,27]. The reduction of the environmental reservoir of nosocomial infection is imperative and the current study adds further evidence of the role that the HINS-light EDS may have in achieving this.

Previously published data on the use of the HINS-light EDS as a method of decontamination for hospital inpatient environments, demonstrated reductions in the total number of environmental staphylococcal-type bacteria of between 56% and 86%, when samples were collected at 0800 h [13]. The current study logically develops that work by investigating the reduction achieved at three different times of day, in rooms housing different burn patients, and examining specifically its use in both the inpatient and outpatient setting in one of the most important areas for infection control in the hospital: the burn unit. In the burn inpatient isolation room, the HINS-light EDS has proved to have a significant benefit in reducing environmental contamination levels by between 27% and 75% on samples taken at 0800 h, over and above the hospital's current stringent infection control and hygiene measures. This effect was achieved with an exposure of 14 h a day for two consecutive days, with the light being switched off overnight, in order that it did not affect the patient's sleep.

Differences in the levels of bacterial contamination during daylight hours – likely due to direct contamination by patients or staff, or cleaning by domestic staff – is reflected on sampling at 1500 h and 2200 h when there was much more variability of activity within the room. There is no logical reason to suspect that the HINS-light EDS would be any less effective at these times of day than at 0800 h: indeed it might be expected that 0800 h sampling would produce the least dramatic reduction in contamination levels as the HINS-light EDS had been switched off overnight immediately before samples were

**Table 3 – Results and statistical analysis of data on the effect of use of the HINS-light EDS on Baird Parker isolated bacterial contamination levels during burns outpatient clinics.**

HINS-light EDS on/off during clinics	Sample number (n)	Mean plate counts (cfu/plate)		Mean increase in cfu/plate during clinic	Reduction in increase of cfu with EDS on (95% CI)	Efficacy of reduction in increase of cfu with EDS on (95% CI)	Sig. reduction in increase of cfu with EDS on
		Before clinic	After clinic				
HINS off clinics	100	8.1	22.2	14.1	8.6 (1.4, 15.8)	61.3% (10%, 113%)	Yes ( $p = 0.02$ )
HINS on clinics	100	6.5	12.0	5.5			

taken. The main advantage to sampling at 0800 h is that the activity levels in the room had been relatively constant overnight before the samples were taken, as the patient was asleep in bed and staff had minimal input, preventing large surges or reductions in numbers of bacteria. This allowed a steady level of bacteria and a reliable estimate of contamination levels to be achieved when samples were taken. Although a similar pattern of reduction was demonstrated at the other times of day, there seemed to be considerable variability in staff and patient activity. This was thought to affect contamination levels and produce results that were not significant. For future studies involving environmental contamination, 0800 h sampling is recommended as a model to achieve the most reproducible conditions possible so that the effect of an intervention can be seen.

An incidental observation was the variability in bacterial deposition demonstrated between the three inpatients. Patient A produced higher environmental contamination, with *pre-HINS* levels of 206.7 cfu per plate. Patients B and C had starting populations of 22.5 and 25.3 cfu per plate respectively. There are several possible explanations for this: Patient A was ambulant around the room during the studies, although he was confined to his room. Furthermore he had loose motions on several occasions during the study, and although no infective cause for this was found, and it was assumed to be secondary to antibiotic treatment, it meant he had to go to the en-suite bathroom several times during the day and night. He had the highest % TBSA burns, although comparable with Patient C, and all three patients had MRSA isolated from their wounds. He was also noted to have very dry flaky skin and hair, and was consequently likely to be a relatively heavy shedder of squames when compared to other patients. The exceptional counts observed for one patient at the sink location was thought to arise from gross direct contamination immediately prior to sampling. The contamination must have taken place within the room as agar plates were sealed before being removed from the room for incubation. The level of contamination may have arisen from a number of activities but none could be identified with any confidence.

The outpatient clinic was used as an example of a communal patient room in the burn unit, where it was recognised that organisms may be passed from one patient, onto a surface and thence directly to the next patient in the room. As expected, the starting numbers of bacteria were lower than in isolation rooms housing a patient constantly over long periods of time, however a significant rise in the numbers of bacteria on surfaces at the end of the clinic was seen, despite these being patients with relatively small or partly healed burns. Even though the HINS-light EDS was only on for a total of 8 h, and the room was relatively much cleaner than the inpatient rooms to begin with, significant reductions in the increase of environmental bio burden released during a clinic were still demonstrated, with a 61% efficacy. This may lead to the use of the HINS-light EDS in other communal patient rooms, such as the physiotherapy room or bathroom, where decontamination of all surfaces is unachievable between each patient due to time limitations.

Previous studies into the bactericidal nature of 405 nm HINS-light have demonstrated the effect on a wide range of Gram-positive and Gram-negative organisms [15], and

although levels of staphylococcal organisms were used as the marker for the current study it is important to bear in mind that levels of Gram-negative organisms will also have been reduced through use of the HINS-light EDS. The HINS-light EDS has a unique advantage in its ability to be used continuously throughout daylight hours in inpatient isolation rooms, and constantly through the day and night in other areas of the burn unit. It is efficient, simple to run, unobtrusive, and is neither dependent on staff compliance nor requires any additional staff time to implement. It must be stressed that the HINS-light EDS is not designed to replace standard cleaning routines, and the importance of wiping down surfaces, washing hands and using gloves and gowns remains. Rather, it augments current infection control methods. The HINS-light EDS is thought to have its main effect against the ubiquitous bacterial reservoirs dispersed into the air during periods of activity in the room, such as bed changes or burn dressing changes, settling on hard surfaces around the source. When surfaces are touched directly by a patient or healthcare worker, the density of organisms is more likely to be greater, so a longer exposure to the HINS-light EDS is required to decontaminate. It is probable that routine physical cleaning would take place before this, so the HINS-light EDS is not a replacement for excellent physical cleanliness in burn units, but has still been shown to maintain consistently lower levels of environmental bacteria than that achieved by physical cleaning alone.

The study of the inpatient rooms was limited in that it only examined the effect of the HINS-light EDS for a relatively short period of between 8 h and 14 h a day on two consecutive days. It is not yet known if leaving the system on for longer periods of time (for example overnight in the outpatient clinic, or at lower levels during the night in the inpatient rooms, or for more consecutive days) would continue to reduce overall levels of bacteria, or if the contamination levels would plateau after a time: this is an area of interest for future studies. Although HINS-light has wide bactericidal activity, as demonstrated *in vitro* [14,15], this study focused on the reduction of staphylococcal type organisms, which account for over 50% of wound contaminations and infections in the GRI burn unit and give an indication of organisms which have originated from a human source, and are thus potential pathogens. While the experiment could be repeated using an agar that would allow estimation of total viable counts of all bacteria, the large number of cfu arising from some surfaces would also make accurate enumeration very difficult. Future work may address the impact of the HINS-light EDS on Gram-negative organisms, by sampling using an agar that selects for Gram-negatives alone. Further laboratory studies on the effect of the HINS-light EDS on bacteria subject to various stressing factors, or the formation of biofilms would also be of interest.

These studies provide convincing evidence that this novel technology achieves a reduction in environmental contamination levels. To demonstrate that this translates into a reduction in colonisation and infection in burn patients, in the context of the huge numbers of variables in the patients, burns and treatment administered, would be the ideal next stage, but would probably require a multi-centre trial over months or years. Such difficulties account for the paucity of evidence that many other established infection control methods and

disinfection technologies have achieved reductions in infection rates. Rather, a logical and pragmatic approach has been adopted that a cleaner environment and cleaner hands are likely to result in the transfer of fewer numbers of bacteria to patients, and thus generate fewer infections. The impact of surface disinfection in hospitals cannot be dismissed due to the lack of outcome trials, as HAI as an outcome has reasonably low frequency, so any potential trial would suffer from low statistical power [28,29].

The findings of this work provide evidence that the HINS-light EDS is an effective treatment for the reduction of environmental bacterial contaminants in different clinical situations on the burn unit. The percentage reduction observed for counts taken at different times during the day were broadly comparable for the room containing the same patient. In contrast, the percentage reduction at the same time of day for rooms housing different patients varied considerably. This is not unexpected, as contamination levels are known to differ depending on the patient, the size of burn and the patient environment [30]. A total of 34 different burn patients were treated in the outpatient clinic room, yet the presence of the HINS-light EDS in the room while they were being treated significantly reduced the environmental bacterial contamination they produced. These results suggest that for burn patients, the HINS-light EDS can potentially make an important additional contribution to the reduction of nosocomial infections which originate from transmission of pathogens from the environment, by significantly reducing the contamination of the surrounding environment.

### Conflict of interest statement

The intellectual property rights of the HINS-light EDS belong to the University of Strathclyde. As co-inventors, MM, SJM and JGA have a share of the intellectual property rights. SEB, GGJEC and IT have no claim to intellectual property. The University has made all HINS-light EDS for research purposes only and no commercial company manufactures or sells this technology.

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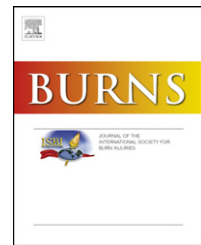
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# Quantifying bacterial transfer from patients to staff during burns dressing and bed changes: Implications for infection control

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## ABSTRACT

Routine nursing activities such as dressing/bed changes increase bacterial dispersal from burns patients, potentially contaminating healthcare workers (HCW) carrying out these tasks. HCW thus become vectors for transmission of nosocomial infection between patients. The suspected relationship between %total body surface area (%TBSA) of burn and levels of bacterial release has never been fully established.

Bacterial contamination of HCW was assessed by contact plate samples ( $n = 20$ ) from initially sterile gowns worn by the HCW during burns patient dressing/bed changes. Analysis of 24 gowns was undertaken and examined for relationships between %TBSA, time taken for activity, and contamination received by the HCW.

Relationships between size of burn and levels of HCW contamination, and time taken for the dressing/bed change and levels of HCW contamination were best described by exponential models. Burn size correlated more strongly ( $R^2 = 0.82$ ,  $p < 0.001$ ) than time taken ( $R^2 = 0.52$ ,  $p < 0.001$ ), with levels of contamination received by the HCW. Contamination doubled with every 6–9% TBSA increase in burn size.

Burn size was used to create a model to predict bacterial contamination received by a HCW carrying out bed/dressing changes. This may help with the creation of burn-specific guidelines on protective clothing worn by HCW caring for burns patients.

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## 1. Introduction

Advances in fluid resuscitation, organ support, and early excision and grafting have all improved survival rates following a severe burn [1]. However, this has also had the effect of shifting the cause of morbidity and mortality away

from hypovolemia and towards sepsis. Sepsis is a primary risk factor of mortality following a burn [2,3]. It is now estimated that in patients with burns over 40% total body surface area (TBSA), 75% of all deaths are related to infection and/or inhalation injury [1]. Following a severe burn, physical, non-specific and specific immune defences are all affected, leading to a state of immunosuppression. Coupled with large bacteria-

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harbouring wounds, this renders burns patients both susceptible to infection and potent dispersers of bacteria [4]. The consequences of nosocomial propagation can be felt throughout the entire hospital, increasing costs and the risk of outbreaks of multidrug-resistant bacteria on the burns unit and beyond [5].

Transmission of infection between burns patients mainly occurs through airborne transmission or direct and indirect contact [1,6]. Routine nursing activity may create periods of increased bacterial dispersal into the air and onto surfaces and other individuals present in the vicinity. The present study examines the contamination of healthcare workers (HCW) resulting from burn wound dressing changes, which are often coupled with bed sheet changes.

Dressing changes on even small non-burn wounds create airborne dispersal of bacteria [7]. Bed sheet changes have also been shown to liberate bacteria into the air [8]. In the 1970s, attempts were made to link the size of a burn and the airborne dispersal of *Staphylococcus aureus* during a dressing change, which implied that the size of the burn was related to levels of bacteria found on settle plates over a period of days [9]. More recently, it was shown that 31% of dressing changes on methicillin resistant *S. aureus* (MRSA) positive burns patients liberated the organism into the air [10].

HCW uniforms are a potential reservoir of infection [11–13], and their contamination can be directly attributed to patients [14,15]. Not only can bacteria be transferred from burns patients to uniforms during dressing changes, but also laboratory simulations have demonstrated that these bacteria can be transferred from the uniform to patients [17,18]. Despite this, there is little consensus for the appropriate protective attire to be worn by HCW carrying out dressing changes on burns patients. In a survey of US burns units, only 24% of units required full protective coverage on entering a patient's room and changing a dressing [19]. UK guidelines are similarly vague and not burns-specific [20–22]. Quantitative data on key issues may help in their development. In this context, the current study was set up to address the hypothesis that the level of contamination received by a HCW would be related to the size of the burn and the time taken for the dressing change.

## 2. Materials and methods

### 2.1. Setting

Quantification of HCW contamination was carried out during burn dressing changes. For patients with larger burns, the dressing change would usually also incorporate a bed sheet change while rolling the patient to apply bandages (hereafter termed 'dressing/bed change'). Data including age of burn, recent routine wound swab results, time taken for the dressing/bed change to take place and the %TBSA burn were recorded for each patient. Patients were treated according to standard practice on our burns unit. We aim for early excision and split thickness skin autograft or coverage with a dermal substitute in all deep dermal and full thickness burns. Patients with superficial burns, or those deemed too sick for surgical intervention are managed conservatively with dressings and

topical agents. Patients with burn wounds over 10 days old were excluded from the study.

### 2.2. Sample standardisation

To ensure that samples were taken from a standardised baseline, HCW were asked to don sterile, impermeable, disposable full-body gowns over their uniforms prior to performing dressing/bed changes. This was done to eliminate natural variations in bacterial contamination between different HCWs before the beginning of the dressing/bed change. It also provided a consistent sampling material, which was preferable to sampling from a variety of textures and surfaces including cotton and skin. Gowns were thus worn by the HCW only to facilitate the study design and sampling objectives. Usually, disposable plastic aprons would be worn over uniforms as routine bed/dressing changes are carried out. All HCW maintained standard hand hygiene by decontaminating hands and putting on fresh disposable gloves before entering the patient's room to carry out the nursing activity. Thereafter, with the exception of wearing disposable gowns rather than disposable plastic aprons over uniforms, the HCW carried out the dressing/bed change in the usual manner. Gloves were removed and hands washed following the dressing change and gown sampling, before leaving the room.

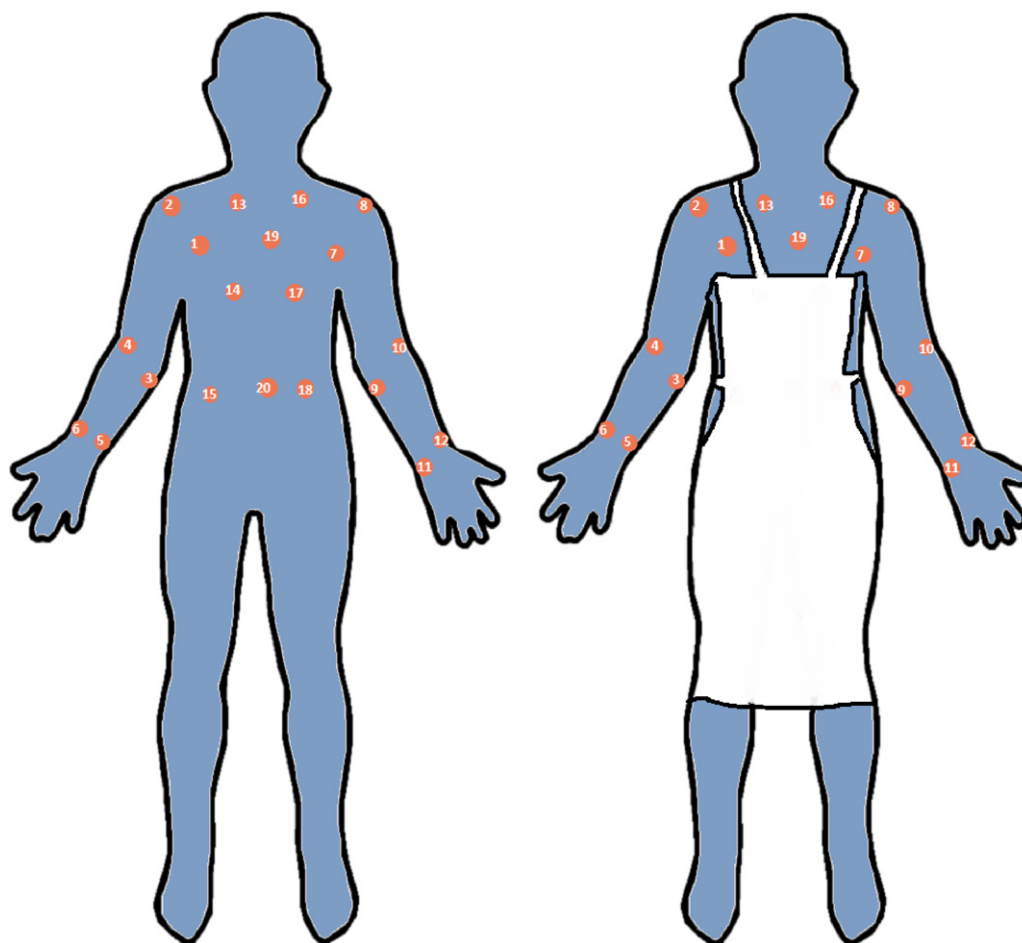
Samples were taken from the two most 'involved' HCW carrying out the dressing change, each of whom would usually stand either side of the bed and carry out undressing and redressing of wounds alongside one another. For smaller burns, one HCW often carried out the dressing change alone, and only one set of samples was obtained. Sampling during dressing/bed changes on any one patient was only carried out once.

### 2.3. Sampling sites

Following the dressing/bed change, and while the HCW was still wearing the disposable gown, and remained in the patient's room, the gown was sampled. To estimate the contamination that would be received during a dressing/bed change by a HCW who had not been wearing an apron, samples were taken from 20 sites across the front of the gown. The 20 'no apron' sites are illustrated in Fig. 1. Of note, the sites are all across the front of the gown, as it was the aim of the study to collect samples from areas that were likely to become most contaminated during dressing/bed changes. In order to estimate the protection afforded had a disposable plastic apron been worn, a subset of 15 'with apron' sites were analysed separately. These excluded five sampling sites on the chest and abdomen that would normally be covered by a disposable apron. These are also demonstrated in Fig. 1.

### 2.4. Bacteriological methods

Samples were taken from the 20 sites using 25 cm<sup>2</sup> Baird Parker Agar (BPA) contact plates that were pressed firmly against the sampling site for approximately 2 s, by the same investigator (SEB). BPA allows for selective isolation of staphylococcal-type organisms, which are an accepted marker of bacteria originating from a human source [23]. A selective



**Fig. 1 – Diagram to demonstrate sampling sites on the front of HCW gowns. The image on the left shows the positions of all 20 sampling sites (termed ‘no apron’ sites). The image on the right highlights the 15 sampling sites left exposed if the HCW had been wearing an apron (termed ‘with apron’ sites). The two sets of samples were analysed separately.**

agar was chosen over a non-selective agar as preliminary studies indicated that non-selective agar yielded too many bacterial colony-forming units (cfu) per agar plate to accurately enumerate. Contact agar plates allow direct sample collection from the contaminated gowns, and enable accurate reproduction of sampling due to the defined surface area of the agar plates. Sample plates were incubated at 37 °C for 48 h before enumeration.

The time taken for the dressing/bed change to take place was measured from when the HCW entered the patient’s room to commence the dressing/bed change (the point at which they would usually don a plastic apron). It finished at the point when the dressing and bed change (if that was also being carried out) was completed, when they would usually remove their apron and gloves prior to leaving the room. At this point the gown was sampled. Any further activities, including tidying the room, assisting with feeding, or brushing the patient’s hair or teeth were not included in the time taken for dressing/bed change. The gown was sampled before these extra activities took place. This meant that the contamination measured was that received only during the dressing/bed change. It was not possible to separate the dressing and bed change components of the activity, as the bed sheet change

was often integrated into the dressing change when the patient was rolled for application of bandages. We intended to mimic real-life situations as much as possible and did not want to inconvenience the patient or HCW, or prolong the activity by carrying out separate dressing changes and bed changes, during what can be a distressing and uncomfortable time.

## 2.5. Statistical analysis

In undertaking the study consideration was given to power and sample size required for the purposes of the regression and correlation analysis. It was estimated that measurements would be required on bacterial cfu and associated %TBSA for a minimum of 10 patients in order to have in excess of 90% statistical power to detect a correlation of 0.9 with 95% confidence. A random sample size of between 10 and 15 patients was planned with replicate cfu measurements being observed on up to two HCW carrying out dressing/bed changes per patient.

HCW bacterial contamination was expressed as mean number of bacterial cfu per 25 cm<sup>2</sup> agar plate, or mean cfu/plate. For each sampling session this was calculated for all 20

'no apron' sites, and also for the 15 'with apron sites', excluding those 5 sites that would have been covered by a disposable plastic apron, had one been worn. Statistical analysis was carried out using NCSS Windows Version 7 software. Relationships were examined for between three variables: %TBSA and HCW contamination; time taken for the dressing/bed change and HCW contamination; %TBSA and time taken for the dressing/bed change. Separate analysis was carried out on all 20 'no apron' sites, and on the 15 'with apron' sampling sites. Mathematical modelling was used to identify equations which best described the three relationships. These were used to predict the contamination a HCW would receive during dressing/bed change of a burn patient by %TBSA. The coefficient of determination,  $R^2$  was used to measure how well the model fitted to the observed data and  $p < 0.05$  was considered significant.

### 3. Results

#### 3.1. Patient demographics and wound information

Samples were collected from the gowns of 24 HCW carrying out dressing changes on 15 different patients, with a mean burn size of 19%TBSA (range 1–51%TBSA). Mean age of patient was 39 years (range 19–85 years). Samples were taken a mean of 6.4 days after the burn (range 2–10 days). Mean time taken for the dressing change was 45 min (range 10–90 min). The most common organism identified on routine wound swabs was *S. aureus*. *Bacillus* sp., coliforms, and *Streptococcus* sp. were also commonly isolated. Results are summarised in Table 1.

#### 3.2. Relationship between time taken for dressing/bed change and %TBSA

A significant relationship was demonstrated between the time taken for the dressing/bed change to take place and the size of the burn (%TBSA). This was explained by a linear correlation (coefficient of determination,  $R^2 = 0.76$ ;  $p < 0.001$ ). This is demonstrated in Fig. 2.

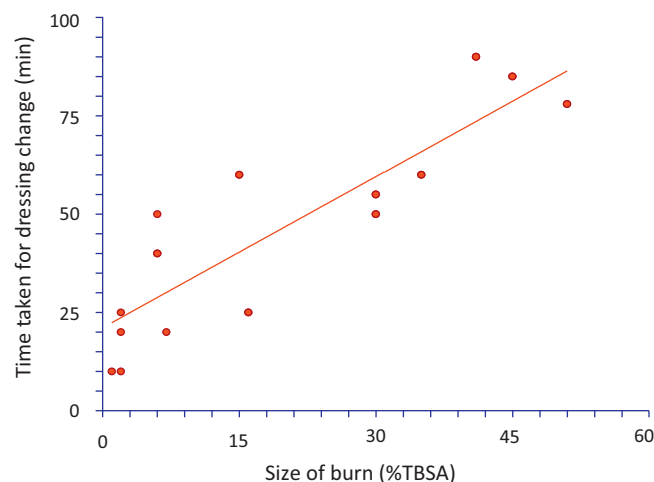


Fig. 2 – Chart demonstrating linear relationship between %TBSA of the burn, and time taken in min to complete the dressing/bed change.

#### 3.3. Analysis of 20 'no apron' sites

The variation in contamination received by a HCW during a dressing/bed change when 20 'no apron' sampling sites were analysed was examined in relation to %TBSA of the burn and time taken for the dressing/bed change. Both relationships were explained by exponential models. These were as follows:

Relationship between HCW contamination and %TBSA (coefficient of determination,  $R^2 = 0.82$ ;  $p < 0.001$ ):

$$\text{Mean cfu/plate} = 8.59 \text{ Exp}^{0.080 \times \%TBSA}$$

Relationship between time taken in min for dressing/bed change and HCW contamination (coefficient of determination,  $R^2 = 0.52$ ;  $p < 0.002$ ):

$$\text{Mean cfu/plate} = 17.44 \text{ Exp}^{0.034 \times \text{time taken in min}}$$

These curves are illustrated in Fig. 3. Both charts demonstrate an exponential relationship between the variable (%TBSA or time taken for the dressing/bed change to take place) and the contamination received by the HCW. However, although they are both significant relationships, time taken correlates less strongly than %TBSA as shown by the lower  $R^2$ . %TBSA is a more accurate predictor of HCW contamination than time taken for the dressing/bed change to take place.

#### 3.4. Analysis of 15 'with apron' sites

The variation in contamination received by a HCW during a dressing/bed change when 15 'with apron' sampling sites was examined in relation to %TBSA of the burn and time taken for the dressing/bed change. Both relationships were explained by exponential models. These were as follows:

Relationship between HCW contamination and %TBSA (coefficient of determination,  $R^2 = 0.86$ ;  $p < 0.001$ ):

$$\text{Mean cfu/plate} = 2.05 \text{ Exp}^{0.110 \times \%TBSA}$$

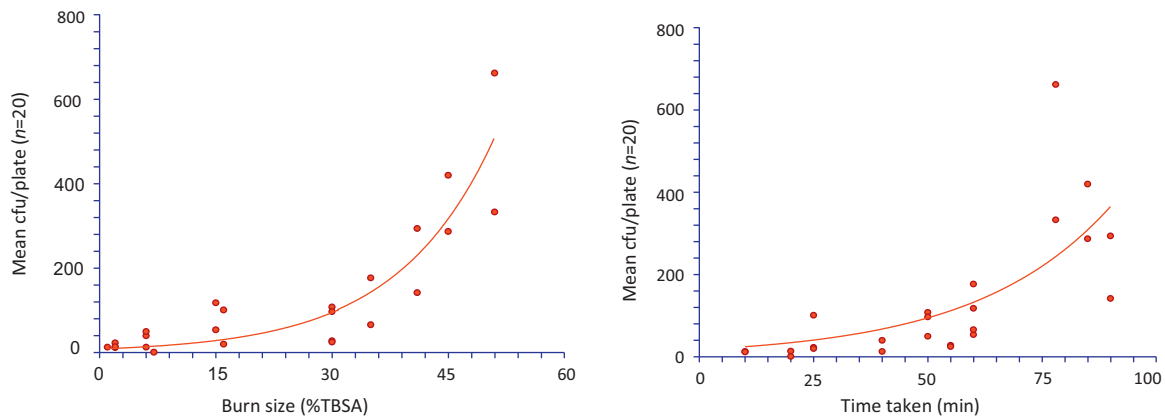
Relationship between HCW contamination and time taken in min for dressing/bed change (coefficient of determination,  $R^2 = 0.44$ ;  $p = 0.007$ ):

$$\text{Mean cfu/plate} = 15.98 \text{ Exp}^{0.034 \times \text{time taken in min}}$$

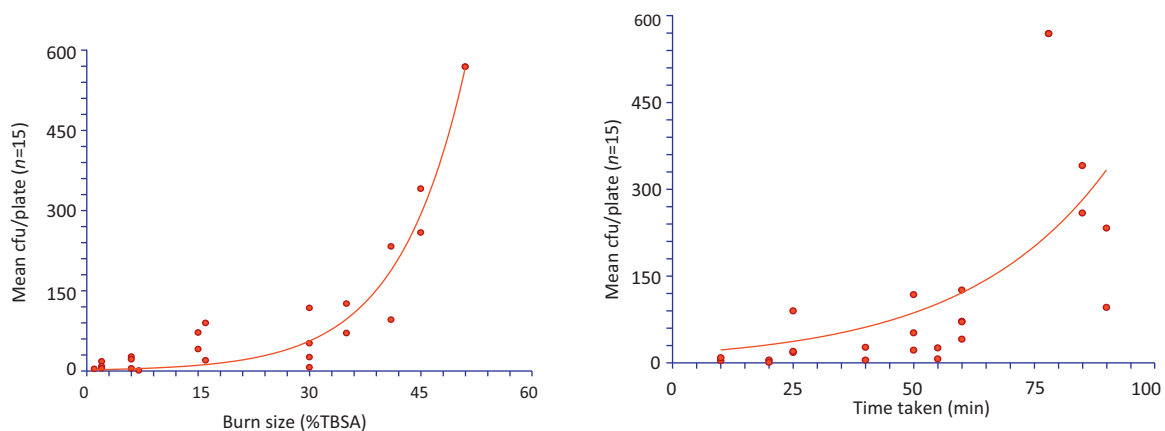
**Table 1 – Summary of all 24 studies of HCW carrying out dressing/bed changes on 15 patients. Details were taken of: size of burn as % TBSA; site of burn (UL, upper limb; LL, lower limb; AT, anterior trunk; PT, posterior trunk; and HN, head and neck); depth of burn (SPT, superficial partial thickness; DPT, deep partial thickness; and FT, full thickness); age of burn in days; the %TBSA that has been harvested as a split thickness skin graft; the %TBSA that has been covered by autograft or dermal substitute; recent wound swabs; whether a dressing change and bed change took place; time taken for the dressing/bed change; and the mean cfu per plate for all 20 ‘no apron’ sites, and the 15 ‘with apron’ sites.**

Study no.	Patient	Pt age (years)	%TBSA burn	Site of burn	Depth of burn	Age of burn (days)	%TBSA donor site harvested	%TBSA covered in skin or substitute	Wound swab results	Dressing change	Bed sheet change	Time taken (min)	Mean cfu/plate 20 sites	Mean cfu/plate 15 sites
1	A	19	1	UL	DPT	6	0	0	Not taken	Yes	No	10	23	18
2	B	24	2	AT	SPT	6	0	0	Not taken	Yes	No	25	12	9
3	C	26	2	AT	SPT	6	0	0	Not taken	Yes	No	10	14	5
4	D	44	2	UL	SPT	10	0	0	Not taken	Yes	No	20	13	4
5	E	34	6	AT	DPT/FT	8	6	6	<i>Staphylococcus aureus</i> , <i>Bacillus</i> sp.	Yes	No	40	40	27
6	E	34	6	AT	DPT/FT	8	6	6	<i>S. aureus</i> , <i>Bacillus</i> sp.	Yes	No	40	13	5
7	F	33	6	LL	DPT	9	6	6	coliforms, <i>S. aureus</i> , Gp G <i>Streptococcus</i> , <i>Bacillus</i> sp.	Yes	No	50	1	1
8	G	22	7	UL	SPT	8	0	0	coliforms, <i>S. aureus</i> , Gp A <i>Streptococcus</i> , <i>Bacillus</i> sp.	Yes	No	20	50	22
9	H	45	15	UL, AT, HN	FT	6	9	15	<i>S. aureus</i> ., <i>Bacillus</i> sp., <i>Clostridium perfringens</i>	Yes	Yes	55	54	41
10	H	45	15	UL, AT, HN	FT	6	9	15	<i>S. aureus</i> ., <i>Bacillus</i> sp., <i>C. perfringens</i>	Yes	Yes	55	50	21
11	I	85	16	AT	DPT/FT	120	0	0	<i>S. aureus</i> , <i>Bacillus</i> sp.	Yes	Yes	25	101	90
12	I	85	16	AT	DPT/FT	120	0	0	<i>S. aureus</i> ., <i>Bacillus</i> sp.	Yes	Yes	25	20	20
13	J	39	30	UL, LL, AT, PT	DPT/FT	7	9	15	<i>S. aureus</i> , <i>Streptococcus pneumoniae</i>	Yes	Yes	50	108	118
14	J	39	30	UL, LL, AT, PT	DPT/FT	7	9	15	<i>S. aureus</i> , <i>S. pneumoniae</i>	Yes	Yes	50	97	52
15	K	46	30	UL, LL, PT	DPT/FT	6	0	0	<i>S. aureus</i> , <i>Streptococcus</i> sp., <i>Bacillus</i> sp.	Yes	Yes	55	28	7
16	K	46	30	UL, LL, PT	DPT/FT	6	0	0	<i>S. aureus</i> , <i>Streptococcus</i> sp., <i>Bacillus</i> sp.	Yes	Yes	55	25	26
17	L	55	35	UL, LL, AT,	DPT/FT	4	0	0	Methicillin resistant <i>S. aureus</i> (MRSA)	Yes	Yes	60	177	126
18	L	55	35	UL, LL, AT,	DPT/FT	4	0	0	MRSA	Yes	Yes	60	66	71
19	M	29	41	UL, PT, HN	FT	8	18	18	coliforms, <i>S. aureus</i> , <i>S. pneumoniae</i> , <i>bacillus</i> sp.	Yes	Yes	90	142	96
20	M	29	41	UL, PT, HN	FT	8	18	18	coliforms, <i>S. aureus</i> , <i>S. pneumoniae</i> , <i>bacillus</i> sp.	Yes	Yes	90	294	233
21	N	45	43	UL, LL, AT, HN	FT	2	1	18	No growth	Yes	Yes	85	287	259
22	N	45	43	UL, LL, AT, HN	FT	2	1	18	No growth	Yes	Yes	85	420	341
23	O	40	51	UL, AT, PT, HN	FT	6	4	32	<i>Enterococcus cloacae</i>	Yes	Yes	78	662	569
24	O	40	51	UL, AT, PT, HN	FT	6	4	32	<i>E. cloacae</i>	Yes	Yes	78	333	569





**Fig. 3 – Charts demonstrating exponential relationships between %TBSA and mean cfu per plate (left) and time taken in minutes for dressing change and mean cfu per plate (right) when all 20 ‘no apron’ sampling sites on a HCW gown are analysed.**



**Fig. 4 – Chart demonstrating exponential relationships between %TBSA and mean cfu per plate (left) and time taken in minutes for dressing change and mean cfu per plate (right) when 15 ‘with apron’ sampling sites on a HCW gown are analysed.**

These curves are illustrated in Fig. 4. Again, both charts demonstrate an exponential relationship between the variable (%TBSA or time taken for the dressing/bed change to take place) and the contamination received by the HCW. However, although they are both significant relationships, time taken correlates less strongly than %TBSA as shown by the lower  $R^2$ . %TBSA is a more accurate predictor of HCW contamination than time taken for the dressing/bed change to take place.

### 3.5. Predicted contamination of HCW

Using the above statistical models, the expected mean number of bacterial cfu per 25 cm<sup>2</sup> plate from a HCW performing a burns dressing/bed change can be predicted. This was produced from data sets for all 20 ‘no apron’ sites and the 15 ‘with apron’ sites. These values are summarised in Table 2. It was found that for every 9%TBSA increase in burn size, the mean number of cfu/plate doubled when all 20 sites were analysed. This was true for every 6%TBSA increase in burn size when 15 ‘with apron’ sites were analysed.

**Table 2 – Predicted mean contamination received by HCW performing a burn dressing/bed change. All 20 ‘no apron’ sites, and the 15 ‘with apron’ sites that would be left exposed if the HCW donned a plastic apron are analysed separately for comparison. Results are expressed as mean bacterial cfu per 25 cm<sup>2</sup> agar plate.**

%TBSA	Predicted mean cfu per 25 cm <sup>2</sup> plate 20 ‘no apron’ sites	Predicted mean cfu per 25 cm <sup>2</sup> plate 15 ‘with apron’ sites
5	13	4
10	19	6
15	29	11
20	43	18
25	64	32
30	95	56
35	141	97
40	211	168
45	314	292
50	469	507

#### 4. Discussion

The consequences of nosocomial infections from a burns patient cross-contaminating other patients are potentially devastating [1,24]. Prevention of cross-contamination is thus becoming an increasingly important area of burn care research. The potential for HCW to act as vectors of transmission between patients, and the increased bacterial dispersal during dressing and bed sheet changes on burns patients has long been known [6–9,11–18]. The current study highlights high levels of HCW contamination following a dressing/bed change and quantifies levels of bacterial contamination for the first time.

During a dressing/bed change the HCW can be expected to come into contact with the patient, their dressings and the surrounding environment, all of which are likely to be heavily contaminated on the burns unit. A HCW who has become contaminated by carrying out a dressing change will proceed to make contact with other patients or environmental surfaces, dispersing organisms, where they can survive for several weeks and form an environmental reservoir [25–27]. The environment may then contaminate another patient directly or indirectly via the hands or uniform of a HCW acting as a carrier for nosocomial infection [28,4,29].

Guidelines on the use of protective clothing for HCW during burns dressing/bed changes are not burns-specific. Based on the results of this study, they may require to be revised with consideration of the amount of contamination received by HCW during performance of these routine nursing activities. The use of gloves and meticulous hand hygiene for all dressing changes is accepted practise and was not examined here [15,30]. Of note, WHO recommend a '5 moments for hand hygiene' approach whereby hands should be cleaned before and after all procedures and contact with patient surroundings [31]. It may be argued that the HCW in this study should have been encouraged to wash their hands several times during the activity, rather than just at the beginning and end. However as they were in constant contact with the environment, patient, and open wounds throughout the duration of the activity, dividing the dressing/bed change into distinct 'moments for hand hygiene' was difficult. One compromise that may be employed in the future is to encourage a pause for hand hygiene and change of gloves only, between removing dressings and applying fresh dressings. The compliance with these recommendations is however unlikely to affect the levels of bacteria found on the gowns, as they concern only hand hygiene.

Disposable full-body gowns were only worn for this study to enable sampling from a surface that was known to be sterile prior to the nursing activities. Standard practice on our unit is for plastic aprons to be worn for most dressing and bed changes, excluding those taking place in ICU or on known heavily contaminated patients. The results of this study have led to a review of our clinical practice, and revised guidelines on protective attire worn by HCW.

The mathematical models produced indicate that a HCW performing a dressing change on a patient with a 15%TBSA

burn could be expected to become contaminated with a mean of 29 bacterial cfu/25 cm<sup>2</sup> if they wore no protective clothing and 11 bacterial cfu/25 cm<sup>2</sup> if a plastic apron was worn, supposing absolute protection is afforded by the apron. For large burns, prediction of levels of contamination when a HCW wears or does not wear an apron highlights the limitation of relying only on the apron as a means of prevention of HCW contamination. For example, 50% TBSA burn is estimated to produce 469 cfu/plate when wearing 'no apron', compared to 507 cfu/plate 'with apron'. The majority of samples were collected from the forearms, arms, shoulders and chest: areas that of skin and uniform which would not be protected or cleaned during hand washing and may come into contact with other patients or equipment. Before the study was initiated, HCW were encouraged to act exactly as they would were they wearing an apron. Whilst this was the agreed intention, it is nevertheless possible that they may have been less careful than usual knowing they were covered by a gown, or more careful as they were conscious they were part of a study. Regardless of this possible effect, the results highlight the need for a review of protective guidelines for HCW.

Burns between 2 and 10 days old were examined, although numerous factors such as the site of the burn, whether debridement had taken place, donor site size, comorbidities and bacteria isolated from the wound were unable to be controlled. Despite the inclusion criteria being fairly broad, %TBSA was still shown to be an important predictor of HCW contamination. Future studies would be useful to monitor the change in HCW contamination as a burn progresses towards healing, or as the patient becomes colonised with increasingly resistant organisms. Furthermore, BPA was used throughout to monitor staphylococcal-type bacteria, but other selective media may be used in the future to identify other organisms that colonise burns wounds, such as Gram-negatives, which may show different transfer characteristics between patients and HCW. Were the studies to be repeated on a larger sample size, quantitative analysis of wound contamination may be attempted, although this would only be an estimate. However this would not be helpful in predicting contamination and thus guiding HCW on which protective attire to wear; results not being known until after the dressing/bed change had taken place.

Despite the relatively small sample size an excellent correlation of 82% was demonstrated, enabling the production of mathematical models. The largest burn studied was 51% TBSA so extrapolation to predict contamination from larger burns was not attempted. Although further studies may help to show the contamination produced by much bigger burns, at the upper limits of %TBSA tested, many agar plates were very heavily contaminated, and much more contamination would probably render the number of bacterial cfu uncountable. Suffice to say contamination to at least the same extent would be expected for burns over 51% TBSA. It is important to note that all results are reported as cfu per 25 cm<sup>2</sup> plate, and the total contamination across a whole gown would be many times this figure. What is not known is what constitutes a 'significant number' of bacteria. Further work would need to be carried out to determine the

transfer rate from the HCW to another surface or patient. In the absence of this, an arbitrary figure may be assigned as a pre-determined cut off point above which full-body protection should be worn. The cost of full body protection must also be considered and weighed up against the perceived risk of transfer from a HCW.

It is logical to assume that in general a larger burn will take longer to dress, and indeed this was shown by a linear relationship between %TBSA and total time taken (Fig. 2). Although time taken was related to the level of HCW contamination, it explained less of the variation than burn size, with a lower coefficient of determination,  $R^2$ . Furthermore, as the time taken for the dressing change will not be known until after the event, and may depend on HCW experience, %TBSA was preferentially considered to predict HCW contamination. A rough guide is that for every 6–9%TBSA increase in burn size, bacterial contamination doubles.

This study increases knowledge of the transfer of bacteria from burns patients to HCW. It highlights the need for guidelines on protective clothing worn by HCW to be developed, as burns patients have been shown to disperse high levels of bacteria onto HCW. For the first time, a quantitative analysis of bacterial contamination received by HCW performing burns dressing and bed changes have been performed. The risks of HCW contamination must be balanced against the cost of protective measures and resources available to burns units worldwide.

### Conflict of interest

All authors declare no financial or personal associations that could inappropriately influence this work.

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### Ethical approval

Ethical approval was granted by the local REC for the study of levels of environmental bacterial contamination around burns patients, as part of a larger body of work. All samples were taken from disused gowns and no direct patient involvement was required to carry out this research. Verbal consent was obtained from the patient and HCW prior to the study.

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# Continuous decontamination of an intensive care isolation room during patient occupancy using 405 nm light technology

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## Abstract

**E**nvironmental contamination within intensive care units (ICU) is recognised as a source of patient infection, and improved cleaning and disinfection methods are continually being sought. Visible light of 405 nm has been shown to have bactericidal properties, and this communication reports on the use of a ceiling-mounted 405 nm light system for continuous environmental disinfection of contact surfaces and air in an occupied ICU isolation room. Levels of bacterial contamination on a range of contact surfaces around the room were assessed before, during and after use of the system. For each study, the lighting units were operated continuously during daylight hours. Results demonstrate that the spatial distribution of bacterial contamination was reduced almost uniformly across all sampled contact surfaces during use of the 405 nm light system. Pooled data showed that significant reductions in overall bacterial contamination around the room were achieved, with bacterial counts reduced by up to 67% ( $p=0.0001$ ) over and above that achieved with standard cleaning and infection control procedures alone. Use of 405 nm light significantly reduced environmental contamination across almost all sampled contact surfaces within the ICU isolation room. This has particular benefit in ICU where equipment and other 'hand-touch' sites make routine cleaning difficult, thus helping maintain a cleaner environment, and contributing to reducing cross-infection from environmental sources.

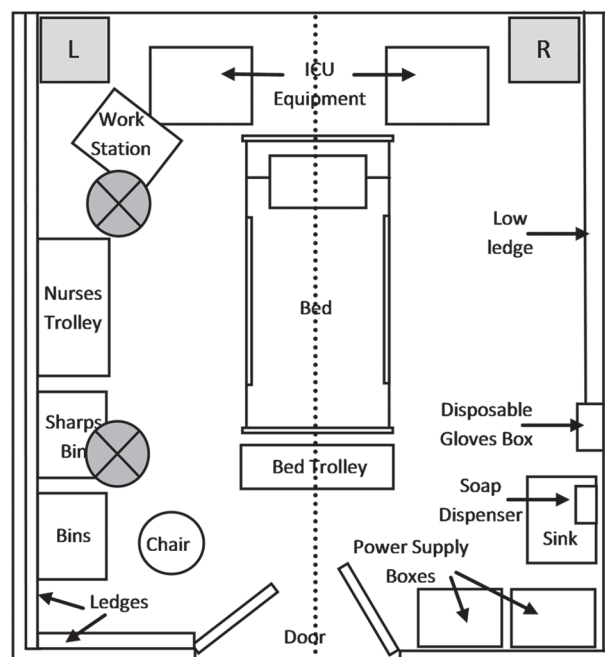
## Background

There are numerous potential sources of patient healthcare associated infection (HAI), including environmental contamination. Direct or indirect contact with contaminated surfaces via the hands of healthcare workers (HCW) or equipment, and airborne transmission, are all potential environmental sources of cross-infection (Beggs, 2003; Bhalla et al, 2004; Duckro et al, 2005; Boyce, 2007; Hayden et al, 2008; Dancer, 2009). Although environmental cleaning is essential for reducing contamination, some surfaces are infrequently cleaned (Carling et al, 2008; Goodman et al, 2008), and responsibility for cleaning patient-related surfaces and medical equipment can be variable (Goodman, et al, 2008; Dancer, 2009).

The high-intensity narrow-spectrum light environmental decontamination system (HINS-light EDS), is an experimental ceiling-mounted lighting system developed to provide continuous disinfection of the air and all exposed surfaces within the illuminated environment. The disinfection effect is based on the use of a narrow bandwidth of visible, violet light with a peak output at 405 nm, which has been proven to have wide antimicrobial activity (Maclean et al, 2009). 405 nm light is bactericidal, and the HINS-light EDS uses irradiances which are sufficient to generate a bactericidal effect while being safe for use in occupied environments. The efficacy of the HINS-light EDS has previously been demonstrated by studies carried out in a burns unit setting (Maclean et al, 2010; Bache et al, 2012).

In this paper we wish to present the results of three studies conducted to assess the efficacy of the HINS-light EDS for





**Figure 1.** Schematic diagram of the ICU isolation room. The two HINS-light EDS were installed along the left-hand side of the room, and their ceiling-mounted positions are designated by the grey crossed circles. The left (directly illuminated) and right (indirectly illuminated) sides of the room, as used in Study 3, are highlighted by the dashed line.

environmental decontamination of an occupied isolation room within the ICU. The first objective of this paper was to demonstrate that the decontamination effect of the HINS-light EDS could be replicated in the ICU environment by looking at not only the environmental staphylococcal bacterial levels, which were investigated in previous studies, but by also expanding the study to assess the effect of the light on the levels of total bacterial contamination around the room. Further objectives, which differ from the previous studies, were to investigate the spatial decontamination effect of the system by assessing the levels of bacterial contamination on specific sampling sites around the isolation room, and how the position of the HINS-light EDS units influences the decontamination effect.

## Methods

### Setting

Glasgow Royal Infirmary (GRI) intensive care unit has 12 level-3 and eight level-2 beds, arranged as six isolation rooms and two seven-bed open bays. The isolation room selected for use in the studies tends to house serious burn trauma or critical postoperative care patients. It has an area of 30 m<sup>2</sup> (5×6m), and air entering the room passes through HEPA filters, with the room being maintained at positive pressure. The room was cleaned daily: domestic staff clean the floor, sink, all surfaces, bins and ledges, and nursing staff damp-dust all frequently touched surfaces and equipment. Cleaning is monitored fortnightly by Facilities staff, adhering to NHS Scotland National Cleaning Services Specifications. GRI infection control policies were adhered to throughout (NHS GGC, 2012).

### Operation of HINS-light EDS

Two ceiling-mounted HINS-light EDS units were installed in the isolation room (Figure 1). The units were positioned above what was deemed to be the most active area of the room, directly illuminating the nurses' work station, the nurses' trolley and the bins. The units were powered using mains electricity and controlled by automatic

timer switches. The HINS-light EDS units were operated with irradiance levels which were within safety limits as stipulated within international guidelines (ICNIRP, 1997, 2004; ACGIH, 2007). This enabled the systems to be operated continuously in the presence of patients and staff from 0730 hours till 2200 hours in synchrony with hospital lighting. Ethical approval for this work was granted by National Health Service Scotland (West of Scotland Research Ethics Service).

### Microbiological sample collection

Environmental contamination was assessed by sampling bacterial levels on a wide range of surfaces within the isolation room. These were frequently touched contact surfaces, including the nurses' trolley, bins and chairs, as well as surfaces likely to have high contamination levels due to aerial deposition, such as ledges. Bacterial levels were assessed using 55 mm contact agar plates (Cherwell Laboratories Ltd, UK), with a surface area of 23.76 cm<sup>2</sup>, which were inoculated by pressing the agar surface onto the environmental surface, and then incubated within 30 minutes of sampling. For Studies 1 and 2, Baird Parker with egg yolk tellurite agar (BPA) contact plates were used. BPA is a selective medium for the growth of staphylococcal-type organisms, and is a good indicator of contamination of human origin. Tryptone soya agar contact plates (TSA), which use non-selective growth medium, were used in Study 3 to obtain total viable bacterial counts (TVC). Microbiological assessment, as colony forming unit (CFU) counts, was based upon growth on the contact agar plates after incubation at 37°C for 24 hours (TSA plates) or 48-hours (BPA plates).

For each study, between 40 and 84 contact plate samples were collected during each of three phases: (1) before the HINS-light EDS was in use (*pre-HINS*); (2) after the HINS-light EDS had been in operation for a set period (*HINS*); and (3) after the HINS-light EDS had been turned off for a set period (*post-HINS*). Contact-plate sampling was routinely performed at 0730 hours, by the same personnel in order to negate collector bias.

**Table 1. Results and statistical analysis of pooled data on the effects of the HINS-light EDS for reduction of environmental contamination in an occupied ICU isolation room. The HINS-light EDS was used as well as routine cleaning and infection control measures, which were maintained throughout all studies.**

Study	Bacterial count	Mean cfu/plate (least squares means $\pm$ SE)			cfu reduction by EDS use (with 95% CI)	cfu increase after EDS switch off (with 95% CI)	% reduction by EDS use (*significant reduction if $p < 0.05$ )	% increase after EDS switch off (*significant increase if $p < 0.05$ )
		Pre-HINS	HINS	Post-HINS				
Study 1	Total BPA	29.0 $\pm$ 2.9 (n=40)	9.6 $\pm$ 2.9 (n=40)	– <sup>†</sup>	19.4 cfu (11.4, 27.4)	– <sup>†</sup>	66.8% * ( $p=0.0001$ )	– <sup>†</sup>
Study 2	Total BPA	22.4 $\pm$ 6.0 (n=40)	13.9 $\pm$ 6.0 (n=40)	63.4 $\pm$ 6.0 (n=40)	8.5 cfu (–11.8, 28.8)	49.5 cfu (29.2, 69.8)	37.9% ( $p=0.4207$ )	357.1% * ( $p=0.0000$ )
Study 3	TVC	57.7 $\pm$ 4.9 (n=84)	30.0 $\pm$ 4.9 (n=84)	47.2 $\pm$ 4.9 (n=84)	30.8 cfu (14.9, 46.6)	20.2 cfu (4.4, 36.1)	53.3% * ( $p=0.0029$ )	75.0% * ( $p=0.0024$ )

cfu: colony forming units; HINS-light EDS: high-intensity narrow-spectrum light environmental decontamination system; BPA: Baird Parker with egg yolk telurite agar

\*Significant reduction by HINS-light EDS use/significant increase after HINS-light EDS switch off ( $p < 0.05$ ).

<sup>†</sup>Samples unable to be collected due to study being discontinued.

### Statistical analysis

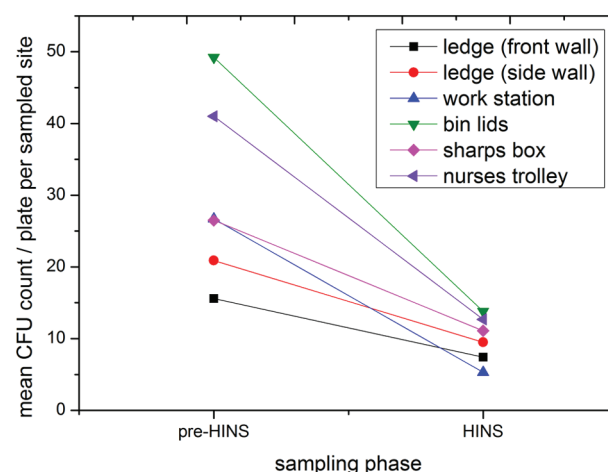
The studies had been powered based on previous study findings (Maclean et al, 2010) which estimated a greater than 80% chance of detecting a 40% change in bacterial counts between *pre-HINS* and *HINS* phases, assuming a 5% significance level. Statistical analyses were undertaken using general linear modelling (GLM) and other statistical procedures in the Minitab proprietary statistical software package version 15. For each study, bacterial counts were analysed for significant differences between *pre-HINS*, *HINS* and *post-HINS* phases using a two-factor model to take account of sample-site variation. Differences between phases were compared using Tukey simultaneous pairwise comparisons. Data were logarithmically transformed before analysis and estimates were obtained of the mean difference in counts between phases along with associated 95% confidence intervals (CI) and of percentage increase or decrease in mean counts between phases.

### Study design and results

#### Reduction of environmental staphylococcal contamination

**Study 1.** Study 1 was conducted while the isolation room was occupied by a 48 year old male patient with 25% total body surface area (TBSA) burn and smoke inhalation injury. The patient was admitted to the isolation room nine days before the start of the study and had developed hospital-acquired bloodstream infection and multi organ failure. Sampling sites were restricted to the left side of the room to investigate the localised decontamination effect of the HINS-light EDS. Forty sample sites were included: ledge along the front wall (n=5); ledge along the side wall (10); nurses' work station (3); nurses' trolley (8); bin lids (6); sharps box (8). These sites were sampled with BPA contact plates before the HINS-light EDS units were switched on, and again after five days of HINS-light EDS use. *Post-HINS* samples were not collected during this study because of the death of the patient.

The environmental contamination levels on contact surfaces were reduced after a five-day use of the HINS-light EDS, compared to baseline. These data are presented in Table 1. Calculation of the pooled data for each of the two phases (*pre-HINS* and *HINS*) demonstrates a statistically significant mean percentage reduction in staphylococcal counts of approximately 67% ( $p=0.0001$ ), with a mean plate count reduction of 19.4 CFU (95% confidence interval (CI) 11.4 to 27.4). Figure 2 shows the change in the mean levels of

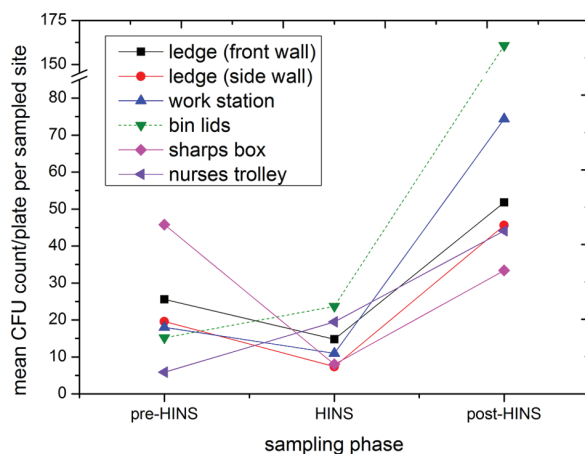


**Figure 2.** Study 1 results demonstrating the reduction in mean colony forming unit levels of environmental staphylococcal-type bacteria on a range of contact surfaces in an ICU isolation room before and during use of the HINS-light EDS.

staphylococcal bacteria observed on each of the tested surfaces between *pre-HINS* and *HINS* phases. There is marked variation in the bacterial levels between the sample sites in the *pre-HINS* phase. Despite this, there was a uniform decrease in staphylococcal-type bacterial contamination at all tested sites.

**Study 2.** During Study 2, the room was occupied by a 67 year old male post-laparotomy patient with intra-abdominal sepsis. The patient was admitted into the room approximately 12 hours prior to the start of the study. This study was conducted over a three-day period with the HINS-light EDS in use for one day. The sampling sites were the same as for Study 1. BPA contact plate samples were collected immediately prior to the HINS-light EDS units being switched on. *HINS* samples were collected the following morning, with *post-HINS* samples being collected after the HINS-light EDS had been off for 24-hours.

*Pre-HINS* counts for Study 2 were relatively low, likely due to the patient only being admitted 12 hours earlier. Despite the low initial contamination levels (mean 22 CFU/plate;  $n=40$ ), there was a 38% mean reduction of staphylococcal-type counts achieved across the 40 sites after one day of HINS-light EDS use (Table 1). Contact-plate samples collected *post-HINS* showed a 357% ( $p=0.00005$ ) mean



**Figure 3.** Study 2 results demonstrating the mean colony forming unit levels of environmental staphylococcal-type bacteria on a range of contact surfaces in an ICU isolation room before, during and after use of the HINS-light EDS. The break in the y-axis scale was to allow convenient representation of the data.

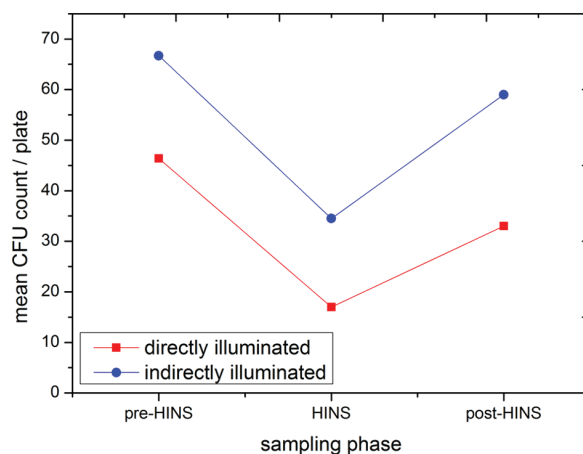
increase in the staphylococcal bacterial levels across the same 40 sampling sites 24 hours after treatment had stopped, with the mean CFU/plate count rising from 14 to 63. The average change in bacterial contamination on each of the sampled surfaces, shown in Figure 3, demonstrated that despite initial contamination levels being low, reductions were still achieved during use of the HINS-light EDS, followed by significant increases in contamination 24 hours after the system had been switched off. Exceptions to this were the bin lids and the nurses' trolley, for which staphylococcal counts taken after 24 hour use of the HINS-light EDS were not reduced.

#### Reduction of total environmental bacterial contamination

**Study 3.** During Study 3, the room was occupied by a 68 year old female burn patient with 25% TBSA. This patient had myotonic dystrophy, and she had developed cardiovascular and respiratory failure and a Gram-negative sepsis. This study aimed to investigate the effect of the HINS-light EDS on the total bacterial contamination levels across the entire room. TSA contact plates were used to sample a range of sites on both sides of the room, with the room being categorised into two sides: directly and indirectly illuminated (left-hand and right-hand sides, respectively – see Figure 1). Eighty-four samples were collected from across the room (42 from each side) during each of the three study phases. In addition to the 40 samples collected from the directly illuminated (left-hand) side of the room in Studies 1 and 2, two samples were also taken from a visitor chair. The sampling sites on the indirectly illuminated (right-hand) side of the room were identified as: sink and taps ( $n=4$ ); soap dispenser (2); paper towel dispenser (2); disposable apron holder (2); glove boxes (3); top of the X-ray view box (5); ICU equipment stack (4); EDS power supply boxes (8); low ledge (12).

This study was conducted over a five-day period: TSA contact samples were collected, and the HINS-light EDS was operated for two days, after which the HINS samples were collected. Post-HINS samples were collected after 48 hours with the HINS-light EDS turned off. The results are shown in Table 1.

As in Studies 1 and 2, the sample sites under direct illumination from the HINS-light EDS units were analysed to assess the levels of bacterial contamination present before, during and after use of the HINS-light EDS. Figure 4 shows that when looking at the mean contamination levels per contact plate collected across this side of the room there was an overall 63% reduction in mean bacterial levels across these sites during use of the HINS-light EDS, with the mean post-HINS bacterial level rising thereafter by 94%. Study 3 also looked



**Figure 4.** Study 3 results comparing the mean reductions in total viable bacterial contamination on surfaces located in the directly and indirectly exposed areas of the isolation room. Results from all sampled surfaces have been pooled to assess the overall decontamination effect on each side of the room.

at the environmental bacterial levels across 42 sample sites indirectly exposed to the HINS-light EDS (on the right side of the room). Results showed an overall 48% mean percentage reduction in total bacterial counts, followed by a 71% increase in bacterial counts after switching off the HINS-light EDS (Figure 4). It can be seen from these results that the effect of the HINS-light EDS was stronger on the surfaces directly illuminated by the HINS-light, although significant inactivation was achieved on the indirectly illuminated surfaces, demonstrating that the decontamination effect occurs throughout the room, not only on surfaces in close proximity to the lighting systems.

Analysis of the whole room data was also performed (Table 1). Use of the HINS-light EDS resulted in a 53.3% ( $p=0.0029$ ) mean percentage reduction in environmental bacterial levels across the whole room, and a 75% increase ( $p=0.0024$ ) in bacterial counts occurred after stopping the HINS-light EDS treatment.

#### Discussion

This paper describes three intervention studies in which a new experimental light-based decontamination technology, which uses bactericidal 405 nm light, was deployed for environmental decontamination of an occupied ICU isolation room. The ICU was chosen as the setting for these studies due to the increased prevalence of HAI in ICU compared to general wards (Cairns et al, 2010). The results demonstrated that use of the HINS-light EDS significantly reduced both the total bacterial contamination and the staphylococcal-type contamination and that contamination levels returned to pre-treatment and higher levels after the HINS-light EDS treatment was terminated. Importantly, results also demonstrated that the spatial distribution of bacterial contamination was reduced almost uniformly across all the sampled contact surfaces, each of which has the potential to harbour bacteria and act as a reservoir for cross-transmission of infectious pathogens.

Study 1 results demonstrated a 67% reduction of contamination levels across all the sampled sites during use of the HINS-light EDS. Study 2 also demonstrated reductions in contamination levels during use of the HINS-light EDS (38%); however, this did not reach statistical significance. This was probably because the patient was only admitted 12 hours prior to the first study samples being collected. In this case, the room had recently undergone terminal cleaning before patient admission and consequently natural background contamination levels had not been achieved. The 375% increase in the bacterial bioburden post-HINS provides support for HINS-light EDS maintaining low levels of contamination.

Although Studies 1 and 2 assessed the decontamination effect on surfaces directly below the HINS-light EDS, Study 3 assessed the decontamination effect on surfaces spatially directly below the HINS-light EDS as well as on indirectly exposed surfaces on the other side of the room. Although there were differences in the decontamination results between the two sides, there was nevertheless reduction of bacterial contamination with the use of the HINS-light EDS, and an increase after the system was turned off, on both sides of the room. This suggests that the installation positions of the HINS-light EDS units within a room may not be critical, and that killing of airborne bacteria contributes to the reductions in bacterial contamination levels. Further studies are required to estimate the relative effects of decontamination in the air and on contact surfaces.

The results of the present study provide significant new information on the spatial distribution of bacterial contamination within an ICU isolation room, and evidence of the efficacy of the HINS-light EDS for achieving an almost uniform reduction across the room. With regards to the overall efficacy of the HINS-light EDS, the results of the present study concur well with previous studies on the use of the HINS-light EDS. Studies in a burns unit demonstrated that staphylococcal contamination on surfaces around an isolation room occupied by a patient with methicillin resistant *Staphylococcus aureus* (MRSA) were reduced by 56–86%, over and above those achieved through standard cleaning and infection control measures alone, and when used in an unoccupied isolation room, a 90% reduction in staphylococcal contamination was achieved (Macleane et al, 2010). The HINS-light EDS was also effective when used in an outpatient clinic with a 61% efficacy achieved (Bache et al, 2012). The ICU results correlate well with this, with reductions of up to 67% and 63% being achieved for staphylococcal and total viable bacterial contamination, respectively.

There were a number of limitations in the study, mostly relating to difficulties associated with carrying out the work in an active clinical environment. The studies varied in length due to a number of patient-related factors. Also, study durations were short with samples being collected once during each phase due to the uncertainty of how long each patient would remain in the isolation room. Unusually high counts were also sometimes recorded – for example on the lids of bins and on the nurses' trolley in Study 2 – and this may have been caused by hand-contact contamination just prior to sampling. Such instances are impossible to control and can complicate interpretation of the results. The use of the HINS-light EDS was also restricted to during the day, in synchrony with hospital lighting; overnight use was not performed to avoid disruption of the patient's sleep. It is likely that extending the period of use would enhance the decontamination effect achieved, and a further development consideration would be to include a 'dimmer' function which could provide night-lighting.

With regards to the scope of the microbiological data, Baird Parker agar was used to sample for staphylococcal-type bacteria, which provide a good indication of contamination originating from human sources and as such, it is an accepted marker of hospital environmental contamination in studies of hospital cleanliness (Dancer et al, 2008; Mulvey et al, 2011). A recent study which surveyed the global epidemiology of ICU infections found that although *S. aureus* was the predominant infecting organism, Gram-negative bacteria were more commonly isolated than Gram-positive bacteria (Vincent et al, 2009). Previous laboratory research has demonstrated that a wide variety of the bacterial pathogens responsible for nosocomial infections, including Gram-negatives, are also susceptible to inactivation from HINS-light exposure (Macleane et al, 2009). As infections in the ICU are caused by a wide range of pathogens, it was important to establish that, in situ, the HINS-light EDS would have a disinfecting effect on the total environmental bioburden, although it was appreciated that only a proportion of the environmental microflora would have possessed pathogenic potential. This was done for the first time in Study 3,

using Tryptone Soya agar contact plates, for the assessment of total viable bacterial counts. Also, with regards to discussing the decontamination efficacy of 405 nm HINS-light, previous work has demonstrated that up to 9-log<sub>10</sub> orders of reduction in bacterial population in test suspensions can be achieved (Macleane et al, 2009). However, when looking at the efficacy of the system in situ within the hospital environment, the efficacy must be evaluated against the existing levels of bioburden found around the environment (approximately 10–200 CFU per 24 cm<sup>2</sup> surface area).

Emphasis on environmental cleanliness is gaining importance in the prevention of HAI due to numerous studies highlighting that bacterial contamination around the environment can be transferred, directly and indirectly, to patients, to the hands and uniforms of HCW, and to other contact surfaces within the clinical environment (Bhalla et al, 2004; Hayden et al, 2008; Carling et al, 2008; Goodman et al, 2008). In addition to improvements in traditional cleaning and the promotion of hand hygiene, new methodologies for enhanced environmental cleaning of wards and isolation rooms are emerging. Many of these technologies (hydrogen peroxide vapour (French et al, 2004), steam cleaning (Department of Health, 2007), super-oxidised water fogging (Clark et al, 2006) and ultraviolet light (Andersen et al, 2006) are designed for whole-room decontamination. Although effective for deep cleaning of a room, they do not maintain low levels of contamination, with the bioburden returning to pre-decontamination levels within a few days (Hardy et al, 2007). These methods are also restricted for use in unoccupied, sealed rooms, resulting in rooms being out-of-commission for periods of time, which is both costly and undesirable in busy areas. Also, the HINS-light EDS utilises visible light wavelengths therefore it is very unlikely to have any deleterious effect on materials and equipment, unlike higher energy UV-light wavelengths, which can cause polymer degradation.

Cleaning, disinfection and hand hygiene are critical for maintaining a clean environment and minimising spread of potential pathogens. Compliance with hand-washing tends to be low after direct contact with a patient, and even lower after contact with environmental surfaces around patients, even though these surfaces can be reservoirs of potential pathogens that can persist on surfaces in the hospital environment for significant periods of time – even after cleaning – thus facilitating their transmission between patients, staff and the environment (Bhalla et al, 2004; Dancer, 2009). Use of the HINS-light EDS can augment this by further reducing the levels of contamination achieved with intermittent cleaning. This will be beneficial in areas such as ICU where electronic equipment and other 'hand-touch' sites make routine cleaning difficult. The pervasive yet safe nature of the light emitted by the HINS-light EDS also permits continuous treatment of air and exposed surfaces during periods of intense activity, such as bed and dressing changing and visiting times, which are associated with high bacterial transmission (Sergeant et al, 2012). Because of the low light irradiance emitted by the HINS-light EDS, and also skin attenuation, there will be negligible superficial effects on patient's skin microflora, because a major reservoir of skin microflora is within sebaceous glands and hair follicles.

This paper presents further clear evidence that use of the HINS-light EDS reduces environmental bacterial contamination across all sampled contact surfaces within occupied isolation rooms. Importantly, these results were achieved over and above the standard cleaning and infection control measures which were maintained throughout the three studies. Current thinking is that the environment is a source of nosocomial pathogens, therefore additional measures such as use of the HINS-light EDS can make a contribution to the reduction of pathogens in the environment, thereby reducing the chances of pathogen transmission from the environment to patients, and thus contributing



to controlling HAIs resulting from cross-infection from environmental sources.

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## Conflict of interest

None declared.

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Review

# 405 nm light technology for the inactivation of pathogens and its potential role for environmental disinfection and infection control

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## SUMMARY

**Background:** Although the germicidal properties of ultraviolet (UV) light have long been known, it is only comparatively recently that the antimicrobial properties of visible violet–blue 405 nm light have been discovered and used for environmental disinfection and infection control applications.

**Aim:** To review the antimicrobial properties of 405 nm light and to describe its application as an environmental decontamination technology with particular reference to disinfection of the hospital environment.

**Methods:** Extensive literature searches for relevant scientific papers and reports.

**Findings:** A large body of scientific evidence is now available that provides underpinning knowledge of the 405 nm light-induced photodynamic inactivation process involved in the destruction of a wide range of prokaryotic and eukaryotic microbial species, including resistant forms such as bacterial and fungal spores. For practical application, a high-intensity narrow-spectrum light environmental disinfection system (HINS-light EDS) has been developed and tested in hospital isolation rooms. The trial results have demonstrated that this 405 nm light system can provide continuous disinfection of air and exposed surfaces in occupied areas of the hospital, thereby substantially enhancing standard cleaning and infection control procedures.

**Conclusion:** Violet–blue light, particularly 405 nm light, has significant antimicrobial properties against a wide range of bacterial and fungal pathogens and, although germicidal efficacy is lower than UV light, this limitation is offset by its facility for safe, continuous use in occupied environments. Promising results on disinfection efficacy have been obtained in hospital trials but the full impact of this technology on reduction of healthcare-associated infection has yet to be determined.

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## Introduction

Although intensive efforts over recent years are making an impact, healthcare-associated infections (HCAIs) still regularly occur and continue to pose a major challenge. In addition to the significant morbidity and financial costs, concern over

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contraction of HCAs is one of the greatest fears of patients being admitted to hospital.<sup>1</sup> Infection control procedures such as handwashing are of critical importance in addressing the HCAI problem; however, greater awareness of the hospital environment as a source of nosocomial pathogens has led to renewed focus on hospital cleaning and disinfection. Whereas effective physical cleaning remains essential for infection control and aesthetic reasons, there has been an upsurge of interest in the development of new cleaning and decontamination technologies.<sup>2,3</sup> Several of these employ novel methods of delivering antimicrobial chemicals, whereas others use the antimicrobial properties of light to enhance disinfection, and it is this latter approach that forms the topic of this review.<sup>4–6</sup>

The most germicidal wavelengths of light fall within the ultraviolet (UV) range and UVC (240–260 nm) irradiation has traditionally been used for disinfection, particularly for air and medical device decontamination applications.<sup>7–9</sup> More recently the antimicrobial properties of violet–blue visible light have emerged as an area of increasing research interest. Although less germicidal than UVC light, violet–blue light with wavelengths in the region of 405 nm has proved effective for inactivation of a range of microbial species, and exploitation of these wavelengths may provide alternative methods of antimicrobial treatment for infection control applications. This paper supplies a brief background on the use of light for environmental decontamination applications within hospitals before presenting a detailed description of the broad spectrum antimicrobial effects of violet–blue light and how this knowledge has led to the development and clinical evaluation of a 405 nm light environmental disinfection system. In addition to environmental decontamination applications, other potential uses of violet–blue light for infection control purposes such as skin and wound treatment have been highlighted in recent literature but these topics are out with the scope of the current review.<sup>10–17</sup>

## Inactivation of micro-organisms by light in the hospital environment

Records of observations on the antibacterial effects of light go back to the latter part of the 19th century and these early historical observations have been documented by Kowalski.<sup>18</sup> The germicidal effects of light received further attention during the early part of the 20th century and the appreciation of the decontamination effect of light was translated into early hospital design features where natural ventilation and exposure to sunlight were regarded as beneficial.<sup>19</sup> The roles of sunlight and natural ventilation for controlling the transmission of infections within healthcare settings has recently been reviewed by Hobday and Dancer, who provide a detailed record of the early–mid-20th century observations on the effects of natural sunlight on a wide range of nosocomial pathogens.<sup>20</sup> Although natural light and ventilation were originally considered beneficial, modern hospital design has tended to reduce these features. Recent interest in the application of ‘artificial’ lighting within hospitals has been with regard to energy reduction issues but also how lighting can affect the mood and circadian rhythm of patients.<sup>21,22</sup> Light from artificial sources with wavelength emission in the UV range can have significant antimicrobial effects and new technologies for hospital decontamination have been developed around this concept.<sup>6,23–25</sup>

The most widespread applications of ultraviolet germicidal irradiation (UVGI) has been for air and water disinfection, as well as for decontamination of devices.<sup>26–28</sup> More recently, with the increased emphasis that has been directed towards enhanced decontamination of the hospital environment, novel technologies have been developed for the rapid delivery of UVC radiation to exposed surfaces in clinical areas. Several of these are automated or manually positioned robotic systems using either continuous or pulsed UV emission sources.<sup>6,25</sup> Detailed information on UVGI and other ‘no-touch’ automated room disinfection systems is provided in a recent review by Otter et al.<sup>6</sup>

## Antimicrobial effects of violet–blue light

Until relatively recently light within the visible spectrum (400–700 nm) was considered to have little biocidal effect compared to UVC light due to the lower photon energy of these wavelengths. Wavelengths of violet–blue light, particularly around 405 nm, have, however, been shown to possess antimicrobial capabilities, and there is scope for exploiting these wavelengths for the control of problematic micro-organisms in many areas of application including the disinfection of air and exposed surfaces in the clinical environment. The following section provides an overview of the antimicrobial inactivation mechanism, and the antimicrobial efficacy of high-intensity 405 nm violet–blue light.

### Violet–blue light inactivation mechanism

Investigations into the mechanism of action of 405 nm violet–blue light indicate that photodynamic inactivation occurs as a result of the photo-excitation of intracellular porphyrin molecules within the exposed bacterial cells. Laboratory studies have shown that a range of violet–blue light wavelengths in the region 400–425 nm can be used for bacterial inactivation; however, optimal antimicrobial activity has been found at 405 nm.<sup>29–35</sup> This peak in activity correlates with the absorption maximum of porphyrin molecules, termed the Soret band, being in this wavelength region.<sup>36</sup> Exposure to light of this wavelength induces an oxygen-dependent photo-excitation reaction within exposed micro-organisms, where excited porphyrins react with oxygen or cell components to produce reactive oxygen species (ROS), causing oxidative damage and microbial cell death.<sup>29,37–41</sup> Cell death has been accredited to oxidative damage to the cell membrane, with a recent study demonstrating disruption of the cytoplasmic content and cell walls of exposed *Staphylococcus aureus*, and it is likely that, due to the non-selective nature of ROS, multi-target damage will be induced in the microbial cells.<sup>10</sup>

### Antimicrobial effects of violet–blue light

Extensive laboratory studies have shown that 405 nm light, and the wider violet–blue light wavelengths, have a broad spectrum of activity, with successful inactivation demonstrated for a wide range of organisms, including antibiotic-resistant bacterial strains such as methicillin-resistant *Staphylococcus aureus* (MRSA).<sup>30–32</sup> Bacterial species which have demonstrated susceptibility include HCAI-associated organisms, including *S. aureus*, *Clostridium difficile*, *Acinetobacter*

*baumannii*, *Escherichia coli*, *Staphylococcus epidermidis*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Streptococcus pyogenes* and *Mycobacterium* spp.<sup>29–33,42,43</sup> Bacterial sensitivity to violet–blue light inactivation tends to be species dependent; however, the general trend suggests that Gram-positive bacteria tend to be more susceptible to inactivation than Gram-negative species.<sup>32,44</sup>

Two of the most significant pathogens associated with HCAI are MRSA and *C. difficile*, and vegetative cells of these species both show susceptibility to violet–blue light inactivation. Vegetative cells of *C. difficile* are particularly sensitive to inactivation, and this is likely to be due to this organism being an obligate anaerobe, giving it increased sensitivity to oxidative damage.<sup>33</sup> *C. difficile* spores are a significant issue for infection control, particularly due to their prolonged survival in the environment, and their resilience to disinfection technologies is well documented.<sup>45–47</sup> *C. difficile* spores can be successfully inactivated by exposure to 405 nm light, but, as expected, significantly higher doses (~50 times) are required for inactivation compared to vegetative cells.<sup>33</sup>

Laboratory studies have demonstrated the successful antimicrobial efficacy of violet–blue light for the inactivation of bacterial contamination in liquid, artificially seeded on surfaces, and most recently in biofilms.<sup>10,11,29–32,34,42,44,48</sup> Within the clinical environment, biofilm formation is a major cross-contamination risk, with the presence of patient fluids such as saliva, blood and urine influencing biofilm adhesion and development on surfaces.<sup>49</sup> Indeed, a recent study attributed the presence of *Pseudomonas aeruginosa* biofilms on sinks to the acquisition of infections, with a 33% death rate.<sup>50</sup>

Although the germicidal efficacy of blue light is lower than that of UV light – UV inactivation typically required doses of the order of milli-joules rather than joules, as is the case with violet–blue light – significant bacterial inactivation can still be demonstrated, with up to 9-log<sub>10</sub> orders of reduction being achieved by Maclean et al.<sup>32,51,52</sup> A major advantage of violet–blue light inactivation is that the susceptibility of strains isolated from the clinical environment is similar to their laboratory type strain counterparts, i.e. clinical isolates do not show enhanced resistance and thus can be inactivated by 405 nm light with no inherent problems.<sup>32</sup> Also, it has recently been demonstrated that sublethally damaged bacterial cells are more susceptible to light inactivation; therefore, there is great potential for bacterial contamination that has been sublethally stressed by desiccation and disinfectants during routine cleaning of the hospital environment to be more susceptible to inactivation by exposure to violet–blue light.<sup>48</sup>

In addition to clinically relevant bacteria, the effectiveness of 405 nm light for microbial inactivation has also been demonstrated against bacterial species associated with food-borne infection including *Listeria*, *Campylobacter*, *Shigella* and *Salmonella* spp.; pathogens *Helicobacter pylori*, *Chlamydia* and *Propionibacterium acnes*; oral periodontal pathogens; and fungal organisms including moulds and yeasts such as *Candida*.<sup>5,29,32,34,37,43,53–56</sup> To date, the effect of violet–blue

light on viruses has not been fully determined; however, it is expected that, due to the hypothesized involvement of porphyrins in the inactivation mechanism, it is unlikely that viruses will be highly susceptible to light exposure alone, and may require the addition of photosensitizing material to enhance viricidal activity.<sup>57</sup>

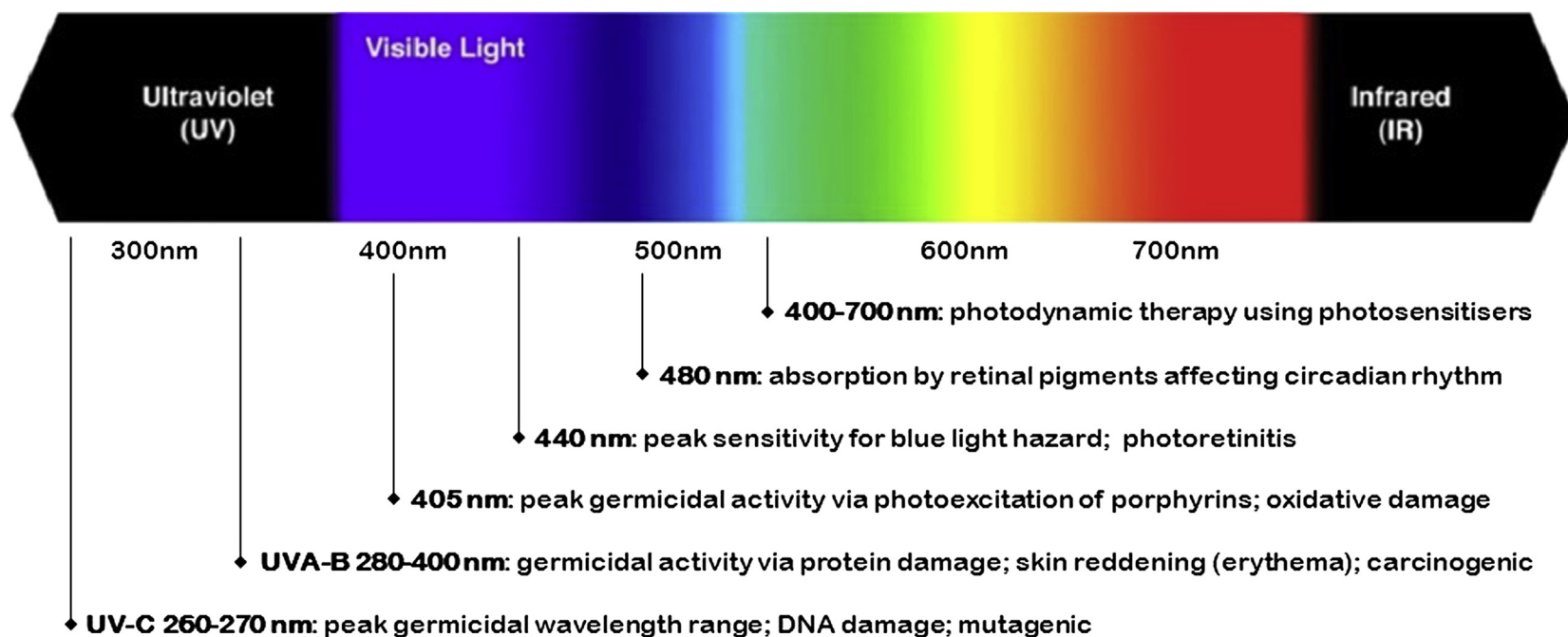
## Use of 405 nm violet–blue light for hospital disinfection

The wide antimicrobial spectrum of activity combined with the ability to apply light intensities safe for human exposure make violet–blue light ideal for decontamination of occupied environments, and the development of a system which uses high-intensity narrow spectrum (HINS) 405 nm light for environmental disinfection of the clinical environment has been recently described.<sup>58–60</sup> This new disinfection technology, termed the HINS-light environmental decontamination system (EDS), is a ceiling-mounted lighting system designed for the reduction of environmental contamination in hospital wards and other areas of the healthcare environment. The antimicrobial light from the system is generated from a matrix of light-emitting diodes (LEDs) which emit low-irradiance violet–blue light with a narrow spectral profile centred on 405 nm.<sup>58</sup> The output of the antimicrobial light has been set to ensure, with reference to international guidelines, that the light source does not pose a blue light hazard and is safe for use in occupied environments.<sup>61,62</sup> Although biocidal, the 405 nm wavelengths are well below the blue light wavelengths which can impact on human health, particularly in the region of 440 nm which is associated with photoretinitis, and 480 nm which influences mood and circadian rhythm in humans (Figure 1). It is interesting also to note that, when comparing the susceptibility of mammalian cells and bacteria to 405 nm light, mammalian keratinocytes and osteoblasts were considerably more resistant and could be exposed to bactericidal levels of 405 nm light with no loss of cell viability.<sup>10,11,63</sup> The increased resistance of mammalian cells is likely due to the fact that these cells have much more advanced mechanisms for coping with oxidative damage compared to the more primitive microbial cells.

For practical application as an overhead light source, incorporation of white LEDs into the HINS-light EDS system ensures that the illumination output is predominantly white, thus blending with the standard room lighting.<sup>58</sup> The system is designed to be operated continuously, providing ongoing disinfection of the air and all exposed environmental surfaces within the treated area, with no disruption to day-to-day hospital procedures or patient care. Laboratory testing of the system confirms the efficacy for inactivation of a range of bacterial pathogens associated with HCAI.<sup>64</sup> As mentioned, the low irradiance levels employed by the system were deliberately selected to enable continuous disinfection in occupied environments, and therefore require sufficient time to exert the antimicrobial effect. Significant inactivation of microbial contamination on simulated laboratory surfaces can be achieved by ~1–2 h light exposure; however, inactivation kinetics are likely to be significantly enhanced in the 'real' clinical environment due to the stressed and desiccated state of the micro-organisms.<sup>48,64</sup>

## Clinical assessment of 405 nm light for environmental disinfection

Several published studies have presented results from clinical assessment of this 405 nm light system for continuous environmental decontamination of single-bed isolation rooms.<sup>58–60</sup> Evaluation of the technology has been carried out in isolation rooms within two main clinical areas: a burns unit and an intensive care unit (ICU).



**Figure 1.** Ultraviolet (UV), visible light and infrared regions of the electromagnetic spectrum. Highlighted are key UV and violet/blue wavelengths with details of their germicidal action and safety aspects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



For evaluation, systems were installed within isolation rooms, and used as a complementary disinfection procedure, being operated continuously during daylight hours in occupied rooms, under conditions where normal clinical care and infection control measures were implemented. The effect of the system was assessed through contact-plate sampling of bacterial levels on a range of frequently touched contact surfaces (e.g. locker top, bed table, bed rails, bin lids, light switches and door handles) which are commonly associated with being 'high-risk' surfaces for cross-transmission of HCAs, as well as surfaces likely to have high contamination levels due to aerial deposition, such as ledges. Samples were typically collected (i) before use, (ii) during use, and (iii) some time after the HINS-light EDS units had been switched off, with the same contact surfaces sampled throughout each study. Bacterial levels were assessed using 55 mm contact agar plates, with a surface area of 23.76 cm<sup>2</sup>, which were inoculated by pressing the agar surface onto the environmental surface. Studies monitored the levels of staphylococcal bacteria (a good indicator of contamination of human origin), and the total viable bacteria levels in order to establish the effect of the system for reducing levels of bacterial contamination around the isolation room.<sup>58–60</sup> For collection of staphylococcal organisms, Baird Parker with egg yolk tellurite agar (BPA: a selective medium for the growth of staphylococcal-type organisms) contact plates were used. Tryptone soya agar (TSA) contact plates, which use non-selective growth medium, were used to obtain total viable bacterial counts (TVC). Microbiological assessment, as colony-forming unit counts, was based upon growth on the contact agar plates after incubation at 37°C for 24 h (TSA plates) or 48 h (BPA plates).

Several studies also characterized the staphylococcal isolates by subculturing selected isolates and then testing using Staphaurex Plus (Remel Europe Ltd, Dartford, UK) and PBP2 Latex Agglutination Test (Oxoid Ltd), to identify *S. aureus* and methicillin-resistant *S. aureus* isolates, respectively.

### Inpatient studies

An initial study evaluated use of the system for disinfection of an unoccupied isolation room, and results demonstrated a significant 90% reduction ( $P = 0.000$ ) in the staphylococcal contamination on surfaces around the room after 24 h use.<sup>58</sup> Studies in burns isolation rooms occupied by MRSA-positive patients, with treatment periods ranging from two to seven days, demonstrated that staphylococcal contamination on surfaces around the rooms was significantly reduced by 56–86%, over and above the reductions achieved by cleaning alone. Levels of presumptive *S. aureus* and MRSA showed similar reductions.<sup>58</sup> When use of the system ceased, recontamination of the room was observed, to levels similar to pre-treatment contamination levels.

An example of the data from one published study is shown in Figure 2, which demonstrates the mean reductions in the total staphylococcal counts and the presumptive *S. aureus* levels in an occupied burns unit isolation room, before, during and after five-day use of HINS-light EDS. Samples ( $N = 70$ ) were collected twice during each of the three phases, and the results from all sampled surfaces have been pooled to demonstrate the overall decontamination effect the system had across the room. In this study, data demonstrated that a significant 62% decrease in total staphylococcal counts and 50% decrease in presumptive

*S. aureus* were achieved ( $P < 0.05$ ) after five days' use of the system. 'After use' samples, collected during a six-day period after the system had been turned off, showed that contamination around the room had significantly risen, with 126% and 98% increases in the total staphylococci and presumptive *S. aureus* counts, respectively ( $P < 0.05$ ), thus reinforcing the recontamination effect that occurs after removal of the light treatment.<sup>58</sup> Extended use of the system also proved to further reduce the bacterial contamination around the room, supporting the continuous use of this system for maintaining low contamination levels around isolation rooms.<sup>58</sup> Importantly, studies were performed to show that the decontamination effect was not patient or room dependent.<sup>59</sup>

Studies carried out in an ICU isolation room also demonstrated system efficacy, with 60–70% reductions in both the staphylococcal and the total bacterial contamination across the entire sampled room environment.<sup>60</sup> In addition to demonstrating an overall reduction in contamination around the room, results demonstrated that exposed surfaces had reduced contamination levels as a result of use of the system, and an example of this is shown in Figure 3. Levels of bacteria on various surfaces around an occupied ICU isolation room were determined before use of the HINS-light EDS, and resampled after a five-day exposure period. Results demonstrated that despite marked variation in the initial bacterial bioburden there was a marked decrease in levels of bacterial contamination at all tested sites.

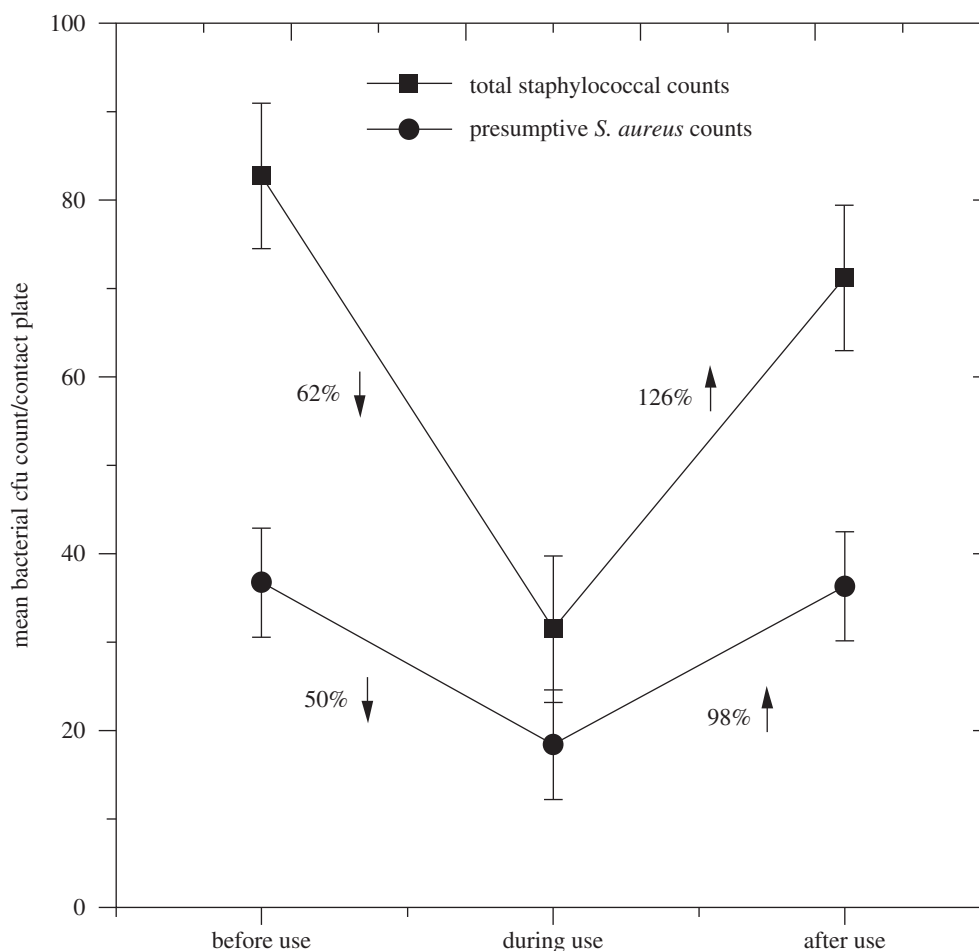
In addition to these findings, a significant factor noted in the studies carried out in the ICU isolation room was that despite asymmetrical positioning of the EDS units within the room, the special distribution of bacterial contamination was reduced almost uniformly across all the sampled contact surfaces. This suggested that disinfection of airborne bacteria contributes to the reductions in bacterial contamination levels, and the installation positions of the systems may not be critical.<sup>60</sup>

### Outpatient studies

In addition to its use for disinfection of occupied inpatient isolation rooms, the HINS-light EDS has also proved effective when used in an outpatient clinic.<sup>59</sup> Communal use of outpatient clinic rooms provides a recognized risk of cross-contamination between subsequently treated patients; therefore it is important to maintain cleanliness in these areas throughout the day. Studies were carried out to evaluate the environmental bacterial levels at the start and end of 8 h clinic sessions, with and without use of the EDS. A statistically significant 61% efficacy was achieved ( $P = 0.02$ ), leading to the suggestion that use of this system would be beneficial in other similar communal patient rooms such as the bathroom or physiotherapy room, where decontamination of all surfaces is unachievable between each patient due to time limitations.<sup>59</sup>

Overall, results have been successful, showing that use of 405 nm light achieves significant reductions in bacterial contamination levels around isolation room environments.<sup>58–60</sup> Results also demonstrated that when switched off, the decontamination effect ceases and bacterial contamination levels return to around pre-treatment levels, further confirming the effectiveness of the 405 nm light. It is important to note that these results were achieved under a range of clinical conditions within a busy city hospital environment, and that the bacterial disinfection results obtained were over and above





**Figure 2.** Mean reductions in the total staphylococcal colony-forming unit (cfu) counts and the presumptive *Staphylococcus aureus* levels across an occupied burns unit isolation room: before, during, and after five-day use of high-intensity narrow spectrum (HINS)-light environmental disinfection system (EDS). Contact plate samples ( $N = 70$ ) were collected twice during each phase and the results pooled to assess the overall decontamination effect. A significant 62% decrease in total staphylococcal counts and a 50% decrease in presumptive *S. aureus* were achieved ( $P < 0.05$ ). 'After use' samples showed that contamination around the room had significantly risen over the six days after the system had been switched off: 126% and 98% increase in the total staphylococci and presumptive *S. aureus* counts, respectively ( $P < 0.05$ ). (Data adapted from Maclean et al.<sup>58</sup>).

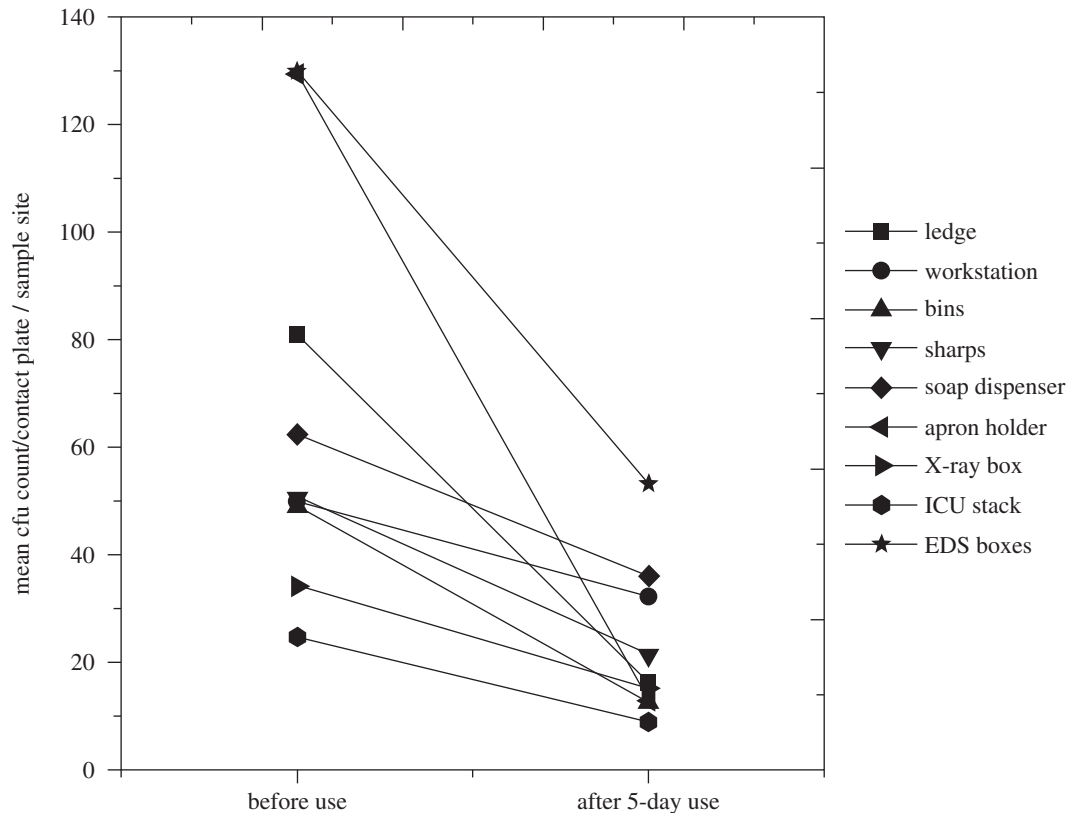
those achieved by the hospital's normal, stringent, infection control procedures which remained fully in place throughout the study.<sup>58–60</sup> Further studies are required to establish the effectiveness of 405 nm light for disinfection of larger communal environments.

### Comparison of 405 nm light with other environmental decontamination systems

Increased awareness of the importance of the hospital environment as a source of nosocomial pathogens has not only focused attention on improving the efficiency of conventional cleaning and disinfection procedures, but has also led to the development of a range of novel technologies for enhanced decontamination of whole-room environments, including new UV systems (as discussed earlier), steam cleaning, hydrogen peroxide vapour, and super-oxidized water fogging.<sup>7,65–67</sup> Although these systems are effective for widespread disinfection of the room environment, they require, for safety reasons, experienced operator supervision and their use is restricted to

unoccupied, sealed rooms, thereby resulting in rooms being out-of-commission for periods of time – a consequence which can be costly and undesirable in busy ward areas. Additionally, whereas these systems provide effective decontamination, studies have found that once treatment has finished, there is rapid and widespread recontamination of the room.<sup>68</sup> In addition to human safety considerations, another problem associated with UV light and chemically based technologies is the potential for long-term material degradation of furniture and equipment within the treated room if these are repeatedly exposed.<sup>69,70</sup> Therefore these methods are best-suited for terminal- and deep-cleaning procedures, but are ineffective for maintaining low levels of contamination.

Whereas UV irradiation and 405 nm light technology possess some similar features, they are in many respects quite distinct technologies both in their modes of action and methods of application (Table 1, Figure 1). Although UV light is strongly germicidal it is dangerous to humans, and the different UV waveband regions corresponding to UVC, UVB and UVA can cause a wide range of detrimental effects on the human eye and skin.<sup>70</sup> Violet–blue wavelengths within the visible



**Figure 3.** Reductions in the mean levels of environmental bacteria on a range of surfaces in an intensive care unit isolation room before and after five-day use of the high-intensity narrow spectrum (HINS)-light environmental disinfection system. Tryptone soya agar contact plate samples were collected from each surface and results pooled to show the mean reduction in contamination on the sampled surface. (Data adapted from Maclean *et al.*<sup>60</sup>).

spectrum can also cause harmful effects at high irradiance levels, especially at 440 nm which can cause photoreinitis, and at 480 nm which is the peak sensitivity of mammalian photo-sensitive retinal ganglion cells (pRGCs) which modulate diverse physiological responses to light, including circadian physiology and pupil constriction.<sup>61,62,76</sup> A comparison of the biological effects of radiation extending from the UV into the visible light regions is presented in Figure 1. Although 405 nm light is germicidal, it falls within a relatively benign wavelength region, and, if operated at appropriate irradiance levels, it is safe for human exposure.<sup>61,62</sup>

The above features explain why the 405 nm light environmental disinfection technology, in comparison with other whole-room decontamination systems including UV technology, can be operated continuously in the presence of patients and staff, thus facilitating a background decontamination effect which maintains low levels of contamination.<sup>58–60</sup> Continuous operation of the 405 nm light system ensures that there is a level of disinfection concurrently being applied even during periods of high activity, such as visiting hours, and bed and bandage changing.<sup>77,78</sup> Whereas disinfectant cleaning and hand hygiene are critical for maintaining a clean environment and minimizing the spread of potential pathogens, compliance with handwashing tends to be low after direct contact with a patient, and healthcare workers are even less likely to wash their hands after being in contact with the environmental surfaces around the patients, even though these surfaces can be reservoirs of potential pathogens.<sup>79</sup> Use of the 405 nm light

technology can strategically augment this by enhancing the low levels of contamination achieved with intermittent cleaning, and also provide decontamination of surfaces within rooms, such as walls and high ledges, as well as delicate equipment, which may not be routinely cleaned using disinfectants. Moreover the system can be automatically operated with no user training required, and consequently problems with staff and patient compliance do not apply.<sup>58–60</sup>

As with all methods of cleaning and disinfection, there are inherent disadvantages with any procedure. A limitation of the 405 nm light technology is that, to ensure that patient-friendly room illumination conditions are used, relatively low irradiance levels are applied and this impacts on microbial inactivation rates which are inevitably lower than can be achieved with other decontamination technologies albeit only in short-term comparisons. The high doses of 405 nm light required for inactivation of endospores means that it is unlikely that 405 nm light alone could be realistically applicable for the specific environmental decontamination of *C. difficile* spores. Nevertheless, enhancement of the inactivation may be achieved when combined with other decontamination methods such as oxidative biocides, due to the similar oxidative damage that is exerted on the bacteria by both treatments.<sup>33</sup> In addition to the resilience of spores, the antiviral efficacy of violet–blue light has not been fully established, and further research in this area is required. Also, similar to UVC technology, 405 nm light effectively treats hospital air, but only surfaces that are directly or reflectively exposed to the light are

Table I

Comparison of the properties of ultraviolet C (UVC) and 405 nm light for environmental disinfection applications

	UVC light	405 nm light
Typical/potential use	Terminal clean of air- and light-exposed surfaces.	Continuous disinfection of air- and light-exposed surfaces.
Safety	Significant safety hazards associated with human exposure; can cause DNA mutations, erythema. <sup>70</sup>	Can be used safely in the presence of people at recommended irradiation levels. <sup>58–60</sup>
Mechanism of action	DNA damage kills cells. Sublethally damaged cells can recover using photoreactivation mechanism to repair DNA. <sup>71,72</sup>	Photo-excitation of intracellular molecules induces oxidation of microbial cells. No known repair mechanism. <sup>73,74</sup>
Antimicrobial activity	Broad-spectrum action against a range of micro-organisms including spores and viruses. <sup>51,52</sup>	Effective against bacteria, fungi, yeasts and spores; antiviral activity not yet fully established. <sup>32,33,56</sup>
Antimicrobial efficacy	Rapid inactivation rate within treatment zone. <sup>6,24</sup>	Comparably slower inactivation rate within treatment zone. <sup>58–60</sup>
Materials compatibility	UV-light-associated polymer damage. <sup>69</sup>	Lower energy 405 nm wavelengths more materials compatible. <sup>69</sup>
Ease of use for environmental disinfection	Rooms/wards need to be vacated during use; operator training required. <sup>6,24</sup>	Can be safely used during room occupation; no operator safety training required. <sup>58–60</sup>
Microbial mutagenic potential	Powerful mutagen that may encourage resistance development.	Multi-target oxidative action mitigates against resistance development. <sup>75</sup>
Penetrability	Does not penetrate through plastics and glass, and weakly penetrates into water and fabrics.	Can penetrate through plastics and glass, and penetrates into water and fabrics. <sup>44</sup>

treated, and the effects on occluded or darkly shadowed areas are limited. It is also the case that whereas all of the new technologies including 405 nm light can claim to have demonstrated enhanced disinfection of the hospital environment, translation of this potential benefit into a significant reduction in infection rates will be required to ensure the widespread uptake of these new disinfection technologies.

### Further commentary regarding the application of 405 nm light for hospital disinfection

Regarding the deployment of the HINS-light system within hospitals, although important issues such as disinfection efficacy and patient safety have been addressed, other questions relating to the use of such a novel light source in clinical settings must also be considered. Undoubtedly enrichment of room lighting with additional violet–blue light will alter the normal lighting effect. This could have some impact on patient and staff comfort levels, and possible effects on medical procedures that involve colour perception must also be considered. In the hospital trials already conducted with the HINS-light EDS, no such issues have been problematic (unpublished observations) but monitoring for such effects must remain during uptake of this technology. Further hospital-based studies, funded by the Scottish Infection Research Network and the Chief Scientist Office, are currently being initiated to investigate the acceptability of the technology, and to ensure that the technology is optimized with staff and patient comfort fully taken into account. There may also be implications for colours employed in hospital furnishings and fabrics, as these may serve to amplify or suppress the reflection or absorption of violet–blue light.

As already discussed, a benefit of 405 nm light over UV-light for disinfection purposes is that, unlike UV-light, 405 nm light, because of its lower photon energy, does not cause photo-

degradation of photosensitive materials such as rubbers and plastics used in the hospital environment and equipment.<sup>69</sup> However, strong visible light can cause photochemical changes in light-sensitive solutions, and this aspect requires consideration if such solutions were to be exposed for long periods. At the relatively low 405 nm light intensities used, and considering the fact that light intensity decreases upon transmission through materials, e.g. plastic tubing or intravenous bag material, then this issue is not anticipated to be problematic but nevertheless must remain a consideration if highly light-sensitive pharmaceuticals were introduced.<sup>58–60</sup>

The HINS-light system uses LED-based technology and, as such, it benefits from the well-established characteristics of LED lighting, namely reduced energy requirements, long operational (lifetime) use, and low maintenance characteristics. In the hospital trials already conducted, the HINS-light EDS unit is designed to be easily retrofitted into the ceiling in place of a ceiling tile. Installed units have remained maintenance-free and fully operational over the trial period, which now extends to several years. From a lighting technology perspective, it is interesting that the introduction of this LED-based disinfection system is concurrent with major potential changes taking place in general lighting technology. Considerable debate is underway regarding the advantages and disadvantages of replacing conventional fluorescent lighting with LED sources, a discussion that is mainly being driven by potential energy efficiency gains associated with LED lighting. Another potential advantage of LED technology is the capacity to blend different colours to 'fine tune' the colour spectrum to suit different environments and applications. In this context it is interesting that it is now appreciated, and as previously discussed in this review, that the nature of the light spectrum can affect circadian rhythmicity, sleep and mood and that this is associated with photosensitive retinal ganglion cells in the eye.<sup>76</sup> Such effects are important not only in the home and

workplace but also for patients in the hospital environment, where it has been suggested that more research is required to better understand how lighting in the hospital environment can influence sleep, mood and pain in medical inpatients.<sup>22</sup> Future development of the HINS-light EDS system will undoubtedly be influenced by the various considerations outlined above.

## Conclusions

Although the germicidal effects of sunlight and UV light have been known for more than a century, it is only comparatively recently that the antimicrobial properties of visible light in the violet–blue region of the spectrum have been recognized and studied in a number of laboratories. Given the severity of current and anticipated future microbiological problems faced by society, the development of any new antimicrobial weapon is to be welcomed. Violet–blue light, with particular efficacy at 405 nm, has been shown to possess broad-spectrum photodynamic antimicrobial activity, so its use has been suggested for a range of potential clinical and medical applications.

One such application is the use of 405 nm light for environmental disinfection. The increased safety of 405 nm light wavelengths compared to UV light has facilitated development of this light technology for safe, continuous disinfection of occupied environments, and results have shown the successful application of this system for environmental disinfection of hospital isolation rooms and clinics. This technology, termed the HINS-light EDS, has demonstrated a significant capability for reducing environmental bacterial contamination in clinical patient areas, over and above reductions achieved using the conventional cleaning and infection control strategies alone. In common with the aspirations of other novel, whole-room disinfection systems, it is intended that this intervention technology, when used in conjunction with conventional infection control procedures, may help reduce numbers of pathogens in the environment, thereby limiting the likelihood of pathogen transmission from the environment to patients, and thus contribute to reducing levels of HCAs.

Whereas violet–blue 405 nm light irradiation represents a new antimicrobial approach, the physical nature of this light source and the limitations of its antimicrobial effects must be understood. Inevitably microbial inactivation rates using 405 nm light are slower than can be achieved with the typical application of many other physical and chemical disinfection and sterilization treatments. This limitation is, however, mitigated by its operational facility for continuous application to disinfect air and all illuminated surfaces in occupied environments and by the biochemical mechanism of 405 nm light inactivation. The photodynamic inactivation process induced by 405 nm light exposure involves a multi-targeted intracellular killing effect resulting from the generation of ROS, a killing mechanism that is not conducive to microbial resistance development. Given these unique features, it is evident that 405 nm violet–blue light technology represents a novel antimicrobial approach that may make some contribution to tackling the challenge posed by ubiquitous environmental contamination, and to the ongoing health and resource problems associated with HCAs.

## Conflict of interest statement

The intellectual property rights of the HINS-light EDS belong to the University of Strathclyde. The University has made all

systems for research purposes only and no commercial company manufactures this technology.

## Funding sources

None.

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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<sup>2</sup> 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 <sup>2</sup> )	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% <sup>a</sup>

HINS-light EDS, high-intensity narrow-spectrum light environmental decontamination system.

<sup>a</sup> 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

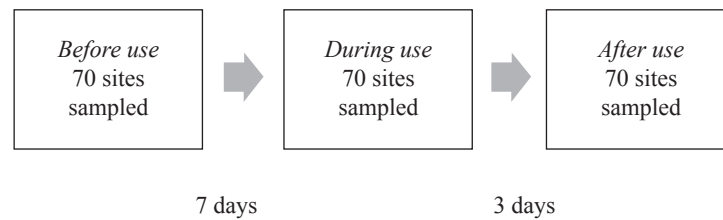
A radiant power meter and photodiode detector (Oriel Instruments, Stratford, CT, USA) was used to measure the irradiance, in mW/cm<sup>2</sup>, received at each of the sampling sites around the isolation room. Measurements were taken with the blue–violet 405 nm light of a single HINS-light EDS switched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

### Statistical analysis

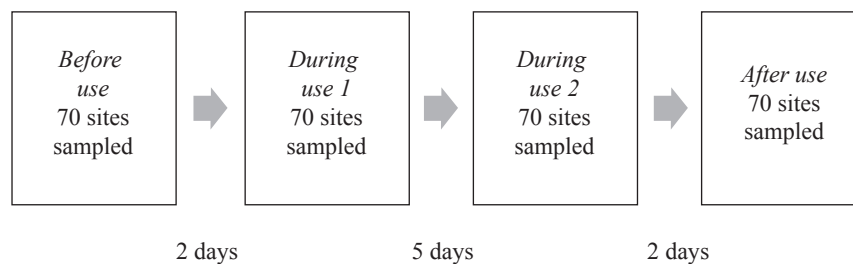
Following enumeration of bacterial colony-forming units (cfu), the mean cfu per plate for each study was calculated. Percentage reduction in bacterial count during use and percentage increase after use were also calculated. Further analysis was performed on log-transformed counts using Mini-tab V16. 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.

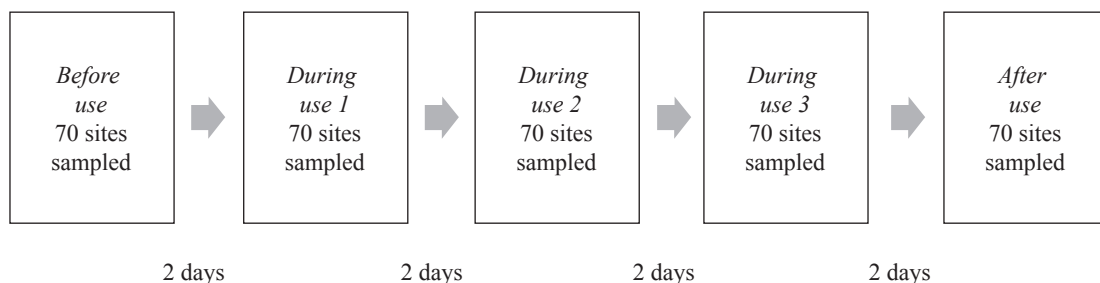
Patient A



Patient B



Patient C



**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

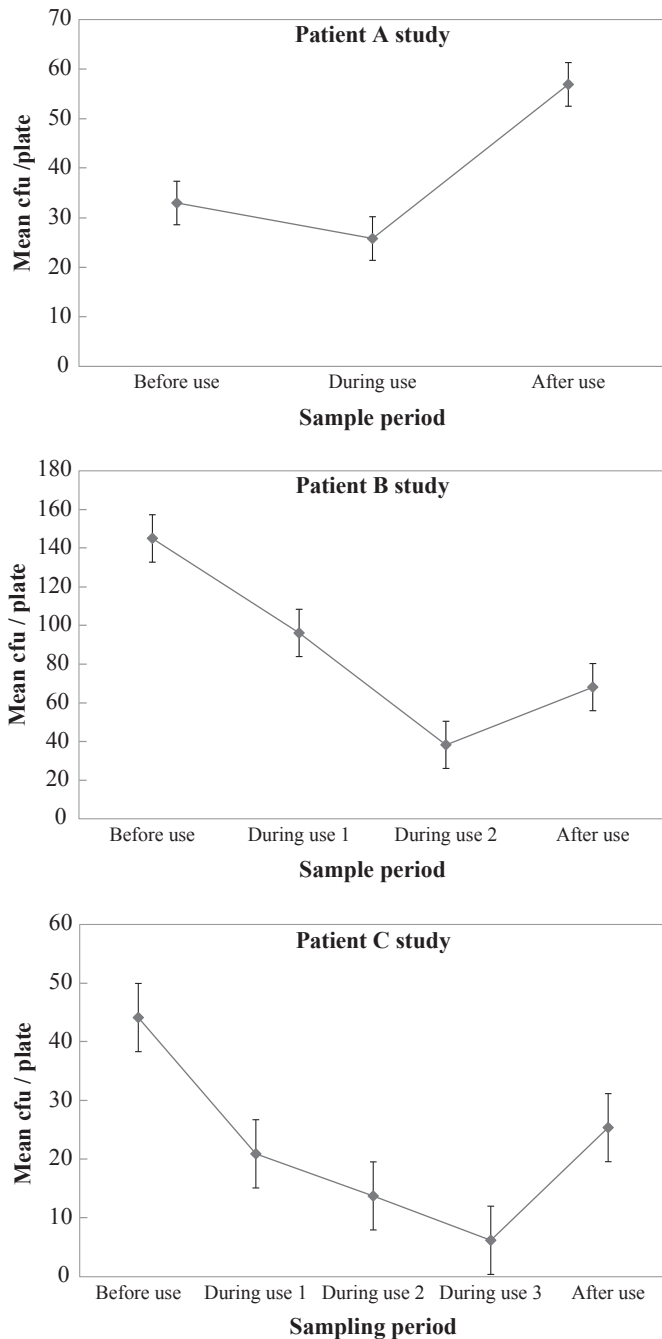
used continuously throughout the day. Another continuous technology under development is the release of essential oil vapour, although no clinical studies have been carried out to date [20]. Other technologies include products with antimicrobial coatings such as silver, but these do not achieve the universal 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<sup>2</sup>), 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.

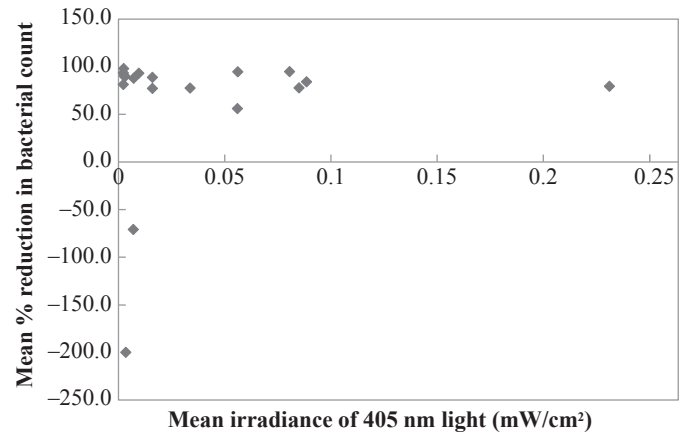
No attempt was made to isolate the bacteria in the environment, other than the use of BPA contact agar plates, which is an indicator of human-originating pathogens. Preliminary studies using broader-spectrum agars yielded too dense a population of bacterial cfu to count in many circumstances, as





**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 bio-burden 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.

## Funding sources

None.

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