Journal of Hospital Infection 153 (2024) 39–46

Available online at www.sciencedirect.com

Journal of Hospital Infection

journal homepage: www.elsevier.com/locate/jhin

Photodynamic coatings kill bacteria on near-patient surfaces in intensive care units with low light intensities

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ARTICLE INFO

Article history:
Received 31 May 2024
Accepted 8 August 2024
Available online 22 August 2024

Keywords:
Antimicrobial surface
Photodynamic coating
Decontamination
Pathogen transmission
Hospital-acquired infections

SUMMARY

Background: Surfaces in close proximity to patients within hospitals may cause healthcare-associated infections. These surfaces are repositories for pathogens facilitating their transmission among staff and patients. Regular cleaning and disinfection of these surfaces provides only a temporary elimination of pathogens with inevitable recontamination. Antimicrobial coatings (AMCs) of such surfaces may additionally reduce the risk of pathogen transmissions.

Aim: To evaluate the efficacy of a standard and a novel photodynamic AMC, even at very low light intensities, in a field study conducted in two ICUs at our university hospital.

Methods: The microbial burden was determined on three coatings: standard photodynamic AMC (A), a novel photodynamic AMC (B), and an inactive AMC as control (C). The control coating C was identical to standard coating A, but it contained no photosensitizer. During a three-month period, 699 samples were collected from identical surfaces using eSwab and were analysed (cfu/cm^2).

Findings: Mean values of all surfaces covered with control coating (C) showed a microbial burden of 5.5 ± 14.8 cfu/cm^2. Photodynamic AMC showed significantly lower mean value of 1.6 ± 4.6 cfu/cm^2 (coating A; $P < 0.001$) and 2.7 ± 9.6 (coating B; $P < 0.001$). When considering a benchmark of 2.5 cfu/cm^2, the relative risk for higher microbial counts was reduced by 52% (coating A) or 40% (coating B), respectively.

Conclusion: Both photodynamic AMCs offer a substantial, permanent risk reduction of microbial counts on near-patient surfaces in ICUs with low light intensities.

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https://doi.org/10.1016/j.jhin.2024.08.006

Introduction

Microbial infections, especially those caused by multidrug-resistant (MDR) bacteria, threaten millions of people worldwide and result in approximately 700,000 deaths each year. Leading researchers believe that in 25 years, up to 10 million people annually could die from infections caused by MDR bacteria. Furthermore, the economic burden is projected to reach US$100 trillion if proactive measures are not taken now [1]. It is widely accepted that inanimate surfaces serve as bacterial reservoirs for transmission both in public spaces and in healthcare-associated facilities [2–4].

In addition to hand hygiene, regular surface cleaning and disinfection in hospitals is intended to keep the microbial burden low. However, both hand hygiene and surface disinfection are prone to errors or neglect and have an effect only in the temporal context of their application [5,6]. Therefore, disinfected surfaces can be recontaminated within the next contact (hands, items), significantly increasing the risk of transmission to patients, staff, and/or other surfaces.

In addition to standard hygiene measures, antimicrobial coatings (AMCs) can help to decrease the risk of bacterial transmission through near-patient surfaces, possibly reducing the risk of nosocomial infections. However, if such AMCs are to benefit public health, it will be necessary to provide testing capabilities for proof-of-concept clinical studies using protocols that reflect safe end-use, that have regulatory guidance, and that are accessible to academic, clinical, and commercial stakeholders who are invested in bringing AMC products to market widely [7].

AMC based on the photodynamic effect has been shown to kill micro-organisms automatically and continuously, thereby significantly reducing the risk of high microbial counts in well-lighted hospital emergency rooms [8]. One coating used in the present study has already shown long-term efficacy in public transportation [9]. The coating is non-toxic, sufficiently stable against abrasion, and tolerates most of the standard surface disinfectants used in hospitals. In the photodynamic mechanism, a non-toxic molecule (photosensitizer) absorbs visible light and transfers the energy to nearby oxygen molecules, creating non-radical gaseous singlet oxygen. Once it is generated in the coating, singlet oxygen can escape from the coating and oxidatively kill microbes on the coated surface [10]. The higher the light intensity on the AMC, the more singlet oxygen is generated for microbial killing.

Intensive care units (ICUs) are one of the most vulnerable parts of a hospital but unfortunately have low light intensities. The present study is a further proof of concept clinical study, in which different surfaces in two ICUs at the University Hospital Regensburg, Germany, were equipped with three different coatings: standard photodynamic AMC (A), a novel photodynamic AMC (B), and an inactive as control (C). The aim of the study was to provide evidence that the photodynamic AMC can significantly reduce microbial burden even under poor light conditions in ICUs.

Methods

Study design

Prior to the field study, the surfaces to be sampled were identified. A hygiene team on-site documented how often individuals touched various surfaces. The most frequently touched surfaces were then selected for the field study (in total 11 hotspots).

Inanimate surfaces of two internal medicine ICUs at the university hospital in Regensburg, Germany, were covered with the standard photodynamic coating (TriOptoTec GmbH, Regensburg, Germany) (A), a further developed coating system (TriOptoTec GmbH; 50% shorter curing time at room temperature and 20% higher abrasion resistance in comparison to standard coating) (B), and the standard coating without photosensitizer (control coating C). A detailed description of the coatings is available in Supplementary Text A1.

ICU 1 (internal medicine) had a total of six rooms, plus one shared room with ICU 2 (cardiology) and vice versa. ICU 1 had 15 bed spaces; ICU 2 had 17 bed spaces (Supplementary Figure A1). Both ICUs had rooms of various sizes, including single-bed, two-bed, and four-bed rooms. The occupancy per room was determined by the interior architecture. Each bed space had the same equipment and size, ensuring equal treatment for every patient (Figure 1).

The two ICUs had a connection near the middle of the stations (only doctors and nurses). During the sampling period, ICU 1 had a bed occupancy rate of 70% and ICU 2 had a rate of 73.2%. The number of visitors is similarly regulated for both units: approximately one or two visitors per patient per day.

Frequently touched surfaces ('hotspots') in patient rooms (shelf below the infusion pump, patient tray, windowsill, nursing cart, PC documentation stations I and II), desks of doctors' and nurses' station, door handles (staff toilet), and blood gas analysis station (used by both ICUs) were symmetrically equipped with coating A, B, or C. The cleaning teams of all areas continued to work according to the hygiene schedule of the hospitals throughout the study. In brief, disinfectant cleaning of larger areas is carried out once a day with glycoprotamine (0.5% IncidinPlus; Ecolab, Monheim am Rhein, Germany) by cleaning staff. Smaller surfaces (e.g. nursing trolleys, infusion trolleys, perfusors, documentation surfaces with PC keyboards) were disinfected once per shift by the nursing staff using hydrogen peroxide (Ecolab Incidin OxyWipeS disinfectant wipes, flowpack with 100 wipes). Moreover, regular assessments were conducted to monitor the stability of each coating.

Sampling and quantification of microbes

The microbial counts (as colony-forming units; cfu) on all included surfaces were measured twice a week in the morning (approximately 08:00–11:00) before the cleaning and disinfection procedures on photodynamic and control coatings (timeline: three months; Supplementary Text A1). Microbial sampling was conducted using 'eSwab regular' (Mast Diagnostica GmbH, Reinfeld, Germany) and each hotspot was sampled within an area of 24 cm^2. The sample sizes were $N = 234$ (coating A), $N = 189$ (coating B), and $N = 276$ (coating C; in total 699 samples). As superordinate control samples, 250 μL of cleaning water of each ICU was transferred to a sterile tube and plated on fresh blood agar (incubation at 37 °C, 18–24 h). Additionally, for each sampling day, a negative control of an eSwab was included. The evaluation of microbial counts was based on European Standard EN13697. Counted values were converted into cfu/cm^2 (surface samples) or cfu/mL (cleaning water/negative control).

Figure 1. A typical patient zone. The red arrows indicate the near-patient hotspots (window sill, patient tray, shelf below the infusion pump).

On-site light conditions

In both ICUs, there was primarily indirect lighting in the patient rooms, whereas, at the doctor and nursing station, the staff toilet and the blood gas analysis station, direct lighting was available. The light intensity is the number of photons that reach the coated surfaces. The mean of all measured values was 8.2 ± 6.3 μW/cm^2 (AvaSpec-ULS2048L-EVO-RS, Avantes, The Netherlands). The measurements only consider photons in the spectral range from 360 to 440 nm and comprise photons from artificial light sources (e.g. LED or fluorescent tubes) and natural sunlight (if windows exist). All rooms used in this study had comparable light conditions.

Statistical analysis

All microbial counts are presented as mean ± SD and were compared between photodynamic and control coatings (A versus C; B versus C) using the non-parametric Kruskal–Wallis test. Microbial counts were further dichotomized using the cut-off >2.5 cfu/cm^2 [11]. Absolute and relative risk reductions as well as odds ratios with corresponding 95% confidence intervals (CI) were calculated as effect estimates. $P < 0.05$ was considered statistically significant. All analyses were performed using IBM SSPS statistics (version 29.0.0.0).

Results

Basic surface contamination on control coating C

In total, 276 samples were taken from the control coatings (C) without photosensitizer. The overall microbial load on all surfaces with the control coating C was 5.5 ± 14.8 cfu/cm^2; the microbial counts ranged from 0 to 124.0 cfu/cm^2 (Table I). Considering control surfaces touched exclusively by staff (N = 190; desks of doctors' and nurses' station (central point; N = 48), door handles (staff toilet; N = 32), blood gas analysis station (N = 16), nursing cart (N = 30), PC documentation station I (N = 32) and II (N = 32)), the microbial load was 3.1 ± 6.3 cfu/cm^2 (0–54.3 cfu/cm^2). Hotspots near patient contacted by both staff and patients and/or visitors (N = 86; 0–124.0 cfu/cm^2; shelf below the infusion pump (N = 29), patient tray (N = 28), windowsill (N = 29)) showed a microbial load of 10.9 ± 24.1 cfu/cm^2.

When comparing both groups, no significant difference was observed (P = 0.45). However, all means on control coating C significantly exceeded the benchmark of 2.5 cfu/cm^2, which indicates hygiene failures [11].

Overall microbial reduction performance of coating A and B

The measurement of microbial counts on all coated surfaces yielded 699 samples. Photodynamic coatings A (N = 234) and B (N = 189) showed an overall microbial load of 1.6 ± 4.6 and 2.7 ± 9.6 cfu/cm^2, respectively. The maximum load of coating A ranged from 0 to 60.0 cfu/cm^2, while that of coating B ranged from 0 to 94.8 cfu/cm^2. Both antimicrobial coatings significantly reduced the microbial count in comparison to the control coating C ($P \leq 0.001$). When comparing coating A with coating B, there was no statistically significant difference (P = 0.735; Supplementary Table A1). The risk for microbial counts >2.5 cfu/cm^2 was 15% for coating A, 19% for coating B, and 31% for coating C (Table II). Regarding a benchmark of 2.5 cfu/cm^2 the data yielded an absolute risk reduction of 16% and a relative risk reduction of 52% (coating A). For coating B the

Table I
Bacterial counts detected on tested surfaces in both ICUs coated with the photodynamically active coatings (A, B) or inactive control coating (C)

Location	Coating A (cfu/cm^2) Mean ± SD (no. of samples), range	Coating B (cfu/cm^2) Mean ± SD (no. of samples), range	Coating C (cfu/cm^2) Mean ± SD (no. of samples), range
Location			
Both ICUs	1.6 ± 4.6 (N = 234) 0–60.0	2.7 ± 9.6 (N = 189) 0–94.8	5.5 ± 14.8 (N = 276) 0–124.0
Only ICU 1	2.4 ± 7.0 (N = 94) 0–60.0	3.9 ± 13.1 (N = 95) 0–94.8	7.0 ± 17.7 (N = 160) 0–124.0
Only ICU 2	1.1 ± 1.5 (N = 140) 0–7.3	1.5 ± 3.1 (N = 94) 0–21.5	3.6 ± 9.2 (N = 116) 0–68.3
Hotspots near patient in patient rooms (both ICUs)	1.1 ± 1.8 (N = 92) 0–8.5	2.7 ± 8.6 (N = 95) 0–71.5	10.9 ± 24.1 (N = 86) 0–124.0
Hotspots distant from patient (both ICUs)	2.3 ± 7.0 (N = 94) 0–60.0	1.8 ± 4.3 (N = 94) 0–29.8	2.9 ± 7.2 (N = 94) 0–54.3
Central (outside patient rooms)	1.4 ± 1.4 (N = 48) 0–5.5	– –	4.3 ± 5.0 (N = 48) 0–20.7
Detailed locations			
Shelf below infusion pump[a]	1.1 ± 1.8 (N = 32) 0–7.3	1.7 ± 2.4 (N = 32) 0–10.0	16.8* ± 32.8 (N = 29) 0–124.0
Window sill[a]	1.5 ± 2.3 (N = 31) 0–8.5	5.4* ± 17.5 (N = 32) 0–94.8	12.1* ± 21.0 (N = 29) 0–90.3
Patient tray[a]	0.8 ± 1.1 (N = 29) 0–3.3	4.0* ± 13.4 (N = 31) 0–71.5	3.4* ± 12.9 (N = 28) 0–68.3
PC documentation I[b]	1.5 ± 3.2 (N = 32) 0–17.0	2.7* ± 4.5 (N = 32) 0–21.5	2.5 ± 4.1 (N = 32) 0–18.3
PC documentation II[b]	0.9 ± 2.3 (N = 32) 0–12.7	2.0 ± 5.6 (N = 32) 0–29.8	2.3 ± 6.5 (N = 32) 0–27.5
Nursing cart[b]	4.5* ± 11.5 (N = 30) 0–60.0	0.6 ± 0.9 (N = 30) 0–3.3	3.9* ± 9.9 (N = 30) 0–54.3
Door handles, staff toilet[c]	–	–	3.4* ± 6.6 (N = 32) 0–31.3
Blood gas analysis station[d]	–	–	0.6 ± 0.9 (N = 16) 0–3.0

ICU, intensive care unit; cfu, colony-forming units; SD, standard deviation.
[a] Hotspots near patient (both ICUs patient rooms).
[b] Hotspots distant from patient (both ICUs patient rooms).
[c] Outside wards.
[d] Inside wards.
* Values >2.5 cfu/cm and were recorded as hygiene failures [11].

absolute risk reduction was 12% and the relative risk reduction was 40% (Table III).

Mean reduction performance in both ICUs

In addition to the overall assessment, we also examined each of the two ICUs individually, as they have their own medical and nursing staff, which did not overlap.

ICU 1

The microbial count of control coating C ranged from 0 to 124.0 cfu/cm^2, with a mean value of 7.0 ± 17.7 cfu/cm^2 (N = 160). The photodynamic coating A showed a microbial count of 0–60.0 cfu/cm^2, with a mean of 2.4 ± 7.0 cfu/cm^2 ($P < 0.001$, N = 94), and the photodynamic coating B yielded a microbial count of 0–94.8, with a mean of 3.9 ± 13.1 cfu/cm^2 (N = 95; P = 0.002) (Table I and Supplementary Table A1). The risk of microbial contamination >2.5 was 16% for coating A, 20% for coating B, and 36% for the control coating (Table II).

Examining the benchmark of 2.5 cfu/cm^2, it becomes evident that coating A demonstrated 21% absolute risk reduction and 56% relative risk reduction (Table III). Coating B showed 17% absolute risk reduction and 45% relative risk (Table III), respectively.

ICU 2

The microbial count of control coating C ranged from 0 to 68.3 cfu/cm^2, with a mean value of 3.6 ± 9.2 cfu/cm^2 (N = 116; Table I). The risk for microbial counts >2.5 cfu/cm^2 is 14% (coating A) and 17% (coating B), whereas on control coating C the risk is 23% (Table II).

Table II
Risk calculations for high bacterial counts on surfaces (>2.5 (cfu)/cm^2) on the tested surface coatings

Locations	Coating A	Coating B	Coating C
All coatings			
cfu/cm^2 >2.5 (in total)	35 (234)	35 (189)	85 (276)
%	15%	19%	31%
ICU 1			
cfu/cm^2 >2.5 (in total)	15 (94)	19 (95)	58 (160)
%	16%	20%	36%
ICU 2			
cfu/cm^2 >2.5 (in total)	20 (140)	16 (94)	27 (116)
%	14%	17%	23%
Hotspots near patient			
cfu/cm^2 >2.5 (in total)	12 (92)	17 (95)	26 (86)
%	13%	18%	30%
Hotspots distant from patient			
cfu/cm^2 >2.5 (in total)	13 (94)	17 (94)	20 (94)
%	14%	18%	21%
Central point (doctors' and nurses' desks)			
cfu/cm^2 >2.5 (in total)	10 (48)	–	23 (48)
%	21%	–	48%
Door handles, staff toilet			
cfu/cm^2 >2.5 (in total)	–	–	10 (32)
%	–	–	31%
Blood gas analysis station			
cfu/cm^2 >2.5 (in total)	–	–	1 (16)
%	–	–	6%

cfu, colony-forming units; ICU, intensive care unit; coating A, photodynamically active coating; coating B, photodynamically active coating; coating C, inactive control coating.

Reconsidering the benchmark >2.5 cfu/cm^2, the ICU 2 data revealed an absolute risk of 9% (coating A) or 6% (coating B), a relative risk reduction of 39% (coating A) or 27% (coating B) (Table III).

Mean reduction performance of hotspots in patient rooms

Each bed space had six hotspots (shelf below the infusion pump, windowsill, patient tray, PC documentation I and II, nursing cart), equipped with either coating A, B, or C (Supplementary Figure A1). For each sampling day and each ICU, samples of each coating were taken, depending on room accessibility (on some days, for example, rooms could not be accessed due to isolation measures).

Hotspots in patient rooms (both ICUs) covered with control coating C sometimes showed significantly increased microbial counts. The microbial means of the surface of the shelf below the infusion pump, the windowsill, the patient tray, and the nursing cart ranged from 3.4 ± 12.9 to 16.8 ± 32.8 cfu/cm^2 with an absolute maximum of 124.0 cfu/cm^2. Only for the PC documentation I and II was the mean value below the benchmark of 2.5 cfu/cm^2 (Table I).

Hotspots covered with the active coating B showed values >2.5 cfu/cm^2 in only three out of six cases (windowsill 5.4 ± 17.5, patient tray 4.0 ± 13.4, PC documentation I 2.7 ± 4.5; Table I).

Coating A exhibited the best results regarding the benchmark of 2.5 cfu/cm^2. Only the nursing cart showed a mean >2.5 cfu/cm^2 with a maximum of 60 cfu/cm^2, all the other five hotspots were significantly below this benchmark.

Furthermore, we categorized the six hotspots in patient rooms into surfaces near the patients and surfaces distant from the patients. Among the hotspots near the patients were the shelf below the infusion pump, the windowsill, and the patient tray. The PC documentation station (two locations) and the nursing cart were among the surfaces distant from the patients. Surfaces near the patients are touched by staff, patients, and visitors or relatives, whereas surfaces distant from the patients are exclusively handled by staff. The microbial counting of hotspots near patients showed means of 1.1 ± 1.8 cfu/cm^2 ($N = 92$; coating A), 2.7 ± 8.6 cfu/cm^2 ($N = 95$; coating B) or 10.9 ± 24.1 cfu/cm^2 ($N = 86$; coating C), respectively. The microbial means of hotspots distant from patients showed a lower burden: 2.4 ± 7.0 cfu/cm^2 ($N = 94$) for coating A, 1.8 ± 4.3 cfu/cm^2 ($N = 94$) for coating B, and 2.9 ± 7.2 cfu/cm^2 ($N = 94$) for control coating C (Table I).

When comparing active coating A or B with control coating C, the *P*-value of hotspots near patient was $P < 0.001$ (A) or $P = 0.030$ (B), while no significant difference was observed for patient-distant hotspots ($P = 0.122$ or $P = 0.858$, respectively; Supplementary Table A1).

Therefore, the risk of high microbial burden (>2.5 cfu/cm^2) of near-patient hotspots was only 13% for coating A, 18% for coating B, and, by contrast, 30% for the control coating (Table II). This resulted in a relative risk reduction of near-patient hotspots of 68% (coating A) and 56% (coating B), respectively (Table III).

Table III
Absolute and relative risk reduction of having a high surface contamination (>2.5 cfu/cm^2) calculated by comparing bacterial counts on photodynamically active coatings (A, B) and inactive control coating C

Locations	Coating A				Coating B			
	AR reduction	RR reduction	OR (95% CI)	*P*-value	AR reduction	RR reduction	OR (95% CI)	*P*-value
All surfaces	16%	52%	0.39 (0.25–0.61)	<0.001	12%	40%	0.51 (0.33–0.80)	0.003
ICU 1	21%	56%	0.33 (0.17–0.63)	<0.001	17%	45%	0.44 (0.24–0.79)	0.006
ICU 2	9%	39%	0.55 (0.29–1.04)	0.064	6%	27%	0.68 (0.34–1.35)	0.264
Hotspots near patient	27%	68%	0.22 (0.11–0.47)	<0.001	22%	56%	0.32 (0.16–0.64)	<0.001
Hotspots distant from patient	8%	36%	0.59 (0.27–1.26)	0.170	3%	16%	0.81 (0.39–1.66)	0.557
Central point (doctors' and nurses' desks)	27%	57%	0.29 (0.12–0.70)	0.005	–	–	–	–

AR, absolute risk; RR, relative risk; OR, odds ratio; CI, confidence interval; cfu, colony-forming units; ICU, intensive care unit.

Considering the risk of microbial counts >2.5 cfu/cm^2, it was 14% for patient-distant hotspots for coating A, 18% for coating B, and 21% for coating C (Table II). The relative risk reduction for patient-distant hotspots was 36% for coating A and 16% for coating B, respectively (Table III).

Mean reduction performance of central meeting point

The two ICUs are centrally connected and the central point serves as a meeting point for doctors and nursing staff. Both ICUs exhibited a comparable frequency of surface contact. For ICU 1, half of the tables and counters of the central point were coated with the control coating C, while the other half for ICU 2 was equipped with the active coating A (Figure 1). The mean microbial count of coating A was 1.4 ± 1.4 cfu/cm^2 ($N = 48$; 0–5.5 cfu/cm^2), whereas the microbial burden of control coating C was 4.3 ± 5.0 ($N = 48$; 0–20.7 cfu/cm^2). Therefore the difference between the two groups is highly statistically significant ($P < 0.001$; Supplementary Table A1). The microbial load on coating A exceeded 2.5 cfu/cm^2 in 10 out of 48 samples (21%), whereas for control coating C, it was observed in 23 out of 48 samples (48%; Table II). This result in an absolute or relative risk reduction for coating A of 27% or 57%, respectively (Table III).

Microbial contamination of the door handles (staff toilet) and at the blood gas analysis station

Outside the two ICUs, a toilet is available for the staff of both units. On each sampling day, samples were taken from both the inside ($N = 16$) and outside ($N = 16$) of the door handles. The overall microbial load was 3.4 ± 6.6 cfu/cm^2 (Table I). Ten out of 32 (31%) samples exceeded the benchmark of 2.5 cfu/cm^2 (Table II). Comparing the inside to the outside of the door handle, the inside exhibited increased microbial counts (>2.5 cfu/cm^2) in seven out of 16 samples (44%), while the outside showed this in only three out of 16 samples (19%). There was no statistically significant difference measured between the two groups ($P = 0.239$; data not shown).

The blood gas analysis station is located centrally between both units (Supplementary Figure A1) and is used by the staff of both units. The samples ($N = 16$) yielded an average of 0.6 ± 0.9 (0–3.0 cfu/cm^2; Table I). In only one case did the microbial count exceed the limit of 2.5 cfu/cm^2 (6%; Table II).

Controls

On each sampling day, the following controls were conducted: 250 µL samples of cleaning water (from the cleaning cart) from both units ($N = 32$), and a negative control of eSwabs ($N = 16$). In no case was the microbial count >2.5 cfu/mL. Regarding the cleaning water, the absolute maximum count of microbes was 2.0 cfu/mL with a mean of 0.1 ± 0.4 cfu/cm^2. The mean count of the eSwab negative control was 0.0 ± 0.0 cfu/mL.

Discussion

Basic contamination of inanimate ICU surfaces

To date there are only a few studies on the microbial contamination of inanimate surfaces in ICUs. Some studies showed microbial counts on ICU surfaces ranging from 1 cfu/cm^2 up to 1.8×10^5 cfu/cm^2 [12–16]. In our tertiary care hospital, two internal medical ICUs were examined for microbial counts on frequently touched surfaces ('hotspots'). The overall bioburden on the control coating C was 5.6 ± 14.9 cfu/cm^2. In comparison to values from the other cited studies, our result seems quite acceptable; however, when considering the benchmark of 2.5 cfu/cm^2, the microbial count on control surfaces is not acceptable due to higher risk for nosocomial infections [11]. On some near-patient hotspots (covered with control coating C) we detected values up to 16.8 ± 32.8 cfu/cm^2 even if the standard hygiene measures for surfaces had been applied in ICUs. It is undisputed that between two cleaning or disinfection measures, microbial contamination of surfaces increases again upon any contact with contaminated hands and/or items. To address such hygiene gaps, we developed an antimicrobial coating based on the photodynamic technology.

Evaluation of microbial counts on coatings A and B showed statistically significantly less contamination as compared to the control coating C. In a previous study conducted in emergency rooms, ambulance cabins, and patient rooms in two hospitals, similar results were observed although the average light intensity was about 10 times higher than in the current study [8]. This demonstrates that the photodynamic AMC effectively reduces the microbial count even under unfavourable light conditions (e.g. indirect or dim lighting in patient rooms).

It is known that in healthcare settings important pathogens are transferred via inanimate surfaces and that these surfaces act as microbial reservoirs [11,17]. It is also worth mentioning that the mean microbial load on the active coatings A is below the benchmark of 2.5 cfu/cm^2. Exceeding this value indicates a hygiene failure with an increased risk of hospital-acquired infections [11].

The values in Table I provide clear evidence that the photodynamically active coatings ensure a significant reduction of the total microbial count on surfaces that leads to a significant risk reduction for microbial transmission through surfaces. This, in turn, may lead to reduced numbers of nosocomial infections.

Furthermore, it is important to know which surfaces in ICUs are more frequently contaminated in order to tailor hygiene measures accordingly. For this reason we categorized hotspots in patient rooms into two different groups: hotspots near patients (shelf below the infusion pump, windowsill, patient tray) and hotspots distant from patients (PC documentation I and II, nursing cart; Table I). Hotspots near patients are frequently touched by staff, patients, and visitors, while hotspots distant from patients are only touched by staff. In our study the highest microbial counts on control coating C were recognized at the shelf below the infusion pump and the windowsill. On such surfaces, items such as dentures, toothbrushes, combs, and bedding were deposited. On average, hotspots near the patient were more contaminated (control coating C) as compared to surfaces distant from patients. This is not surprising, as surfaces can be more heavily contaminated the closer they are to the patient [11,18,19]. Regarding the effectiveness of photodynamic coatings A and B, the microbial burden was significantly reduced, even on highly contaminated hotspots near patient.

The central meeting point was equipped with coating A on one half and with the control coating C on the other half. Only doctors and nurses were active at the central point. The comparison between coating A and control coating C again

showed a significantly lower microbial load. Moreover, the microbial load on coating C significantly exceeded 2.5 cfu/cm^2. This could contribute to a spread of pathogens in ICUs by the staff.

It should be noted that some limitations might have been present in the study. Usually, the microbial counts on inanimate surfaces that are colonized by micro-organisms vary from very small to extremely high values. One reason for this may be that recovery and thus quantification of microbes on surfaces significantly depends on the available measurement method due to dry biofilm formation [17]. Our study used moist swabs for detection of microbes on ICU surfaces ('eSwab regular'). Using swabs we assume that we are likely to recover only planktonic or loosely attached microbes. Moreover, there has been discussion about the epidemiology of dry biofilms on healthcare surfaces and their distribution across frequently touched sites [20,21]. Little is known about the effectiveness of singlet oxygen on dry biofilms so far. In principle, singlet oxygen oxidizes many microbial biomolecules, including those of an extracellular matrix of a biofilm. Various in-vitro studies on wet biofilms have shown good efficacy in laboratory experiments [22]. Thus, it is conceivable that singlet oxygen may also attack biomolecules in dry biofilms, thereby reducing the formation and/or spread of such biofilms. Hence, it would be beneficial to test whether photodynamic coatings can also inhibit the formation of dry biofilms, both in laboratory tests and field studies.

In conclusion, up-to-date, antimicrobial coatings based on photodynamics already showed their effectiveness in several field studies by comparing cfu/cm^2 [8,9,23]. This additional proof-of-concept clinical study demonstrates that photodynamic AMCs can significantly reduce the microbial burden on frequently touched surfaces in ICUs, even under poor light conditions. This reduces the risk of high microbial loads, which in turn can have a positive impact on the transfer of microbes through surfaces. The highest microbial counts were measured on surfaces near patients, therefore hygiene measures should be tailored accordingly. Furthermore, it is worth mentioning that the photodynamic coating, compared to other coatings (e.g. contain metals, biocides, quaternary ammonium compounds), is safe for the environment and humans, does not lead to microbial resistance, and does not release toxic substances into the environment [24,25]. AMC based on photodynamics therefore fulfils all criteria as an effective supplement to traditional infection prevention measures to support the decontamination of the environment and thus prevent nosocomial transmission of microbes.

Acknowledgements

We thank T. Kocyba from the infection prevention team for his excellent technical support.

Conflict of interest statement

D. Raab was an employee of TriOptoTec GmbH until March 31st, 2024. He received consulting fees from Dyphox GmbH. All other authors declare no competing interests.

Ethics statement

Not required.

Funding sources

W. Schneider-Brachert recieved as project leader a grant ('PACMAN'; AZ-1411-19) from the 'Bayerische Forschungsstiftung', Munich, Germany.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhin.2024.08.006.

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