

Utility of nano-impregnated surface coating to achieve continuous active disinfection in ICU of a tertiary trauma center

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Abstract

Introduction: Implementing continuous active disinfection presents challenges as conventional cleaning methods may not fully mitigate risks. Hence, evaluating innovative technologies becomes imperative. This study assessed a nanoparticle-based surface coating containing titanium dioxide engineered into nano-molecules that is activated by normal light and provides ongoing disinfection.

Methodology: The research took place in two intensive care units (ICUs): ICU A (coated) and ICU B (control). Data on healthcare-associated infections (HAIs) and environmental factors were collected pre- and post-coating application to gauge its impact. The change in percentage of positive swabs/HAI cases in ICU A was compared to ICU B and statistically analyzed using a 2-sample test for equality of proportions.

Results: ICU A witnessed a 26.5% decrease in positive environment swabs post-coating, while ICU B saw a 160.9% increase. This disparity was statistically significant ($p = 0.000$). Both ICUs experienced decreased ventilator associated pneumonia (VAP) cases, though central line associated-blood stream infection (CLA-BSI) and catheter associated urinary tract infection (CAUTI) cases increased in ICU A post application. Following coating, positive environmental swabs and VAP decreased by 71.8%, and 72.5%, while CLA-BSI and CAUTI increased by 198% and 43.5%.

Conclusions: The evaluation showed that the coating may serve to supplement traditional cleaning and disinfection methods. Further research into the efficacy and cost-effectiveness of such antimicrobial coating is needed for overall improvement in patient care.

Key words: infection control; hospital acquired infection; continuous active disinfection; antimicrobial; coating; decontamination.

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Introduction

Healthcare-associated infections (HAIs) are the primary cause of preventable mortality and disability among hospitalized patients. HAIs lead to an increase in the length of hospital stay, undue burden on infrastructure, and an increase in direct healthcare costs to the whole system and the patient [1,2]. The pathogens that cause HAIs can survive on inanimate surfaces for weeks, or even months, and can serve as constant sources of transmission in the absence of adequate infection control measures [3]. Though the patient's endogenous flora is most likely the main source of nosocomial pathogens, about 20% to 40% of HAIs have been attributed to cross-infection through the hands of healthcare workers which can get contaminated with multidrug-resistant organisms (MDROs), *Clostridioides difficile* (*C. difficile*), and other common

HAI pathogens after coming in contact with surfaces [4]. Although detergent- and disinfectant-based cleaning does help control these pathogens, surfaces can be re-contaminated immediately after cleaning [5]. There have been mixed results on the benefits of automated devices using hydrogen peroxide (H₂O₂) or ultraviolet (UV) light for surface decontamination [6].

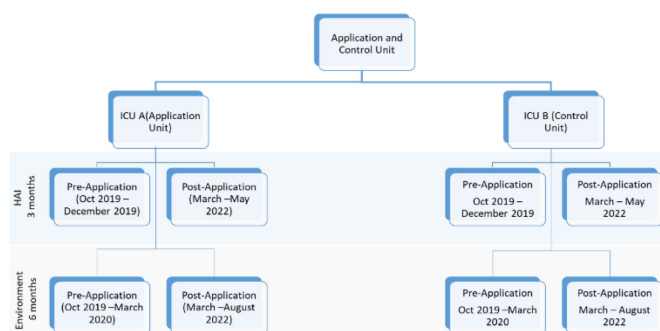
Since there are so many challenges to controlling these notorious nosocomial pathogens, and cleaning and decontamination practices do not necessarily eliminate all the risks, antimicrobial coatings might offer an additional safeguard to routine cleaning. Such coatings may be a useful option to compensate for the daily deficits in routine cleaning and disinfection. Therefore, there is an urgent need for research on new innovative technologies that can confer persistent and continuous antimicrobial activity, with evaluations of

the clinical impacts on patient outcomes.

Although environmental decontamination remains a cornerstone of infection prevention, the effectiveness of routine detergent- and disinfectant-based cleaning is influenced by technique, frequency, contact time, and compliance. Automated adjunctive methods such as UV-C irradiation and vaporized H_2O_2 have demonstrated reductions in environmental bioburden; however, their impact on sustained clinical outcomes has been inconsistent and they do not provide continuous antimicrobial activity. Recent interest has therefore shifted toward engineered antimicrobial surface technologies, including copper, silver, quaternary ammonium compound-impregnated materials, and photocatalytic titanium dioxide (TiO_2) coatings. While several studies have reported significant reductions in environmental colony-forming units following application of such coatings, robust evidence demonstrating consistent reductions in device-associated HAIs remains limited. Thus, there is a gap in understanding whether reduction in environmental contamination translates into meaningful decreases in ventilator-associated pneumonia (VAP), central line-associated bloodstream infection (CLA-BSI), and catheter-associated urinary tract infection (CAUTI), particularly in high-risk trauma intensive care settings.

Given the worldwide concern over escalating antimicrobial resistance, it is clear that more studies on healthcare decontamination are required. This study evaluated a nanoparticle-based surface coating that comprises of TiO_2 engineered into nano-molecules of optimum size, shape, morphology, crystallinity, and concentration, which is activated by normal light, thus providing for continuously active disinfection.

Figure 1. Study design and timeline of data collection in application and control intensive care units (ICUs).



HAI: hospital-acquired infection.

Methodology

The study was conducted in two intensive care units (ICUs) of a 186-bed tertiary care trauma center; hereafter referred to as ICU A and ICU B. ICU A is a 12 bed ICU that usually has trauma patients from surgery and orthopedic divisions. ICU B is a 23-bed ICU and admits trauma patients from the neurosurgery division. ICU A was considered as the application unit where the antimicrobial surface (AMS) coating was applied. ICU B was the control unit where no coating was applied.

Application protocol

Certified technicians followed a uniform protocol for the application of coating after proper preparation of the surface. The procedure of application was closely monitored by the observer representative for quality control purposes. Coating was done on all surfaces including the walls, bed frames, medical equipment, nurses' station, etc.

Prior to applying the coating, the surfaces were evaluated for all physical parameters that play a role in hospital infections such as surface moisture, temperature, corrosion, surface dust, etc.; and the parameters were corrected wherever possible. All the dust particles were removed from the surfaces by lint-free cloth, and from the embedded pores by cyclone suction. Surface de-greasing using a special oxy-detergent was done to remove all slime, oil, and dried blood. Surface autoclaving was done using moist heat with metal ions under appropriate pressure and for appropriate time to eliminate dry surface biofilms, mold, and microbial growth. A base coat was applied using a pneumatic spray system to increase the surface life of the final coating. The final coating was done by administering pure TiO_2 .

The hospital staff maintained their daily cleaning schedule in all areas prior to and after the application of the coating. This involved disinfecting with hospital-grade disinfectants, such as bleach or quaternary ammonium compounds. There were no changes in infection prevention or cleaning protocols throughout the post-application study period.

Two types of data were collected to quantify the impact of the coating–HAI and environmental data. These two types of data were collected for both the ICUs (ICU A and ICU B) and for two time periods (pre-application and post-application; Figure 1).

Impact of coating on HAI

The VAP, CLA-BSI, CAUTI, surgical site infection (SSI), and HAI rates in the 3-month pre-application

period (October 2019 to December 2019) and 3-month post-application period (March to May 2022) were collected for both the ICUs. The change in the percentage of cases of HAIs in the two time periods for both ICUs A and B (application and control unit) was calculated and the change in the application unit (ICU A) was compared to that of the control unit (ICU B). The data for HAIs was collected as a part of routine HAI surveillance in the hospital, following the National Healthcare Safety Network (NHSN) protocols [7].

Impact of coating on hospital environment

Pre-application and post-application environmental samplings were done by swabbing. Cotton swabs were swept from pre-determined sites, immersed in TGB broth, and transported to the microbiology lab. The broth samples were checked for turbidity after overnight incubation. The turbid broth samples were sub-cultured onto agar plates, incubated overnight, and read for growth; the growth was subsequently processed and identified.

The swabs were collected from both the ICUs once every 2 weeks for 6 months from October 2019 to March 2020 (pre-application period) and from March to August 2022 (post-application period). The change in the percentage of positive swabs in the two time periods for both ICU A and B (application and control unit) was calculated, and the change in the application unit (ICU A) was compared to that of the control unit (ICU B).

$$\Delta PS = \frac{PSt - PSp}{PSp}$$

Where:

ΔPS : Change in % positive swabs or HAI;

PSt : % positive swabs or HAI post-application;

PSp : % positive swabs or HAI pre-application.

The key hypothesis in this analysis was that nano paint would result in reduction of percentage of positive environmental swabs/HAI in the application unit compared to the control unit. This hypothesis would hold true if:

1. There was a drop in the percentage of positive swabs/HAI in the application unit that was more than the percentage drop in the control unit.
2. There was a drop in the percentage of positive swabs/HAI in the application unit whereas the percentage of positive swabs/HAI increased or remained the same in control unit.
3. There was a percentage increase in positive swabs/HAI in the application unit; however,

this increase was less than the percentage increase in positive swabs/HAI in the control unit.

4. The hypothesis would be rejected in any other scenario.

Impact of the coating on HAIs in the application unit

The rise or drop in HAIs after application of the coating in ICU A was calculated by comparing the expected percentage (in case there was no coating done in ICU A) of positive swabs or HAI cases and the actual percentage of positive swabs or HAI cases found post-coating by using the formula below:

$$\Delta CaA = \frac{PS_{exp} - PS_{act}}{PS_{exp}}$$

Where:

ΔCaA : Rise or drop after coating in ICU A;

PS_{exp} : Expected % of positive swabs or HAI cases;

PS_{act} : Actual % of positive swabs or HAI cases post coating;

The expected percentage was calculated by assuming that ICU A would have showed the same growth of positive swabs or HAI cases as ICU B in case no coating was done in ICU A. Hence, in order to calculate the expected percentage of positive swabs or HAI cases, the value was extrapolated using the formula below:

$$PSA = \frac{PSA_{pre} \times PSB_{post}}{PSB_{pre}}$$

Where:

PSA : Expected % of positive swabs or HAI cases in ICU A;

PSA_{pre} : % positive swabs or HAI cases in ICU A (pre application);

PSB_{post} : % positive swabs or HAI cases in ICU B (post application);

PSB_{pre} : % of positive swabs or HAI cases in ICU B (pre application)

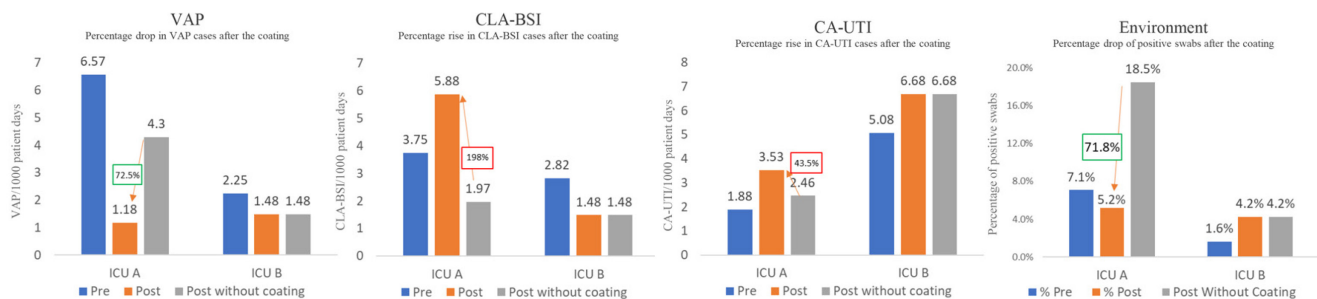
Statistical analysis

The statistical significance of the difference in percentage change of positive swabs or HAI cases was assessed using two sample tests for equality of proportions and the level of significance was determined. The values with 95% confidence intervals at the p value of < 0.05 were considered to be significant.

Table 1. Analysis of environmental sampling for the pre- and post-application time periods and comparison between the application (ICU A) and control (ICU B) units.

Unit	Pre-application period			Post-application period			Change in % of positive swabs	<i>p</i> value
	Positive swabs	Total swabs	% of positive swabs	Positive swabs	Total swabs	% of positive swabs		
ICU A (Application unit)	15	212	7.1%	13	250	5.2%	- 26.5%	0.000; CI: - 0.6385 to 0.8314
ICU B (Control unit)	4	247	1.6%	9	213	4.2%	160.9%	

ICU: intensive care unit; CI: confidence interval.

Figure 2. Percentage drop or rise in positive environmental swabs/HAI cases after the coating.

The grey bar represents the expected percentage of positive swabs/HAI cases in ICU A calculated (using extrapolation by the formula given in methodology) by assuming that ICU A would have showed the same growth of positive swabs/HAI cases as ICU B in case no coating was done in ICU A. HAI: hospital-acquired infection; ICU: intensive care unit; VAP: ventilator associated pneumonia; CLA-BSI: central line associated blood stream infection; CA-UTI: catheter associated urinary tract infection.

Table 2. Analysis of HAI cases for the pre and post time periods, and comparison between the application (ICU A) and control (ICU B) units.

Unit	Pre application period			Post application period			% Change in Episodes	<i>p</i> value
	VAP	Total patient days	VAP/1000 pt days	VAP	Total patient days	VAP/1000 pt days		
ICU A (Application unit)	7	1,066	6.57	1	851	1.18	- 82.4%	0.000; CI: - 0.6385 to 0.8314
ICU B (Control unit)	4	1,771	2.25	2	1,348	1.48	- 34.3%	
Unit	CLA-BSI / 1000 patient days			CLA-BSI / 1000 patient days			% change in episode	<i>p</i> value
	CLA-BSI	Total patient days	CLA-BSI/1000 pt days	CLA-BSI episodes	Total patient days	CLA-BSI/1000 pt days		
ICU A (Application unit)	4	1,066	3.75	5	851	5.88	56.6%	0.000; CI: 0.8972 to 1.000
ICU B (Control unit)	5	1,771	2.82	2	1,348	1.48	- 47.4%	
Unit	CA-UTI / 1000 patient days			CA-UTI / 1000 patient days			% change in episode	<i>p</i> value
	CA-UTI	Total patient days	CA-UTI/1000 pt days	CA-UTI episodes	Total patient days	CA-UTI/1000 pt days		
ICU A (Application unit)	2	1,066	1.88	3	851	3.53	87.9%	0.000; CI: 0.4438 to 0.6861
ICU B (Control unit)	9	1,771	5.08	9	1,348	6.68	31.4%	

Two sample test for equality of proportions was used to test the statistical significance of the difference in the change in percentage of HAI cases, and *p* values were calculated at 95% CI. ICU: intensive care unit; CI: confidence interval; HAI: hospital acquired infection; VAP: ventilator associated pneumonia; CLA-BSI: central line associated bloodstream infection; CAUTI: catheter associated urinary tract infection.

Results

ICU A (application unit) had a 26.5% decrease in percentage of positive environment swabs post coating, whereas ICU B (control unit) had a 160.9% increase in percentage of positive swabs in the same time period (Table 1).

The difference in the change in percentage between the two ICUs was statistically significant. ($p = 0.000$; CI: 0.6385–0.8314).

There was a decrease in the percentage of VAP cases in both ICU A and ICU B, but the decrease was more in ICU A (82.4% decrease) compared to ICU B (34.3% decrease). CLA-BSI cases increased by 56.6% in ICU A, although there was a 47.4% decrease in ICU B. There was an increase in CAUTI cases in both the ICUs, but the increase was greater in ICU A (87.9% increase) compared to ICU B (31.4% increase). There were 2 cases of SSI in ICU A and 3 cases of SSI in ICU B in the pre application period, and no cases were detected in either of the ICUs in the post application period. The results are summarized in Table 2.

If no coating had been applied in ICU A, there would have been 18.5% positive swabs and 4.3 VAP cases for every 1000 days in the post application time period. Hence, there was a 71.8% and a 72.5%, reduction in the percentage of positive environmental swabs and VAP, respectively, due to the coating.

If no coating had been applied in ICU A, there would have been 1.97 CLA-BSI and 2.46 CAUTI cases for every 1000 patient days in the post-application period. Therefore, there was a 198% increase in CLA-BSI and a 43.5% increase in CAUTI following coating (Figure 2).

Discussion

HAIs occur more frequently in trauma patients compared to non-trauma patients. A descriptive study noted that the development of HAIs was associated with all injury sites, except the face, in trauma patients [8]. In a study conducted on inpatient samples in the United States based on a nationally representative database, it was found that trauma patients with HAIs were at a 6 times higher risk for mortality, have 3–4 times longer length of stay (LOS), and suffer 2.6–6 times higher inpatient costs, compared to patients without HAI [9]. Invasive devices and compromised integrity in this subset of population lead to longer ICU stays, potentially aggravating the overall associated costs for the patients and the hospital [10].

It is well established that the contaminated hospital environment facilitates transmission of several important healthcare-associated pathogens, including

vancomycin-resistant enterococci (VRE), *Clostridium difficile*, *Acinetobacter spp.*, methicillin-resistant *Staphylococcus aureus* (MRSA), norovirus, and other MDROs [11]. The source of these pathogens is most frequently the patients themselves and the healthcare workers; and the pathogens are deposited on inanimate surfaces, bed railings, and walls for days or even months, and cause a substantial increase in the risk of infection in susceptible patients [3]. There is a consensual agreement that meticulous cleaning and disinfection of environmental surfaces, patient rooms, and the areas frequently touched by hands is a must for an effective infection prevention program [12]. There is an increased risk of acquisition of MDROs by patients who are admitted to a room where the prior occupant was colonized/infected with resistant pathogens. The major contributor to this was found to be inadequate disinfection at the time of patient discharge [13,14]. There are several factors which affect the cleaning and disinfection process of the patient environment. Effectiveness is also determined by the type of surfaces being cleaned and the type of material used to clean [15,16]. For instance, the durability of the cotton cloth used, its tolerance to high temperature, effect of multiple washings, and binding to the disinfectant used, are all factors which account for the success of pathogen clearance [16]. An alternative is to use microfiber wipes/cloth; but here again there is significant evidence that if these microfiber clothes are not used properly, they can lead to spread of bacteria from one surface to another [17]. A study concluded that there were variations in the amount of time spent cleaning and the level of disinfection achieved by different housekeeping staff [16]. Over-dilution of the disinfectant solution during the preparation step or malfunctioning automated dilution systems results in unsuitable low concentrations of the disinfectants applied [18] or the disinfectants may get contaminated [19].

New disinfectants which include improved liquid preparation of H_2O_2 , combination of peracetic acid- H_2O_2 , electrolyzed water, cold atmospheric pressure plasma, and polymeric guanidine have their own set of disadvantages and do not provide continuous disinfection. For instance, electrolyzed water allowed regrowth of staphylococci after 24 hours of application [20].

Since achieving and maintaining proper levels of continuous disinfection is not short of challenges, there is a dire need to explore the use of new technologies specifically designed to improve this aspect. The coating used in this study has nanoparticles of TiO_2 as

the active agent and is activated by light which breaks down the microbes using catalytic reaction. Very limited number of studies have evaluated TiO₂ as a disinfectant. A study conducted by Bogdan *et al.* showed that such nanoparticles result in reduction of infectious agent transmission due to their self-disinfecting and self-cleaning action [21]. Fluorinated TiO₂ exhibited virucidal action against norovirus surrogates with infectivity reduction up to 2–3 log₁₀ [22].

A study on the impact of an antimicrobial coating at two hospitals showed a 36% decline in pooled HAIs (combined MDRO-BSIs and *Clostridium difficile* infections (CDIs) in the units receiving the coating as compared to the control unit. The total bacterial CFUs at the two hospitals declined by 79% and 75%, respectively, following surface application [23]. This is similar to the present study where there was a 71.8% drop in the percentage of positive environmental swabs in the setting. However, similar to previously published studies, reduction in environmental bioburden did not uniformly translate into proportional reductions across all categories of device-associated HAIs. Several other new products may serve as promising candidates. For instance, a study conducted in Canada used hard-anodized aluminum (AA) materials impregnated with antibacterial agents (quaternary ammonium compounds (QACs) and/or nitrate silver (AgNO₃)) which resulted in elimination of > 99.9% bacteria within 5 minutes [24].

The TiO₂ coating resulted in a statistically significant reduction in environmental contamination, but showed inconclusive results with HAIs. The numbers for CLA-BSI and CAUTI showed a paradoxical increase after the coating. Many other factors may have contributed to this increase. Device-associated infections are influenced by multiple variables, including device-days, adherence to central line and urinary catheter maintenance bundles, patient acuity, and biofilm formation at catheter hubs and internal lumens, which may not be significantly impacted by environmental surface coatings. Additionally, temporal differences between the pre- and post-application periods may have introduced confounding factors affecting infection rates. It has been shown that many factors apart from the hospital environment, such as compliance with central line bundle, hand hygiene, low Glasgow score, total parenteral nutrition (TPN), and reoperation can alter the rates of HAIs [25–27]. The coating may serve to provide continuous disinfection and decrease the environmental burden of pathogens, but its role in

decreasing the overall HAIs, length of stay, and cost per patient requires further research and evaluation.

Conclusions

In this controlled before-and-after evaluation in a tertiary trauma intensive care setting, application of TiO₂ nano-impregnated coating resulted in a significant reduction in environmental contamination in the intervention unit compared to the control unit. A decline in VAP was observed; however, the rates of CLA-BSI and CAUTI did not show similar improvement. These findings suggest that while antimicrobial surface coatings may effectively reduce environmental bioburden, their impact on device-associated HAIs may vary. Moreover, environmental contamination represents only one component of infection transmission dynamics, and successful reduction of device-associated infections requires sustained adherence to insertion and maintenance bundles, surveillance, and device stewardship. Further prospective, adequately controlled, studies are required to determine the long-term clinical effectiveness and cost-benefit implications of continuous active antimicrobial coatings in critical care settings.

Funding

The United Nations Industrial Development Organization (UNIDO) sponsored the painting and coating of the surfaces of the identified clinical units with their approved product. Surveillance for both HAIs and environment sampling was being done as a routine practice at the institute. Hence, no additional resources were needed for this study.

Ethical clearance

The study protocol was reviewed by the institutional ethics committee (Ref no: IEC-327/01.04.2022) and was approved as a quality improvement initiative.

Authors' contributions

SV: methodology, investigation, formal analysis, manuscript—original draft; NM: conceptualization, methodology, implementation, investigation, manuscript—review and editing, supervision; PM: conceptualization, methodology, manuscript—review and editing, supervision; AN: methodology, investigation, manuscript—review and editing, supervision; RM: resources, software, validation; GP: conceptualization, methodology, supervision.

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Conflict of interest

No conflict of interest is declared.

References

- Rahmqvist M, Samuelsson A, Bastami S, Rutberg H (2016) Direct health care costs and length of hospital stay related to health care-acquired infections in adult patients based on point prevalence measurements. *Am J Infect Control* 44: 500–506. doi: 10.1016/j.ajic.2016.01.035.
- Tiwari P, Rohit M (2013) Assessment of costs associated with hospital-acquired infections in a private tertiary care hospital in India. *Value Health Reg Issues* 2: 87–91. doi: 10.1016/j.vhri.2013.03.002.
- Kramer A, Schwebke I, Kampf G (2006) How long do nosocomial pathogens persist on inanimate surfaces? A systematic review. *BMC Infect Dis* 6: 130. doi: 10.1186/1471-2334-6-130.
- Guerrero DM, Nerandzic MM, Jury LA, Jinno S, Chang S, Donskey CJ (2012) Acquisition of spores on gloved hands after contact with the skin of patients with *Clostridium difficile* infection and with environmental surfaces in their rooms. *Am J Infect Control* 40: 556–558. doi: 10.1016/j.ajic.2011.08.002.
- Dancer SJ (2014) Controlling hospital-acquired infection: focus on the role of the environment and new technologies for decontamination. *Clin Microbiol Rev* 27: 665–690. doi: 10.1128/CMR.00020-14.
- Dancer SJ, King MF (2021) Systematic review on use, cost and clinical efficacy of automated decontamination devices. *Antimicrob Resist Infect Control* 10: 34. doi: 10.1186/s13756-021-00894-y.
- Horan TC, Andrus M, Dudeck MA (2008) CDC/NHSN surveillance definition of health care-associated infection and criteria for specific types of infections in the acute care setting. *Am J Infect Control* 36: 309–332. doi: 10.1016/j.ajic.2008.03.002.
- Lazarus HM, Fox J, Lloyd JF, Evans RS, Abouzelof R, Taylor C (2007) A six-year descriptive study of hospital-associated infection in trauma patients: demographics, injury features, and infection patterns. *Surg Infect* 8: 463–474. doi: 10.1089/sur.2005.43.
- Glance LG, Stone PW, Mukamel DB, Dick AW (2011) Increases in mortality, length of stay, and cost associated with hospital-acquired infections in trauma patients. *Arch Surg* 146: 794–801. doi: 10.1001/archsurg.2011.41.
- Hessels AJ, Kuo YH, Ahmed N (2020) Epidemiology and impact of healthcare-associated infections in trauma patients: a national data analysis. *Surg Infect* 21: 871–876. doi: 10.1089/sur.2019.294.
- Fernando SA, Gray TJ, Gottlieb T (2017) Healthcare-acquired infections: prevention strategies. *Intern Med J* 47: 1341–1351. doi: 10.1111/imj.13642.
- Donskey CJ (2013) Does improving surface cleaning and disinfection reduce health care-associated infections? *Am J Infect Control* 41: S12–S19. doi: 10.1016/j.ajic.2012.12.010.
- Goodman ER, Platt R, Bass R, Onderdonk AB, Yokoe DS, Huang SS (2008) Impact of an environmental cleaning intervention on the presence of methicillin-resistant *Staphylococcus aureus* and vancomycin-resistant enterococci on surfaces in intensive care unit rooms. *Infect Control Hosp Epidemiol* 29: 593–599. doi: 10.1086/588566.
- Mitchell BG, Dancer SJ, Anderson M, Dehn E (2015) Risk of organism acquisition from prior room occupants: a systematic review and meta-analysis. *J Hosp Infect* 91: 211–217. doi: 10.1016/j.jhin.2015.08.005.
- Boyce JM, Havill NL, Lipka A, Havill H, Rizvani R (2010) Variations in hospital daily cleaning practices. *Infect Control Hosp Epidemiol* 31: 99–101. doi: 10.1086/649225.
- Engelbrecht K, Ambrose D, Sifuentes L, Gerba C, Weart I, Koenig D (2013) Decreased activity of commercially available disinfectants containing quaternary ammonium compounds when exposed to cotton towels. *Am J Infect Control* 41: 908–911. doi: 10.1016/j.ajic.2013.01.017.
- Bergen LK, Meyer M, Høg M, Rubenhagen B, Andersen LP (2009) Spread of bacteria on surfaces when cleaning with microfibre cloths. *J Hosp Infect* 71: 132–137. doi: 10.1016/j.jhin.2008.10.025.
- Boyce JM, Sullivan L, Booker A, Baker J (2016) Quaternary ammonium disinfectant issues encountered in an environmental services department. *Infect Control Hosp Epidemiol* 37: 340–342. doi: 10.1017/ice.2015.299.
- Weber DJ, Rutala WA, Sickbert-Bennett E (2007) Outbreaks associated with contaminated antiseptics and disinfectants. *Antimicrob Agents Chemother* 51: 4217–4224. doi: 10.1128/AAC.00138-07.
- Stewart M, Bogusz A, Hunter J, Devanny I, Yip B, Reid D (2014) Evaluating use of neutral electrolyzed water for cleaning near-patient surfaces. *Infect Control Hosp Epidemiol* 35: 1505–1510. doi: 10.1086/678595.
- Bogdan J, Zarzyńska J, Pławińska-Czarnak J (2015) Comparison of infectious agents' susceptibility to photocatalytic effects of nanosized titanium and zinc oxides: a practical approach. *Nanoscale Res Lett* 10: 1–5. doi: 10.1186/s11671-015-1023-z.
- Park GW, Cho M, Cates EL, Lee D, Oh BT, Vinjé J (2014) Fluorinated TiO₂ as an ambient light-activated virucidal surface coating material for the control of human norovirus. *J Photochem Photobiol B* 140: 315–320. doi: 10.1016/j.jphotobiol.2014.08.009.
- Ellingson KD, Pogreba-Brown K, Gerba CP, Elliott SP (2020) Impact of a novel antimicrobial surface coating on health care-associated infections and environmental bioburden at 2 urban hospitals. *Clin Infect Dis* 71: 1807–1813. doi: 10.1093/cid/ciz1077.
- Jann J, Drevelle O, Chen XG, Auclair-Gilbert M, Soucy G, Fauchoux N (2021) Rapid antibacterial activity of anodized aluminum-based materials impregnated with quaternary ammonium compounds for high-touch surfaces to limit transmission of pathogenic bacteria. *RSC Adv* 11: 38172–38188. doi: 10.1039/D1RA07159A.
- Zaiton H, Taha N (2014) Effect of implementing central line bundle on minimizing rate of central line-associated bloodstream infection (CLA-BSI) among intensive care patients. *Adv Life Sci Technol* 19: 1–4.
- Allegranzi B, Pittet D (2009) Role of hand hygiene in healthcare-associated infection prevention. *J Hosp Infect* 73: 305–315. doi: 10.1016/j.jhin.2009.04.019.
- Goçmez C, Çelik F, Tekin R, Kamaşak K, Turan Y, Palancı Y (2014) Evaluation of risk factors affecting hospital-acquired infections in the neurosurgery intensive care unit. *Int J Neurosci* 124: 503–508. doi: 10.3109/00207454.2013.863773.