Role of Ultraviolet Disinfection in the Prevention of Surgical Site Infections

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Abstract

The role of the environment in surgical site infections is surprisingly understudied. UV disinfection holds promise for reducing the level of contamination in operating rooms and thereby lowering the risk of infection for patients. Issues such as the frequency, amount and locations for UV disinfection to have an impact on the risk of surgical site infection are recently emerging in the literature. As technologies and knowledge improve, UV disinfection will have a role to play in operating rooms in the future.

Keywords

Surgical site infections • Environmental hygiene • Ultraviolet disinfection • Operating rooms

21.1 Introduction

In this chapter, the role of ultraviolet light disinfection in preventing surgical site infections is presented. The root cause of surgical site infections, specifically the role of environmental contamination serving as a fomite in the surgical theater, will be discussed. We will also address the safety considerations for implementing UV disinfection, and review the differences in the currently available technologies. Finally, we will review the emerging evidence correlating enhanced disinfection in the surgical theater with decreases in infection rates and make recommendations for additional research on the topic.

21.1.1 Burden of Surgical Site Infections

Approximately 51.4 million inpatient surgical procedures are performed annually in the

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United States alone [1]. Of these patients undergoing inpatient procedures, approximately 1.9% (976,000 patients) develop an infection afterward [2]. Depending on the surgical procedure being performed, this infection risk can be higher or lower [3]. Including procedures performed at outpatient and ambulatory surgery centers would further increase the annual number of infections in the U.S. The mortality rate associated with contracting a surgical site infection (SSI) is 3%, with 75% of associated deaths being directly attributed with the infection at the surgical site [4]. Table 21.1 shows the annual case load for select surgical procedures, along with projected infections and deaths based on reported data. It should be noted that disability, morbidity and other forms of suffering are not presented in this table.

A prevalence study conducted in 2011 found that SSIs are the most common hospital associated infection (HAI), representing 22% of all reported cases [5]. Patients who develop a surgical site infection will spend, on average, 12.1 additional days in the hospital [6].

These additional days in the hospital lead to increased costs for both the patient and the hospital providing the care. The average cost attributed to an SSI is estimated to range from $11,874 to $34,670 [7]. This estimate is an aggregate of costs for all surgical procedures; more invasive procedures such at spinal fusions and vascular surgeries can have substantially higher costs and can exceed $100,000 per case [8].

21.1.2 Causes of Surgical Site Infections

The proximal source of the contamination that results in a SSI is often impossible to identify. During the preparation for and performance of a surgery, there are multiple opportunities for pathogenic organisms to enter the surgical wound and cause infection. The most commonly attributed sources of pathogenic organisms are outlined below:

21.1.2.1 Non-sterile Instruments

The instruments used during surgical procedures are reprocessed between each patient to remove blood, tissue, and microbiologic contamination to assure sterility before use on the next patient. Failures in these processes can lead to the introduction of pathogens into the surgical wound. The first step in the decontamination process is to remove blood and tissue from the instruments. Any residual material left behind can impede the sterilization process and provide a haven for pathogens. After complete removal of residual materials, the instruments are sterilized, typically with a steam sterilizer. Steam sterilizers use steam and pressure to sterilize instruments. If appropriate levels of steam and pressure are not achieved throughout the sterilization cycle, pathogens (especially spores) can remain on the instruments. The final step in preventing instrument contamination is to assure that they are stored in a manner and place that prevents recon-

Table 21.1 Number of surgical procedures annually by procedure type

Procedure	Surgical volume	Projected infections	Projected deaths
Coronary artery bypass graft	395,000	8578	257
Total knee replacement	719,000	7200	216
Total hip replacement	332,000	4669	140
Reduction of fracture	671,000	11,044	331
Hysterectomy	498,000	8847	265
Cesarean section	1,300,000	24,349	730
Excision of large intestine	247,000	14,356	430

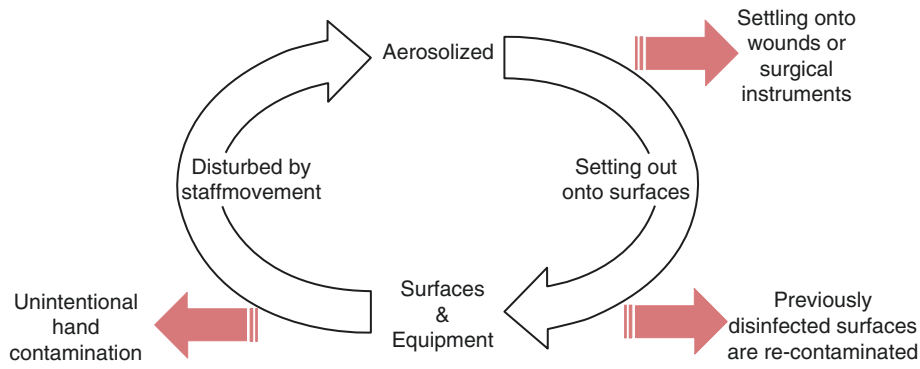

Fig. 21.1 Proposed interaction between surface contamination and airborne contamination for causing surgical site infections

tamination. This is accomplished by assuring that the integrity of the instrument packaging is maintained. The above process can be challenging as more and more surgical instrumentation, such as endoscopes, are becoming more complex devices with imbedded technology, which requires specialized training and processes for sterilization.

21.1.2.2 Patient Factors

The patient themselves can be the source of the organisms that cause infection. Common skin commensals such as *Staphylococcus* spp. can cause infections if skin integrity is compromised at the incision site. Patients with comorbid conditions such as diabetes, obesity, and heart disease are at higher risk of developing an infection. Additionally, the patient's compliance with postoperative wound care measures will impact the risk of developing infection.

21.1.2.3 Environmental Contamination

A contaminated hospital environment can contribute to the transmission of pathogens to patients [9]. Environmental transmission can occur from direct contact with the environment (air or surface) or indirectly from hands that were contaminated by the environment [10]. This interaction of environment and transmission risk could be further complicated in the operating theater, where constant movement of staff members causes air turbulence that disturbs pathogens present on surfaces, causing them to aerosolize. Once the pathogens are in the air, they can resettle onto sterile surgical instruments, previously cleaned surfaces, or even the open surgical wound. See Fig. 21.1.

21.1.2.4 Responsible Pathogens

Magill and colleagues reported on the pathogens associated with 110 surgical site infections identified as part of a multi-state prevalence study. Table 21.2 shows the results of this survey [5]. Additionally, Kramer and colleagues conducted a systematic review which assessed how long pathogenic organisms could persist on inanimate surfaces. This data is presented in Table 21.3 [11].

21.1.3 Effectiveness of Installed UVGI Devices

Ultraviolet germicidal irradiation (UVGI) is a technology that has been used to reduce the microbial contamination in operation rooms (ORs). When installed in ORs, UVGI has proven to be effective in air disinfection. Several studies have shown that the use of a UV device can produce ultraclean (<10 CFU/m^3), or nearly ultraclean, air [12–14]. This is the same level of air quality produced by HEPA air filters [15]. Kowalski suggests that the combination of MERV 13–15 filters and UVGI are equivalent to the effectiveness of HEPA filtration systems with less cost [16]. The same suggestion seems to hold

Table 21.2 Frequency of pathogens attributed to surgical site infections

Pathogen	Number (percent)
Staphylococcus aureus	17 (15.5)
Enterococcus species	16 (14.5)
Klebsiella pneumoniae or *K. oxytoca*	15 (13.6)
Escherichia coli	14 (12.7)
Streptococcus species	8 (7.3)
Pseudomonas aeruginosa	7 (6.4)
Coagulase-negative *Staphylococcus* species	7 (6.4
Enterobacter species	5 (4.5)
Proteus mirabilis	5 (4.5)
Bacteroides species	5 (4.5)
Candida species	3 (2.7)
Acinetobacter baumannii	2 (1.8)
Haemophilus species	2 (1.8)
Peptostreptococcus species	2 (1.8)
Clostridium species other than *C. difficile*	2 (1.8)
Citrobacter species	1 (0.9)
Prevotella species	1 (0.9)
Morganella morganii	1 (0.9)
Other organisms	6 (5.5)
Total	110 (100)

Modified from Magill 2014 [5]

Table 21.3 Persistence of pathogenic organism on inanimate surfaces commonly associated with surgical site infections

Pathogen	Persistence
Staphylococcus aureus	7 days – 7 months
Enterococcus species	5 days – 4 months
Klebsiella pneumoniae or *K. oxytoca*	2 h – >30 months
Escherichia coli	1.5 h – 16 months
Streptococcus species	1 day – 6.5 months
Pseudomonas aeruginosa	6 h – 16 months
Acinetobacter baumannii	3 days – 5 months
Haemophilus species	12 days

Modified from Kramer 2006 [11]

true for laminar air systems as well. In a comparison study done in 1989, the UV lighting system being tested not only worked just as well, if not better, than the laminar air system, but also cost 34 times less [17]. This result has been replicated in multiple studies that have shown that UVGI can reduce airborne bacteria values to a greater degree than laminar air systems [14, 16–18].

In considering installed UVGI as an overall disinfection measure, the system's effect on infection risk must also be taken into account. This subject is closely related to the reduction of airborne microbes. Going as far back as Joseph Lister it has been believed that airborne bacteria represent a significant source of infection, especially in the ORs. [19]. Infection occurs when microbes in the air settle in the operating room, contaminating the wound, the patient, the hospital personnel, and vital medical equipment [16]. It then stands to reason that the fewer bacteria in the room, including in the air, the less risk of infection there is for a patient. One study concluded that the UVGI device was able to disinfect the patients' wounds and possibly operating instruments [14]. The authors stated that this disinfection "negate[d] the argument about the relative effect on air counts. Laminar flow would have to provide considerably cleaner air to produce equally clean wounds." These clean wounds combined with the clean air are the basis of what allows UVGI devices to decrease the risk of infection.

There are many reports of UVGI reducing infection risk in the ORs. An orthopedic study following 5980 joint replacements reported that the odds of infection were 3.1 times greater for patients who had not been operated on under any UV light [17]. The same study reported an infection rate decreased from 1.77% to 0.57%. Others have reported similar findings of reduced infection rate. A study focusing on infection after cardiac operations revealed how using UVC light during operations led to the hospital's overall infection rates being significantly lower than the national averages in the most important risk categories [CDC National Nosocomial Infection Surveillance system, 18]. In 1936 at Duke University Hospital, Hart tried UVGI light after an outbreak of infections in the OR. The infection rate dropped from 11.62% to 0.24%, causing Hart's colleagues to also adopt the practice [20]. UVGI has been recommended as an important tool for operating room personnel to use in order to reduce infection [17, 21]. However, much of

the data on the effectiveness of UVGI in ORs are dated and it is not clear the impact that installed UVGI would have for procedures being conducted under current infection control procedures.

21.1.3.1 Installed UVGI Safety

Kraissl et al. took it a step further and not only researched the effectiveness of UVGI on infectious bacteria, but also investigated the safety of UVGI in regards to the patient [22]. The researchers concluded that there is a danger to the exposed visceral tissue of the patient, if a threshold intensity of light is exceeded. However, they also found that there was significant bacterial killing even when using light intensities well below the damaging threshold. This theme of radiation in moderation persists in all safety matters pertaining to UVGI.

UVGI has been proven to be safe provided the proper measures are taken. It is recommended that light intensity be limited in order to protect the patient and hospital personnel in the room [22, 23]. Lidwell stated that the intensity of light should be kept between 25 and 30 $\mu W/cm^2$, but intensities up to 300 $\mu W/cm^2$ did not produce hazardous results [23]. The light must also be placed so that there is no dangerous exposure to the staff, while still allowing for proper irradiation of the room. Some systems are placed above and parallel to the patient, forming a type of barrier that will deactivate bacteria in the air that would fall on the patient. The height of the system keeps the operation room's personnel safe by preventing direct exposure of the UV light. Even with low intensities of light placed in safe positions, operating room staff should follow the safety precautions and wear protective clothing. Items such as disposable caps, drapes, plastic goggles, face masks, and surgical gloves, can greatly reduce the transmission of UVC light to personnel in the room [12]. Studies on staff who took protective measures showed no harmful effects [18, 24]. However, increases in light intensity and noncompliance with safety precautions can lead to injuries such as erythema, photosensitivity, immune system damage, and even cancer [25]. Eye injury in particular is a hazard when the proper face wear is not used [26]. Eye damage includes damage to the cornea and conjunctiva that can lead to temporary blindness, photosensitivity, benign growth, and corneal degeneration [25].

Hospital personnel have continually cited the uncomfortable nature of personal protective equipment as the main reason they do not utilize it [13, 14, 26, 27]. Wearing heavy protective clothing has proven to be too hot for personnel to work in regularly [14]. Other reasons for noncompliance included the lack of necessary supplies, training, and time, as well as increased work difficulty. Due to this noncompliance, there have been cases of basal cell carcinoma, melanoma, and actinic keratosis in operating room personnel [27]. It could be possible for greater compliance to be achieved if safety precautions were less inhibitive for staff. The future of fixed system UVGI may rest on this, as a lack of compliance and an increase in injuries may lead to the abandonment of the system [26].

Beginning in the late 2000s, portable UV systems have been used routinely in ORs for nightly and, in some situations, between cases [28–30]. These mobile devices allow the operator to place them in the room and exit before any human exposure can occur. This removes the need for heavy or difficult protective equipment as well as the cost of installation. These mobile devices may be an effective alternative to the fixed UVGI system.

21.1.4 Portable Room Disinfection UV Technologies

Portable UV technologies available for disinfecting operating rooms must meet the basic requirements of being safe to use, easy to operate, and effective at reducing the number of pathogens on every possible surface. Personal safety is not typically an issue, as (1) germicidal UV light cannot pass through windows or walls [25], and (2) all devices have a mechanism for automatic shutoff if a person enters the room, and are thus considered safe to operate under normal conditions.

Currently, two types of technologies that meet the aforementioned requirements are commonly used in ORs: those using low pressure mercury lamps and others which employ pulsed xenon lamps. Both have been shown to be effective at reducing a large number of pathogens on the surfaces [30–33], and the incidence of infections in the in-patient environment [34–40]. However, only a pulsed xenon device has been demonstrated to reduce SSIs [28, 29].

The main differences between low pressure mercury and pulsed xenon technologies lie in their spectral output, intensity, and operational modes. In the UV range, low pressure mercury lamps produce a narrow spectrum output that is centered at 253.7 nm (Fig. 21.2), while pulsed xenon lamps emit wavelengths covering the entire germicidal range of 200–320 nm (Fig. 21.3). Pulsed xenon produces intense pulses that last for microseconds while low pressure mercury produces lower intensity light but operates in a constant-on mode that allows for effective doses to be delivered over time (Fig. 21.4). The operational differences between these device types may account for the contrasting ways in which they are utilized. For example, pulsed xenon devices have shorter cycle times when used in the OR setting (8–16 min) compared to

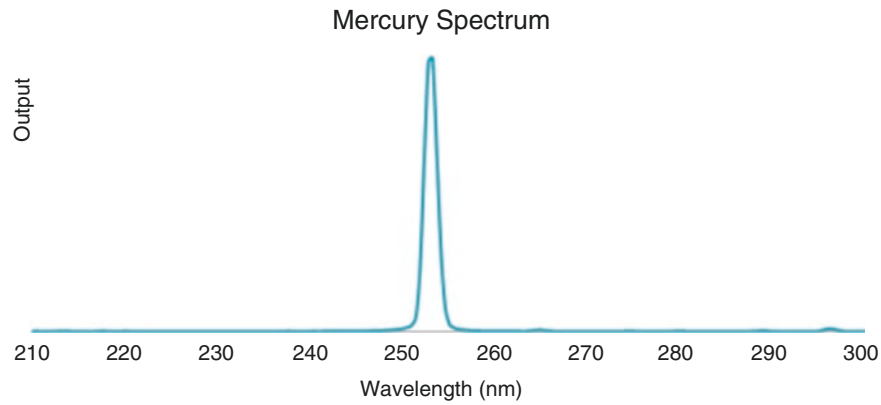

Fig. 21.2 Spectral output of mercury lamp in germicidal UV range

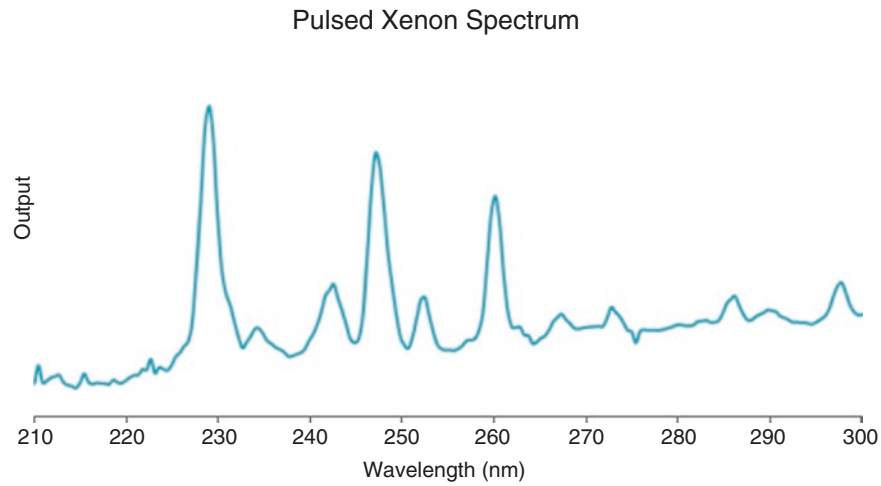

Fig. 21.3 Spectral output of xenon lamp in germicidal UV range

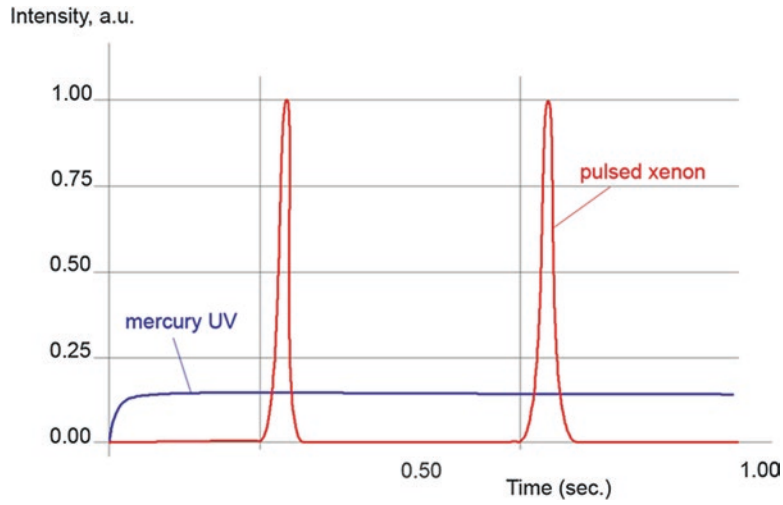

Fig. 21.4 Difference in operational intensity and lamp on-time between mercury and xenon lamps

low pressure mercury (OR times are not specified, but a typical patient room cycle time is 45 min).

21.1.5 Materials Damage

In addition to deactivating microbes present on surfaces in the ORs, UV light also interacts with the objects on which these microorganisms reside. When UV is incident upon a surface, one of three things happens: the light is transmitted, absorbed, or reflected [25]. Because UV is not transmitted through most solid objects and there is relatively little reflection, most is absorbed. This absorption can cause photodegradation (the molecular changes due to light) that result in an alteration to the color, texture or mechanical properties of the object. In the OR's setting, this change is primarily evident in the yellowing of white plastics and fading of lighter colored fabrics and most metal objects remain unaffected.

While exposure to any UV device will change the material properties of a susceptible object to some extent, variables such as distance, exposure time, and spectral output make it difficult to predict the effect. More research is needed to fully understand the material's compatibility of portable UV devices commonly used in the ORs.

21.1.6 Use of Portable UV, Cycle Times and Positioning

The aforementioned portable UV disinfection devices are currently deployed in over one hundred OR settings. Two clinical studies demonstrate great success when used following nightly, standard terminal cleaning practices [28, 29]. These devices can be wheeled into a room, plugged into standard electrical outlets, and then set in a fixed position that is proximal to high-touch equipment within. Following completion of the final disinfection cycle, these devices can be moved around the facility to the next area requiring disinfection. Disinfection is made possible by onboard germicidal lamps that contain either mercury vapor or xenon gas. Although different, both technologies have been found to be effective at decreasing environmental bioburden in patient care areas [41, 42].

Regardless of what technology is used, UV disinfection efficacy is highly dependent on the distance between the lamp and the surface being targeted. The propagation of light intensity decreases exponentially with increasing distance from the lamp, so proximity to areas being disinfected will require significantly shorter cycle times. Put simply, doubling the distance between the lamp and the target will quadruple the origi-

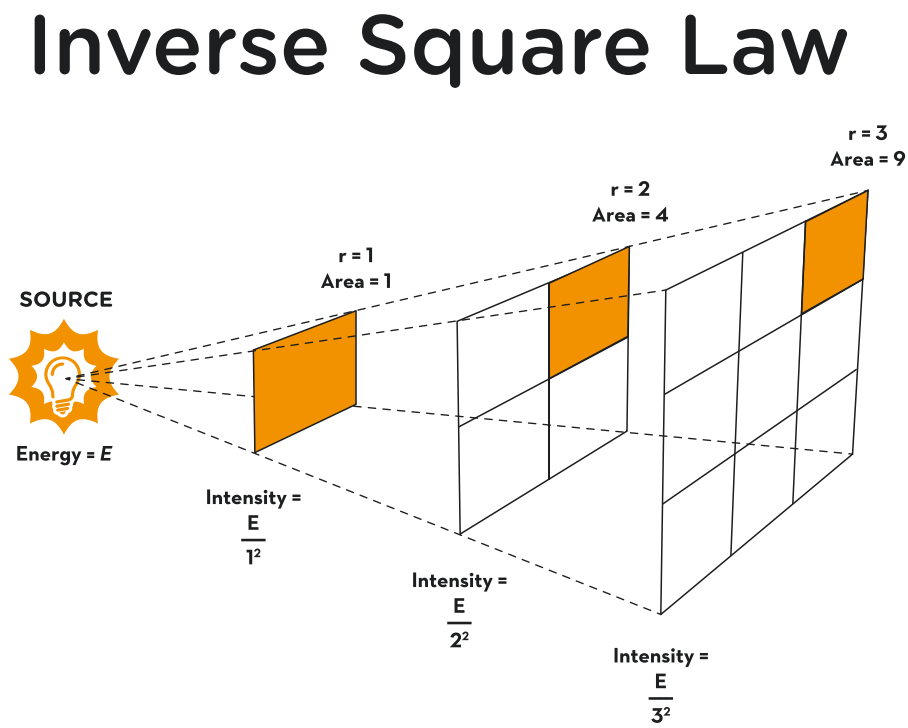

Fig. 21.5 Visual propagation of light following the inverse square law

nal time required for disinfection (See Fig. 21.5). Therefore, if it takes 5 min to disinfect a target 2 meters away, it should take approximately 20 min to produce the same amount of germicidal energy at 4 meters. A publication by Nerandzic and colleagues explores the impact of distance on UV efficacy against both methicillin resistant *S. aureus* (MRSA) and *C. difficile* spores in the laboratory setting [41].

In addition to distance, the reliance on UV reflection to reach targeted areas should also be considered. Common hospital materials are poor at reflecting germicidal UV, with wall paint and linen curtain material reflecting less than 25% of incoming light [25]. Multiple studies have confirmed that reflected light is significantly less effective than direct light at eliminating pathogens when considering the same disinfection time [32, 43]. For these reasons, disinfection will always be best when surfaces are in close proximity and within direct line of site of the lamp.

When considering physical limitations alone, the fastest UV room disinfection would consist of multiple positions and minimal distances from all target areas. However, because user intervention is required for every additional position implemented, this can add burden for the person performing the terminal cleaning. Considering this, two strategies are available for the OR; those using one position, and those using multiple (2–3) positions. Table 21.4 summarizes the pros and cons of each strategy.

One-position devices require minimal user assistance, but require longer periods to disinfect. One manufacturer implementing this strategy uses UV sensors on their devices to detect a set UV germicidal dose [44]. During the disinfection cycle, UV light reflects around the room, and some returns to the sensors. Once the sensors are saturated, the device will consider the room disinfected, and shut itself off. Depending on where the device is placed, and thus the amount of UV sensor activity, cycle times can vary considerably. While not OR-specific, publications report an average median cycle time of 45 min in acute care patient rooms [44, 45]. Despite longer

Table 21.4 Assessing the pros and cons of one versus multiple position UV disinfection

Multiple position devices	One position devices
Pros	Pros
Fast disinfection time	No repositioning required
Known cycle time	Cons
Clinical outcome studies in the OR	Longer disinfection time
Cons	Unknown cycle time
User repositioning required	No known clinical outcomes in the OR

cycles, housekeepers are free to perform other activities such as manual cleaning of other OR suites while UV disinfection is taking place. A handheld tablet tracks the progress of the disinfection taking place.

Multiple position devices are more time efficient, but require some user repositioning. Rather than measuring reflected light, multiple positions allow these systems to rely on direct line of site to disinfect. For this reason, cycle times are known for objects that are within specific distances of the devices. Several publications reporting reductions in SSIs following UV disinfection interventions required only two 5-min cycle times on either side of the OR table to fully disinfect high-touch surfaces within the room [28, 29]. When considering the time to reposition this system, disinfection can be completed in 15 min or less using the multiple position strategy. In addition to the success as an adjunct to terminal cleaning practices, UV disinfection might be a consideration for between case cleaning practices, in particular for quick disinfections when moving from dirty to clean procedures in the same suite.

21.1.7 Evidence for Benefit of Terminal UV Disinfection

Current literature shows that both cleaning and disinfection of the OR environment may be inadequate. An observational study examining OR cleaning found that only 25% (237/946) of fluorescent UV markers were removed from equipment surfaces following terminal cleaning [46]. In another study, only 47% of UV markers (284/600) were removed during the terminal cleaning process [47]. When air and surface microbial cultures were obtained from UV marker sites prior to surgical cases the following morning, 16.6% of surfaces remained contaminated with potentially infectious organisms such as *Pseudomonas spp.*, *Acinetobacter spp.*, *Klebsiella spp.*, and *Enterococcus spp.* [47].

Failure of disinfection practices leaves a potential risk of infection transmission from contaminated surfaces [48, 49]. As described earlier, this transmission risk is exceptionally high in the perioperative setting. Given the high volume of worker traffic, there are many opportunities for transmission between the susceptible patients, hands of healthcare workers, and environmental contamination in air and on surfaces. Multiple publications have reported substantial transfer of bacterial species from the anesthesia work area to intravenous stopcock sets [50, 51]. Furthermore, a recent study confirms that high touch areas of the operating room harbor significant bacterial contamination [52], suggesting greater attention should be paid to disinfecting these areas.

Mobile UV disinfection has demonstrated efficacy beyond what is possible by manual chemical disinfection alone, and can serve as an additional measure to reduce residual contamination. Data on one UV device have been collected from several ORs. For one facility, mean heterotrophic plate count for high-touch surfaces after manual cleaning was 2.73 colony forming units (CFUs) per 25 cm^2 [53]. Following a manual clean plus mobile UV disinfection, mean plate counts decreased 62% to an average of 1.05 CFUs per sample ($p < 0.001$). When comparing contamination levels for select surfaces, researchers determined a 64%, 87% and 94% improvement for the anesthesia cart, OR light and OR table, respectively. In a second study, quick cleaning plus UV disinfection resulted in a 55% and 81% reduction in positive surface cultures and overall bioburden, respectively [54]. UV disinfection also decreased air contamination by 46% during surgical cases when used for between case cleaning, and 100% following terminal cleaning practices [54]. Beyond the OR environment, the efficacy of UV disinfection has been studied in the acute care set-

ting [30, 32, 33, 41–44, 55–60]. Several studies report exceptional decreases in both MRSA and vancomycin resistant *Enterococci* (VRE) contamination following terminal UV disinfection practices [59, 60]. Although the recovery of specific pathogens on OR surfaces is difficult, the laboratory efficacy of UV disinfection against common pathogens has been evaluated, with exceptional efficacy at 1 meter in as short as 5 min for select species [61].

Improvements in SSI rates following terminal UV disinfection interventions have now been published, providing additional evidence that enhanced cleaning with UV is thorough enough to remove exogenous sources of infection from the inadequately cleaned environment. In these studies, a baseline period that involves only manual disinfection for nightly terminal cleans is compared to interventions in which nightly UV disinfection is added in addition to the baseline procedure. Following this disinfection procedure, and as part of a bundled approach including other interventions, one facility reduced the incidence of total-hip and total-knee infections from 7 out of 544 procedures down to 0 out of 585 procedures [29]. In a second study evaluating terminal UV disinfection, SSIs following Class I (clean) procedures were reduced by 46%, contributing to 23 fewer infections over the 21 month intervention period [28]. Infections associated with clean-contaminated Class II procedures did not decrease during the intervention. Class I procedures involve clean incisions, so the wound site has minimal contamination prior to operation. These infections are more likely to be due to environmental transmission routes than infections associated with clean-contaminated Class II procedures, since contamination of the surgical site is already present at the time of the incision in these cases.

Evidence suggests that the risk of surgical site infections caused from the OR environment can be minimized by using terminal UV disinfection. Substantial evidence exists showing the role of environment in SSIs, and the ability of UV disinfection to provide an improvement beyond the capabilities of standard manual cleaning/disinfection. While quasi-experimental studies attribute reductions in SSIs following this application, future research into molecular epidemiology that maps the clonal spread of pathogens from surfaces to patients could provide additional insight into specific transmission dynamics [62].

21.2 Conclusion

UV disinfection holds great promise for improving the safety of the operating room environment. Additional research and improvements in available UV technologies should provide practical, operational solutions for ORs. As reimbursement changes further incentivize reductions in surgical site infection rates, investments in UV technologies should not only make financial sense, but also provide improved outcomes to patients.

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