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Ultraviolet Lighting During Orthopaedic Surgery and the Rate of Infection

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Background: Ultraviolet lighting is an alternative to laminar airflow in the operating room that may be as effective for lowering the number of environmental bacteria and possibly lowering infection rates by killing the bacteria rather than simply reducing the number at the operative site. The purpose of the present study was to compare the infection rates following joint replacement procedures performed by one orthopaedic surgeon with and without the use of ultraviolet lighting.

Methods: From July 1986 to July 2005, one surgeon performed 5980 total joint replacements at one facility. In September 1991, ultraviolet lighting was installed in the operating rooms. All procedures that were performed before the installation of the ultraviolet lighting utilized horizontal laminar airflow, whereas all procedures that were performed after that date utilized ultraviolet lighting without laminar airflow. Factors associated with the rate of infection were analyzed.

Results: Over a nineteen-year period, forty-seven infections occurred following 5980 joint replacements. The infection rate without ultraviolet lighting (and with laminar airflow) was 1.77%, and the infection rate with ultraviolet lighting was 0.57% ($p < 0.0001$). The odds of infection were 3.1 times greater for procedures performed without ultraviolet lighting (and with laminar airflow) as compared with those performed with only ultraviolet lighting ($p < 0.0001$). The infection rate associated with total hip replacement decreased from 1.03% to 0.72% ($p = 0.5407$), and the infection rate associated with total knee replacement decreased from 2.20% to 0.50% ($p < 0.0001$). Revision surgery, previous infection, age, total body mass index, use of cement, disease, and diagnosis were not associated with an elevated infection rate.

Conclusion: When appropriate safety precautions are taken, ultraviolet lighting appears to be an effective way to lower the risk of infection in the operating room during total joint replacement surgery.

Level of Evidence: Therapeutic Level III. See Instructions to Authors for a complete description of levels of evidence.

A postoperative wound infection following total joint replacement is a complication that is dreaded by surgeon and patient alike. Much emphasis has been placed on decreasing infection rates in order to ensure a more successful operative outcome. Reduced infection rates have been associated with controlling for various environmental factors in the operating room with a great variety of means, including systemic antibiotics^{1,3}, laminar airflow¹², antibiotic-loaded bone cement^{3,4}, and ultraviolet lighting⁵⁻¹¹.

Contamination most often occurs as a result of bacteria that are emitted from the various surgical personnel in and

around the operating room¹². At some facilities, laminar airflow is used as an environmental control because it reduces the number of bacteria in the air, and thus, the possible number of infectious colony-forming units. The use of ultraviolet radiation to minimize the number of bacteria in the air has been studied since the 1930s⁷. Although typically associated with laminar airflow, ultraclean air (air with <10 colony-forming units/m³) has been documented in association with the use of high-intensity ($290 \mu\text{W cm}^{-2} \text{ s}^{-1}$) ultraviolet light⁸. The use of lower intensities (25 to $30 \mu\text{W cm}^{-2} \text{ s}^{-1}$) of ultraviolet light along with body exhaust suits and filtered air has been

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associated with low infection rates, perhaps as the result of a cumulative effect^{4,10,11}.

The purpose of the present study was to compare the infection rates following procedures performed by one surgeon before and after the implementation of surgical ultraviolet lighting in order to determine the efficacy of ultraviolet radiation as an infectious environmental control during total joint replacement surgery.

Materials and Methods

Prior to September 16, 1991, all operations at the Center for Hip and Knee Surgery involved the use of only horizontal laminar airflow. In September 1991, ultraviolet lighting (American Ultraviolet, Lebanon, Indiana) was installed in all four operating rooms. After that date, one surgeon exclusively used ultraviolet lighting without using laminar airflow. The present study represents a consecutive series and includes all of the total joint replacements that were performed by this surgeon over the included time-period. Perioperative antibiotics were given to all patients preoperatively at the time of surgery and postoperatively for twenty-four hours. The present retrospective study was approved by the institutional review board.

All of the operations that involved the use of horizontal laminar airflow were performed so that none of the surgical personnel could be in the path of the clean airflow. This placement of personnel was accomplished by positioning the instrument table parallel to the face of the laminar airflow unit. The operating table was then placed perpendicular to this flow wall and the two tables (patient and instrument) were connected to one another with sterile drapes. Body exhaust suits were used for all operating personnel.

With the implementation of ultraviolet lighting in the operating room, protective clothing was needed for all surgical staff. Besides the standard cotton short-sleeve blouses and pants, all nonsterile personnel wore long-sleeve jackets, hoods, and protective eye-shields. The surgical team wore long-sleeve gowns as well as body exhaust systems with an ultraviolet protective face shield. Exposed skin required the application of sunscreen. The patient was protected with eye ointment or an eye shield, and any exposed areas other than the incision site were covered with blankets.

During each operation, the ultraviolet lights were turned on once all personnel were gowned and the patient was fully prepared and draped for surgery, or approximately two to three minutes prior to incision. The ultraviolet lights remained on until the wound was closed and the dressings were in place. They were off between procedures and were turned on again when the next patient was fully prepared for surgery. The operating room was kept at a temperature of 60°F to 70°F (16°C to 21°C) and at a humidity of 30% to 50%.

The intensity of the lights was set by the circulating nurse at $23 \mu\text{W cm}^{-2} \text{ s}^{-1}$ and at a frequency of 2537 Å as this frequency has been found to have the maximum bactericidal effect⁷. To ensure proper intensity levels, the ultraviolet lights were calibrated once a week at night with a radiometer that

was calibrated annually. In addition, the lights were cleaned once a week and as needed with an alcohol-soaked cloth.

From July 9, 1986 to July 15, 2005, one surgeon performed 5980 total joint replacements in 3846 patients at our facility. The procedures included 4071 total knee replacements (68.1%) and 1909 total hip replacements (31.9%), with 5428 (90.8%) of the operations being primary procedures and 552 (9.2%) being revisions. The preoperative diagnoses associated with all procedures (primary and revision) included osteoarthritis (5171 procedures; 86.5%), failed total hip replacement (346 procedures; 5.8%), failed total knee replacement (206 procedures; 3.4%), osteonecrosis (119 procedures; 2.0%), rheumatoid arthritis (ninety-seven procedures; 1.6%), and other diagnoses (forty-one procedures; 0.7%). Among the 552 revision procedures, 346 (62.7%) were hip replacements (of which thirteen [3.8%] were performed because of prior infection) and 206 (37.3%) were knee replacements (of which thirty-nine [18.9%] were performed because of prior infection). Overall, there were 2317 female patients (60.2%) and 1529 male patients (39.8%).

Of the 5980 total joint procedures, 4909 (82.1%) were performed with use of ultraviolet lighting without laminar airflow and 1071 (17.9%) were performed with use of laminar airflow without ultraviolet lighting (Table I). Of the 4909 total joint replacements performed with use of ultraviolet lighting, 1519 (30.9%) were hip replacements and 3390 (69.1%) were knee replacements. Of the 1519 hip replacements performed with use of ultraviolet lighting, 261 (17.2%) were revision procedures. Ten (3.8%) of these hip revisions were performed because of prior hip infection. Of the 3390 knee replacements performed with use of ultraviolet lighting, 163 (4.8%) were revision procedures. Twenty (12.3%) of these revisions were performed because of prior knee infection. Of the 1071 procedures performed with laminar airflow and without ultraviolet lighting, 390 (36.4%) were hip replacements and 681 (63.6%) were knee replacements. Of the 390 hip replacements performed without ultraviolet lighting, eighty-five (21.8%) were revision procedures; three (3.5%) of these revision procedures were performed because of prior hip infection. Of the 681 knee replacements performed without ultraviolet lighting, forty-three (6.3%) were revision procedures; nineteen (2.8%) of the 681 knee replacements were performed because of prior knee infection.

Two thousand and twenty-two joint replacements were performed as unilateral procedures, and 206 of these were revisions. Two thousand four hundred and seventy-eight joint replacements were performed as simultaneous procedures involving two joint replacements in one patient, and fifty-five of these procedures were revisions. Furthermore, fifty-two of these joint replacements were performed as contralateral or ipsilateral procedures. Nine hundred and twenty-eight joint replacements also involved two joint replacements in one patient; however, the operations for the two joints were staged. One hundred and forty-four of these staged joint replacements were revisions. Three hundred and three joint replacements involved three staged or three simultaneous joint

TABLE I Demographic Data

	Age* (yr)	Body Mass Index*	Revised†	Rheumatoid Arthritis†	Osteonecrosis†	Previous Infection†	No. of Hips (%)
All procedures							
No ultraviolet lighting (n = 1071)	68.8 ± 9.6 (26 to 88)	29.1 ± 4.9 (10.9 to 47.7)	128 (12.0%)	31 (2.9%)	25 (2.3%)	22 (2.1%)	390 (36.4%)
Ultraviolet lighting (n = 4909)	67.6 ± 10.1 (18 to 96)	31.8 ± 6.3 (16.5 to 64.3)	424 (8.6%)	66 (1.3%)	94 (1.9%)	30 (0.6%)	1519 (30.9%)
Type of joint replacement							
Hip (n = 1909)	66.5 ± 12.2 (18 to 96)	29.9 ± 6.0 (10.9 to 58.1)	346 (18.1%)	28 (1.5%)	99 (5.2%)	13 (0.7%)	—
Knee (n = 4071)	68.4 ± 6.2 (34 to 93)	32.3 ± 6.3 (16.5 to 64.3)	206 (5.1%)	69 (1.7%)	20 (0.5%)	39 (1.0%)	—
Hips							
No ultraviolet lighting (n = 390)	67.8 ± 11.2 (26 to 88)	27.5 ± 5.4 (10.9 to 41.2)	85 (21.8%)	8 (2.1%)	15 (3.9%)	3 (0.8%)	—
Ultraviolet lighting (n = 1519)	66.2 ± 12.5 (18 to 96)	30.1 ± 6.0 (16.5 to 58.1)	261 (17.2%)	20 (1.3%)	84 (5.5%)	10 (0.7%)	—
Knees							
No ultraviolet lighting (n = 681)	69.3 ± 8.5 (34 to 87)	29.4 ± 4.8 (17.5 to 47.7)	43 (6.3%)	23 (3.4%)	10 (1.5%)	19 (2.8%)	—
Ultraviolet lighting (n = 3390)	68.2 ± 8.7 (34 to 93)	32.6 ± 6.3 (16.5 to 64.3)	163 (4.8%)	46 (1.4%)	10 (0.3%)	20 (0.6%)	—
*The values are given as the mean and the standard deviation, with the range in parentheses. †The values are given as the number of replacements, with the percentage in parentheses.							

replacements in one patient. Nine of the 303 joint replacements were performed as simultaneous procedures in one patient, and the remainder were staged. Seventy-five of the 303 joint replacements were revisions. One hundred and eighty-eight joint replacements occurred in patients with a total of four total joint replacements. Forty-nine of these joint replacements were revisions. Sixty-one joint replacements were performed in patients who had five or more joint replacements. Twenty-three of these joint replacements were revisions.

An infection was classified as deep if it was deep to the fascia with a delay in wound-healing or persistent discharge¹¹. Total joint replacement was considered to have failed if the joint had a deep infection, excision, and/or revision because of infection.

Statistical Analysis

Patient-related and operative factors associated with the rate of infection were analyzed by means of logistic regression, the chi-square statistic, and, in limited instances, the two-sample t test. The factors that were analyzed included the age of the patient at the time of surgery, the preoperative body mass index, the presence of ultraviolet light at the time of surgery, the joint being replaced (hip or knee), the type of procedure (primary or revision), the type of fixation (cemented or uncemented), the diagnosis at the time of surgery (osteoarthritis, rheumatoid arthritis, or osteonecrosis), and the performance of revision surgery because of a prior infection.

Variable selection for the logistic regression was performed with the forward stepwise procedure, with entry and removal criteria as defined by a parameter estimate level of significance of 0.10. Separately, each nonsignificant explanatory variable was tested along with the significant variable of ultraviolet lighting for the final reported p values. For significant p values, there was one final overall total joint replacement model reported, one final model for knees reported, and one final model for hips reported. For logistic regressions that selected only one explanatory variable, the chi-square test or Fisher exact test was reported, either when appropriate or when the odds ratio was not appropriately calculated.

Results

Forty-seven deep infections were identified in association with 5980 total joint replacements that were performed over a nineteen-year period (prevalence, 0.79%). The average duration of follow-up was 5.2 ± 4.0 years (range, 0.2 to 18.5 years), and 712 joints (11.9%) were completely lost to follow-up. Within one month, one-half of all infections had occurred; the median time to infection was one month (thirty days). The most frequently reported time to infection was fourteen days, with 19% (nine) of the forty-seven infections occurring at that time. Thirty-five (74%) of the forty-seven infections occurred within four months.

The binomial distribution indicates that for the 712 joints that were lost to follow-up, we can expect 5.6 ± 2.4 ad-

TABLE II Rate of Infection for Primary and Revision Hip Replacements with and without Ultraviolet Lighting

	Rate of Infection		P Value
	No Ultraviolet Lighting	Ultraviolet Lighting	
All	1.0% (4 of 390)	0.7% (11 of 1519)	0.5407
Primary	1.3% (4 of 305)	0.7% (9 of 1258)	0.3038
Revision	0% (0 of 85)	0.8% (2 of 261)	1.0000

ditional infections (95% confidence interval, 0.8 to 10.4). Statistically, there was an approximately 95% chance of observing between one and ten additional infections among the 712 joints that were lost to follow-up.

As it is most likely that the 712 joints that were lost to follow-up populated both the infected and noninfected subsets in a similar fashion and ratio as the 5980 joints that were originally observed (with six expected infections among the 712 joints that were lost, compared with forty-seven observed infections among the 5980 joints in the original group), there is a 95% chance of observing any reported result within the 95% confidence interval of the rate reported in the present study. Furthermore, although it is difficult to calculate the impact of each possible alternate scenario had we been able to include the 712 lost joints, at a minimum we have the usual statistical confidence that the results would not have been highly altered by the inclusion of the lost joints, primarily because of the large number of cases (5980) and the reasonable size of the group of lost joints (11.9%; 712 of 5980).

Previous studies of total joint replacement have examined the effect of cases that are lost to follow-up¹³, with the observation that missing cases do not necessarily represent poor results. With respect to the outcomes of revision and satisfactory results following total knee arthroplasty, missing patients actually tended to do better than returning patients. In that report, 440 of 563 patients were followed and 123 (21.8%) were lost to follow-up.

In the present study, the infection rate was 1.77% (nineteen of 1071) following procedures performed without the use of ultraviolet lighting and 0.57% (twenty-eight of 4909) following procedures performed with the use of ultraviolet light ($p < 0.0001$). After separating the data according to the type of total joint replacement (hip or knee), the data revealed that the infection rate associated with total hip replacement decreased from 1.03% to 0.72% after the installation of ultraviolet lighting ($p = 0.5407$) (Table II). A post hoc power analysis demonstrated that 32,000 total hip replacements would be needed to demonstrate a significant difference at this rate. The infection rate associated with total knee replacement decreased from 2.20% to 0.50% when ultraviolet light was utilized ($p < 0.0001$) (Table III).

The odds of infection were 3.1 times greater (95% confidence interval, 1.8 to 5.6) for all joint procedures performed

without ultraviolet lighting as compared with those performed with ultraviolet lighting ($p < 0.0001$). With the numbers available, revision surgery ($p = 0.1528$), body mass index ($p = 0.1117$), patient age ($p = 0.7261$), the use of a cemented prosthesis ($p = 0.5206$), rheumatoid arthritis ($p = 0.9381$), osteonecrosis ($p = 0.9304$), and a history of infection (odds ratio = 2.1, $p = 0.0557$) were not found to be associated with an elevated risk of infection, regardless of whether or not ultraviolet lighting was utilized. In the years following the implementation of ultraviolet lighting in the operating room, the average patient age decreased and the average body mass index increased (Table I). When body mass index is taken into account, despite the fact that it was not a significant effect, the odds ratio for an infection increased to 6.9 (95% confidence interval, 4.0 to 13.5) ($p < 0.0001$).

The odds of infection were 4.5 times greater (95% confidence interval, 2.3 to 9.3) for knee procedures performed without ultraviolet lighting as compared with those performed with ultraviolet lighting ($p < 0.0001$). Logistic regression analysis revealed that, in the setting of revision surgery, the odds of infection were 3.5 times greater (95% confidence interval, 1.003 to 12.2) for procedures performed without ultraviolet lighting as compared with those performed with ultraviolet lighting ($p = 0.0494$). Following primary knee replacement, the infection rate was 1.9% (twelve of 638) for procedures performed without ultraviolet lighting and 0.5% (seventeen of 3227) for procedures performed with ultraviolet lighting ($p = 0.0003$) (Table III). Following revision knee replacement, the infection rate was 7.0% (three of forty-three) for procedures performed without ultraviolet lighting and 0.0% (zero of 163) for procedures performed with ultraviolet lighting ($p = 0.0086$) (Table III). With the numbers available, body mass index (odds ratio = 1.05 per unit of body mass index; $p = 0.0887$), age (odds ratio = 0.96 per year of age; $p = 0.0712$), the diagnosis of rheumatoid arthritis (odds ratio = 3.8; $p = 0.0887$), the diagnosis of osteonecrosis ($p = 0.9798$), or a history of previous infection (odds ratio = 2.1; $p = 0.0685$) were not found to be significantly associated with infection. There were no uncemented knee replacements in the current cohort.

The odds of infection were 1.4 times greater for hip procedures performed without ultraviolet lighting than for those performed with ultraviolet lighting; however, this finding was not significant ($p = 0.5407$). With the numbers available, revi-

TABLE III Rate of Infection for Primary and Revision Knee Replacements with and without Ultraviolet Lighting

	Rate of Infection		P Value
	No Ultraviolet Lighting	Ultraviolet Lighting	
All	2.2% (15 of 681)	0.5% (17 of 3390)	<0.0001
Primary	1.9% (12 of 638)	0.5% (17 of 3227)	0.0003
Revision	7.0% (3 of 43)	0% (0 of 163)	0.0086

sion surgery (odds ratio = 1.5; $p = 0.6238$), body mass index ($p = 0.9377$), age ($p = 0.1572$), a cemented prosthesis ($p = 0.3878$), the diagnosis of rheumatoid arthritis ($p = 0.6530$), the diagnosis of osteonecrosis (odds ratio = 2.8; $p = 0.1536$), or a history of previous infection ($p = 0.7607$) were not found to be associated with infection.

The overall infection rate following primary joint replacement was 0.77% (forty-two of 5428). The infection rate was 1.70% (sixteen of 943) following primary procedures performed without ultraviolet lighting and 0.58% (twenty-six of 4485) following primary procedures performed with ultraviolet lighting. The overall infection rate following revision was 0.91% (five of 552). The infection rate was 2.34% (three of 128) following revisions performed without ultraviolet lighting and 0.47% (two of 424) following those performed with ultraviolet lighting. The infection rate for joints with a prior infection was 1.9% (one of fifty-two). The infection rate was 0.40% (ten of 2488) for joints undergoing a simultaneous bilateral procedure and 0.1% (one of 928) for those undergoing a staged bilateral arthroplasty (in this case, with the infection occurring after the second stage). The infection rate for patients after three or more procedures was 0.63% (one infection among 159 patients undergoing 552 total joint replacements), and the infection rate for those undergoing four or more procedures was 0% (zero infections among fifty-eight patients undergoing 249 total joint replacements).

Discussion

In 1937, Duke University implemented ultraviolet radiation in the operating room after infection rates at their facility remained elevated for a period of five years. Since 1940, the infection rate at Duke University remained below 0.5% for all orthopaedic procedures through 1973, demonstrating the strong bactericidal effect of ultraviolet light⁵. There have been many changes in the operating room since 1973, but little has been reported with regard to ultraviolet lighting⁵⁻¹¹. In 1964, the National Research Council carried out a double-blind, randomized study that involved the use of ultraviolet lighting at five institutions⁷. The investigators reported that the only procedures with significant improvement due to ultraviolet radiation in the operating room were those procedures involving refined-clean wounds. Today, this wound category would contain joint replacement procedures. In this category, which represented 19.2% of all infections in the study, the postoperative infection rate decreased from 3.8% to 2.9%.

Despite the benefits of laminar airflow in reducing the number of bacteria at the wound site during total joint replacement, it has been shown that the infection rate associated with total knee replacement can actually increase when horizontal laminar airflow is used. This discrepancy is related to the placement of operating personnel during surgery¹⁴. This positioning problem has been controlled to a degree for more than thirty years at our hospitals by positioning the instrument table and the operating table so that the operating personnel are in a less risky position. However,

the operating personnel still lean into the path of the air on occasion to check the position of their instruments and the alignment of the knee. This factor may account for the elevated infection rates following total knee replacement as compared with total hip replacement.

The infection rate in our operating room decreased significantly, from 1.77% to 0.57%, in association with the use of ultraviolet lighting, even with the elimination of laminar airflow. The decrease in the infection rate for total knee replacement from 2.2% to 0.5% was significant ($p < 0.0001$). Reduction in the operative time could have been a positive factor influencing this result. Over these years, one would expect our techniques to improve and the operating times to decrease. We used the exact same knee arthroplasty system during the entire period of time. We evaluated all of the knee procedures in March of 1991 and March of 2003 with regard to the duration of surgery; the average duration was sixty-three minutes (range, forty-eight to 115 minutes) in 1991 and fifty-eight minutes (range, fifty to 113 minutes) in 2003. Therefore, shortened operating time probably was not a factor.

The use of ultraviolet lighting as an environmental control brings about several concerns, especially the safety of the patient and the operating room personnel. The recommended intensity for ultraviolet lighting is 25 to 30 $\mu\text{W cm}^{-2} \text{s}^{-1}$ in order to prevent overexposure¹⁰. Eye protection for both the patient and the operating room personnel is critical in order to prevent severe conjunctivitis. Even two to three minutes of direct exposure is enough to cause conjunctivitis. Longer periods of exposure without proper protection may lead to blindness. In order to prevent the superficial erythema that can result after fifteen to twenty minutes of ultraviolet exposure, a hood, jacket, and gloves must be worn when ultraviolet lights are in use. Failure to comply with these protective measures may result in serious burns of the cornea and skin. At our facility, we provided an educational video about ultraviolet lighting and effective protection for all staff in order to guarantee awareness of the dangers of noncompliance. Because of these concerns, many of the personnel find the use of the ultraviolet lights an inconvenience. Nevertheless, they have adapted well to the change in environment.

Additional concerns with ultraviolet lighting include the temperature and humidity of the room. High temperatures may cause excessive sweating, whereas low temperatures may reduce the efficiency of the ultraviolet lights⁵. A decrease in efficacy is seen at >60% humidity, and the ultraviolet lights become almost ineffective at 80% humidity. For this reason, we keep the temperature in our operating rooms between 60°F and 70°F (16°C and 21°C), and we keep the humidity level between 30% and 50%.

One feature that makes ultraviolet lighting so attractive is the relatively low cost of its installation and maintenance. In 1989, ultraviolet lighting was thirty-four times less expensive than the ultraclean air enclosure unit⁹. At our facility, each operating room was equipped with ultraviolet lighting for approximately \$2000. In contrast, laminar airflow enclosures for the same room cost approximately \$200,000. With appropri-

ate and relatively simple safety measures, ultraviolet lighting appears to be a cost-effective environmental control that can maintain relatively low infection rates.

Postoperative infection after total joint replacement is a devastating event for all those involved, often resulting in a failed arthroplasty and substantial patient morbidity. The use of ultraviolet lighting in the operating room appears to be an effective adjunct to ultraclean air enclosures for reducing the rate of infection following total joint replacement, particularly total knee replacement. In situations in which a particular sur-

geon or procedure has an elevated infection rate, we highly recommend ultraviolet lighting as an effective environmental control to minimize the infection risk. ■

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