Clin Orthop Relat Res (2011) 469:945–953
DOI 10.1007/s11999-010-1688-7

SYMPOSIUM: PERIPROSTHETIC JOINT INFECTION

Current Concepts for Clean Air and Total Joint Arthroplasty: Laminar Airflow and Ultraviolet Radiation

A Systematic Review

Richard P. Evans MD

Published online: 16 December 2010

Abstract

Background With the trend toward pay-for-performance standards plus the increasing incidence and prevalence of periprosthetic joint infection (PJI), orthopaedic surgeons must reconsider all potential infection control measures. Both airborne and nonairborne bacterial contamination must be reduced in the operating room.

Questions/purposes Analysis of airborne bacterial reduction technologies includes evaluation of (1) the effectiveness of laminar air flow (LAF) and ultraviolet light (UVL); (2) the financial and potential health costs of each; and (3) an examination of current national and international standards, and guidelines.

Methods We systematically reviewed the literature from Ovid, PubMed (Medline), Cochrane DSR, ACP Journal Club, DARE, CCTR, CMR, HTA, NHSEED, CINAHLPLUS, and Google Scholar published until June 2010 focusing on ultraclean air, ultraviolet light, and laminar air.

Results High-level data demonstrating substantial PJI reduction of any infection control method may not be feasible as a result of the relatively low rates of occurrence and the expense and difficulty of conducting a large enough study with adequate power. UVL has potentially unacceptable health costs and the Centers for Disease Control and Prevention (CDC) recommends against its use. European countries have standardized LAF and it is used by the majority of American joint surgeons.

Conclusions Both LAF and UVL reduce PJI. The absence of a high level of evidence from randomized trials is not proof of ineffectiveness. The historically high cost of LAF has decreased substantially. Only LAF has been standardized by several European countries. The CDC recommends further study of LAF but recommends UVL not be used secondary to documented potential health risks to personnel.

The author has received research support from Cubist Pharmaceuticals (Boston, MA) and is a consultant with DePuy (Warsaw, IN) and Smith and Nephew (Memphis, TN).

R. P. Evans (✉)
Department of Orthopaedic Surgery, #531, University of Arkansas for Medical Sciences, 4301 West Markham, Little Rock, AR 72205, USA
e-mail: evans@uams.edu

Introduction

Epidemiologic studies reveal the incidence and prevalence of periprosthetic joint infection (PJI) may be increasing. Kurtz et al. [22, 23] reported an overall incidence of infection after THA of 0.88% in the United States with urban nonteaching hospitals accounting for the majority of these. They noted this incidence was apparently increasing and the infection rate for revision THA is more than double that for primary procedures. With the trend toward pay-for-performance standards, orthopaedic surgeons must reconsider all potential infection control measures. In Europe, infection surveillance standards have been implemented and surveillance is becoming compulsory. For example, infection registration in The Netherlands is obligatory and insurance companies use the data when making decisions regarding which orthopedics departments and hospitals are contracted to implant prostheses [46]. Multiple infection control measures have improved PJI rates substantially, but there are no data to suggest that other infection control methods are not additive. A recent evaluation of prophylactic antibiotics concluded that as a result of the current low prevalence of PJI, any intervention

designed to further reduce infection is difficult and expensive requiring a large number of study patients [31]. Similarly, high-level data of clean air technology (CAT) effectiveness in the modern operating room are limited secondary to the feasibility of conducting a study large enough to define substantial differences on PJI rates.

A recent study cites PJI rates of 1.9% of knee and 1.7% of hip arthroplasties [12]. A power study assuming a 1.5% to 2.0% infection rate would require on the order of 10,000 patients to determine the effect of any one independent variable (power greater than 80%). Multiple variables (eg, to test two or three variables) would require approximately 70,000 patients. This also makes cost-to-benefit comparisons difficult [16]. Consequently, the use of CATs remains controversial in some quarters. The lack of high level of evidence from a randomized trial is not, however, proof of ineffectiveness.

Although a definitive study that could define the absolute clinical benefit of these technologies has yet to be proposed, the existing evidence remains compelling. A systematic review of available studies contributes contemporary data to consider when deciding whether to use these technologies. How these technologies are used and their limitations need to be explored to implement or use one of these technologies to good effect because the data show they can be harmful if used inappropriately.

The aims of this article are to examine (1) the most recent evidence and experience of laminar air flow (LAF) and ultraviolet light (UVL) effectiveness; (2) the known financial and potential health costs of each; and (3) the national and international standards, regulation, and guidance.

Search Strategy and Criteria

The literature search results for CAT used the reference database Ovid. Using the search terms ("laminar air" OR "laminar air flow" OR "laminar air-flow" OR "laminar airflow" OR ultraclean OR "Ultraviolet Rays"[Mesh] OR "ultraviolet light" OR "uv rays" OR "uv light") and ("Operating Rooms"[Mesh] OR "General Surgery"[Mesh] OR "operating room" OR "operating suite" OR "operative suite" OR surgery OR surgical) were combined with ("Cross Infection"[Mesh] OR "Infection Control"[Mesh] OR "Environment, Controlled"[Mesh] OR "cross infection"[tiab] OR "infection control"[tiab] OR "controlled environment"[tiab]); 268 items were identified in PubMed (Medline).

Using the same strategy, 25 items were found in Web of Science (includes SCI and SSCI), 11 items were found in Evidence Based Medicine Reviews (Cochrane DSR, ACP Journal Club, DARE, CCTR, CMR, HTA, and NHSEED), 26 items were found in CINAHLPLUS, and none were found in International Pharmaceutical Abstracts 1970 to May 2010.

Google Scholar was searched with ([laminar air], [laminar air flow], [laminar air-flow], [laminar airflow], [ultraclean], [Ultraviolet Rays], [ultraviolet light], [uv rays], or [uv light]) and identified 48 articles. Abstracts of all papers were independently reviewed by the author (RPE). We identified two prospective randomized controlled trials.

Each of these was reviewed and items were removed manually that did not pertain to any surgery in an inpatient hospital operating room.

Results

Laminar Air Flow Effectiveness

Vertical LAF ensures directional air flow through high-efficiency particulate air (HEPA) filters and positive air pressure within the canopied area at the surgical site. Outside the canopy area, the downward flow of air is brought up and recirculated along with new air. In 2003, the National Institutes of Health (NIH), Office of Research Services, Division of Engineering Services, conducted an extensive study of operating room ventilation system designs and their effect on the protection of the surgical site [32]. The overwhelming conclusion was that systems providing LAF regimes represent the best option for an operating room in terms of contamination control, because they result in the smallest percentage of particles impacting the surgical site.

Multiple studies have described improved PJI rates with LAF [2, 10, 11, 13, 15, 17–19, 22, 24–27, 32, 34, 36, 42, 48]. In 1969 and 1972, Charnley [10, 11] reported an initial infection rate of 9.5% for his series of primary THAs. Using a combination of clean air systems and occlusive operating gowns, he reduced PJI nearly 20-fold to 0.5%. Historical high-level data demonstrate that LAF technology without systemic antibiotics reduces the prevalence of infection from 3.4% to 1.2% [26].

LAF systems have evolved considerably through the years from horizontal to vertical and now vertical exponential designs. Horizontal LAF designs push a HEPA-filtered positive pressure plane of air or plenum in a horizontal direction over the surgical site. Vertical LAF push LAF plenums from the ceiling to the floor. Vertical designs are superior to horizontal with the latest vertical exponential system designs directing focal sterile air turnover at and then away from the surgical wound. Vertical exponential design LAF air plenums have the shape of the end trumpet sitting front end down on the floor and air

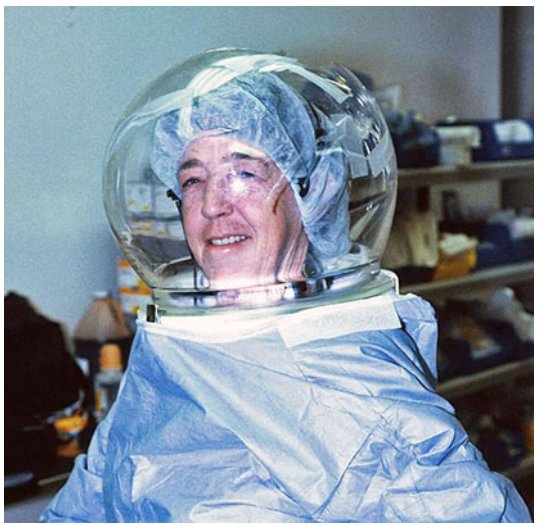

Fig. 1 A hip arthroplasty laminar flow space suit developed by Martin Marietta circa 1972 is shown. Reprinted with permission of Colleen Mann.

intake is at floor level. LAF is designed for use with body exhaust suits to decrease bacterial and skin particle (squame) shedding from operative personnel into the air plenum. Thousands of squames are shed per minute by each person in the operating room. The early body exhaust suit design was inspired after astronaut suits and some were obtained from the Jet Propulsion Laboratory (JPL) in Pasadena, CA (Fig. 1). Contemporary gear has an untethered self-contained air feed and options for a headlight and two-way radio (with all operative personnel on the same radio band width) and even a feed for music or radio.

Studies documenting the merits of any one LAF system or technology usually do not include system design data and therefore specific system comparisons and recommendations cannot be made. With the use of nonlaminar HEPA filters in conventional operating room ventilation systems, there is a tendency to promote them as having clean room technology standards used in industry. This claim is based on measuring the presence of airborne particles of varying sizes and numbers, which may be better suited than bacterial sampling but is not standardized. Similarly, there are no standardized methods or frequency for bacterial air sampling. Few countries have set bacterial threshold limits for conventionally ventilated operating rooms, although most recommend 20 room air changes per hour to obtain 50 to 150 colony-forming units/m^3 of air. Standard operating room air systems have evolved as well and are sometimes promoted as LAF-equivalent, although performance and design differences remain substantial. Specifically, standard systems create turbulent air as the performance increases, which increase the risk of mixing newly filtered air with less clean air or aerosolizing surfaces particles.

In contrast, an exponential vertical LAF system is defined with these basic specifications: a canopy of approximately 18 inches high and approximately 10 feet square attached to the ceiling containing a full diffuser to focus and direct the filtered air plenum downward over the wound site and the immediate surgical team and a downward air speed of approximately 75 feet per minute with a circulation rate of approximately 450 changes per hour. In this manner, the surgical team is continually "washed" with clean filtered air in a positive pressure air environment. LAF results in a reduction in airborne bacterial colony-forming units and dust or squames large enough (greater than 10 μm) to carry bacteria aloft. A count of one or two particles of greater than 2 μm/m^3 of airflow at the wound level in this type of system is typical.

Charnley realized that one of the main routes of wound contamination and infection was the air in the operating room. By using occlusive garments for operating room personnel, he was able to achieve a 20-fold reduction of his infection rates [10, 11]. The only randomized controlled trials of LAF were conducted on 8055 patients undergoing knee and hip surgery in a multicenter, multinational trial reported by Lidwell in 1982, 1986, and 1987 [26–28]. This study examined the effect of conventional ventilation, LAF ventilation with body exhaust suits, and LAF without body suits on surgical site infection after joint surgery. Although this study demonstrated a decrease in air contamination coupled with a decrease in clinical joint infections with LAF ventilation, the study has been criticized for not strictly controlling the use of prophylactic antibiotics. Of note, however, is that in over 8000 arthroplasties, the PJI rate after operations where ultraclean LAF was used alone and without antibiotics decreased from 3.4% to 1.6%, whereas the rate for those who received only antimicrobial prophylaxis and no LAF decreased from 3.4% to 0.8%. When both interventions were used in combination, the PJI rate decreased from 3.4% to 0.7%. The Centers for Disease Control and Prevention (CDC) stated these findings suggest both ultraclean LAF and antimicrobial prophylaxis can reduce the incidence of PJI, but antibiotic prophylaxis is more beneficial than LAF [30]. The British North West Hip Arthroplasty Register published data for 86 surgeons from 26 hospitals where all operating rooms had vertical LAF systems; 93.3% of operations were performed in the surgeon's usual operating room, 42.2% of respondents routinely used exhaust suits, and 68.1% of respondents routinely used impermeable disposable gowns [29]. The cultural acceptance of LAF as a best practices measure results in Charley's LAF etiquette being followed. This in turn reduces the paradoxical increase in PJI rates found when the air is contaminated by personnel standing upstream to the surgical wound [1], not wearing body exhaust suits and helmets [41, 45], or allowing too many

people or unnecessary activity in the operating room [8, 10, 11]. Strict attention to LAF protocol is essential [14] because there can be paradoxical increases in the rates of infection if these concepts are disregarded [41].

In contrast, recent retrospective German experience [6] claimed a paradoxically higher risk of PJI after hip prosthesis when surgery was performed in HEPA-filtered vertical LAF ventilation versus turbulent ventilation with HEPA-filtered air. This study included 99,230 operations (hip and knee arthroplasty, appendectomy, cholecystectomy, colon surgery, and herniorrhaphy) from 63 surgical departments participating voluntarily in the German hospital infection surveillance system, Krankenhaus Infektions Surveillance System (KISS). Participation in KISS is explicitly recommended by the German state authorities and postdischarge surveillance is strongly recommended, although a "gold standard" method to do so is not available. It is unclear in this study whether all of the patients with infections were identified and counted and whether the most important confounders contributing to infection risk were identified. Postoperative surveillance, obesity, smoking, glucose, temperature control, and information about patient-specific antibiotic prophylaxis and LAF etiquette were not standardized or included as part of the data collection or analysis. Of note, in a 2006 German study by the same author [7] in the KISS system, multiple logistic regression analyses of pooled data for all operative procedures revealed that participation in the KISS surveillance system was a notable independent protective factor. The surgical site infection incidence was reduced by one-fourth as a result of the surveillance-induced infection control efforts alone. The PJI rate in 35,587 THAs performed by both orthopaedic and trauma general surgeons was reduced from 2.15% in Year 1 to 1.61% in Year 4. It is unclear if this protective effect was only temporary based on the subsequent LAF article 2 years later.

In the United States, 6489 knee arthroplasties were performed using vertical LAF, body exhaust suits, and 24 hours of perioperative antibiotics resulting in a PJI rate of 0.43% [35]. This was compared with an earlier study at the same institution by Salvati et al. [41] that showed an increased early infection rate (3.9%) using horizontal LAF without exhaust suits. This study has been quoted as demonstrating that LAF is not beneficial and even deleterious. However, this paradoxical increase in PJI was determined to be secondary to personnel placement in the LAF upstream to the surgical wound. Strict attention to the LAF protocol is essential because there can be paradoxical increases in the rates of infection if these concepts are disregarded [41, 45].

Even without the availability of other high-level data, this knowledge can be useful during investigations of healthcare facilities where local PJI rates increase inexplicably. Termination of an infection outbreak is often the result of application of multiple interventions directed at multiple risk factors [8, 16], the majority of which cannot be independently and rigorously evaluated. The author participated as a member of a team of experts representing various specialties in the evaluation of a Virginia hospital that had suddenly suffered dramatically increased PJI rates when apparently adequate infection control was in place. The factor identified as the greatest threat was a change in operating room air cleanliness after conventional operating room air function was "upgraded" to that of a modern office building. PJI rates returned to the previous average after conventional operating room air exchange and distribution was corrected and vertical LAF units were installed for prosthetic surgery (written communication, Evelyn Barram-Clothier, American Medical Foundation, Philadelphia, PA).

Ultraviolet Light Effectiveness

Air decontamination using UVL has been pioneered in the United States. Before 1936, Duke University had infection rates of 11.3% with mortality rates from infection of 1.3% for all surgery types. In 1936, UVL units were installed plus modern air conditioning with its rapid air change and bacterial dilutional effects, which reduced air contaminants. By 1960 [20], this brought the infection rate to 0.24% and the death rate to zero. In 1980, Duke University [28] demonstrated that the PJI rate of hip arthroplasty fell from 3.1% to 0.53% with the use of UVL at intensities of 25 to 30 $\mu W/cm^2$.

Studies examining UVL have studied a variety of ultraviolet intensities in association with other infection control methods and surgical techniques. Short-wavelength ultraviolet germicidal irradiation (UVGI) is a UVL that has a sufficiently short wavelength to destroy microorganisms. The efficacy of UVL, specifically UVGI, for intraoperative infection control is not well defined in modern operating room environments. Several investigators have shown that UVL is reduces the risk of surgical site infection or has been used in conjunction with LAF or body exhaust techniques [3, 39, 46]. Initial levels of ultraviolet radiation used were selected based on health and safety concerns, but more recent studies have used intensities of up to 300 $\mu W/cm^2$ without reporting side effects [39]. Lidwell [25] reported a similar level of decontamination can be achieved with either LAF or UVL at 300 $\mu W/cm^2$ but only if there is relatively low contamination present to begin with. Other studies demonstrated colony counts in air treated with UVL at 290 $\mu W/cm^2$ were less than in operating rooms with Charnley-Howarth vertical LAF

enclosures [3]. Taylor et al. [46] performed a similar study in LAF operating rooms using UVL at 300 μW/cm^2 and looked at colony counts on the wound edges and in the air during THA. UVL was left off for the first 15 minutes of the procedure and then turned on. These authors found high levels of air and wound contamination without UVL, but after 15 minutes of UVL exposure, these areas were sterile.

In 2007, Ritter et al. [39] documented, over a 19-year period, 47 infections occurred after 5980 joint arthroplasties. The infection rate without UVL (and with LAF) was 1.77%, and the infection rate with UVL was 0.57% ($p < 0.0001$). The odds of infection were 3.1 times greater for procedures performed without UVL (and with LAF) as compared with those performed with only UVL ($p < 0.0001$).

In a controlled trial by the National Research Council of North America, postoperative infection in the "refined clean" surgical procedures decreased significantly (3.8%–2.9%). However, they found little benefit using UVL in clean cases and no benefit when using on previously contaminated wounds [38]. The efficacy of UVL is decreased in the presence of blood [40].

Laminar Air Flow Costs

LAF systems have historically been a high-cost technology and this has been used as a rationalization not to invest in the technology. That used to be true. Costs of a $50,000.00 LAF operating room in 1974 [21] is equivalent to $219,035.50 in 2009 dollars [9], whereas the actual cost today ranges from $60,000.00 to $90,000.00 for construction and installation of an exponential LAF system into a new operating room (written communication, James A. Nagel, President, BioAir Systems, 2010).

By comparison, the cost of a single total hip infection in one study is as high $156,830.00 in 2005 dollars and averaged 4.8 times higher than the direct medical costs associated with primary THA [5]. Additionally, infection is currently the most frequently reported reason for revision in TKA [4]. The cited costs of a single PJI treatment do not include the costs associated with retreatment of failed treatment. Treatment costs per patient grow dramatically with each applied treatment.

Ultraviolet Light Costs

UVL is relatively inexpensive and easy to install and run. However, at the high-intensity ultraviolet radiation levels used in recent years, there are implications of health and safety costs. In particular, all exposed skin must be protected and it is recommended that the operating team needs to wear two caps, visors, and occlusive clothing.

The latest CDC recommendations in 2003 recommended not using UVL to prevent surgical site infection [43]. This was a Category IB recommendation—strongly recommended for implementation and supported by certain experimental, clinical, or epidemiologic studies and a strong theoretical rationale. The NIH, CDC, National Science Foundation/American National Standards Institute, and the American Biological Safety Association all agree ultraviolet lamps are not recommended. The safety hazards associated with UVL exposure include cornea burns and skin cancer.

Finally, in 2007, a major eastern academic hospital requested an evaluation of their previous years of use of UVGI light in their operating rooms by the National Institute of Occupational Safety and Health (NIOSH). The request was for a determination of the health and safety analysis of current ultraviolet use and whether to put UVL into newly constructed operating rooms. The evaluation found ultraviolet exposure was six to 28 times greater than the recommended exposure limit. Furthermore, some surgical masks and one reinforced gown did not reduce UVL to safe limits. Of 14 current orthopaedic operating room nurses and technicians, five reported having symptoms possibly related to ultraviolet exposure. Three employees had eye changes, one had skin changes, and one had eye and skin changes. Three employees were diagnosed with melanoma, three with basal cell carcinoma, and five with actinic keratoses out of 22 skin screenings since 2003. This NIOSH report also documents UVGI lights were never installed in this hospital's new operating rooms [44]. Thus, the important potential costs associated with UVL are in terms of health of operating room personnel.

Laminar Air Flow National and International Standards and Guidelines

The majority of total joint surgeons in the United States use LAF and body exhaust suits when available. A recent four-state survey revealed 30% of hospitals reported greater than 75% use of LAF in greater, and 42% regularly used body exhaust, whereas only 5% regularly used UVL [33]. The other hospitals in this survey used LAF and body exhaust suits less than 75% of the time.

In 1999, the CDC suggested both ultraclean air and antimicrobial prophylaxis can reduce the incidence of surgical site infection in orthopaedic implant operations [30]. The CDC, in 2003 [43], stated no recommendation is offered for performing orthopaedic implant operations in rooms already supplied with LAF and classified it as an unresolved issue.

The CDC also provides guidance and regulation of product and personnel protection for healthcare LAF "clean benches" used in clinical, pharmaceutical, and laboratory facilities. These Biological Safety Cabinets (BSCs) use HEPA filtration and vertical LAF across the work surface. The CDC [43] also provides guidance and regulation of the use of a one-piece, ventilated positive-pressure personnel suit protection often used with Class III BSCs [47]. It appears inconsistent that the CDC recommends the use of LAF in medical cabinets but not in joint arthroplasty. In contrast, CDC recommendations are consistent for UVL, which are not recommended in the operating room nor permitted in BSCs. Like in previous CDC guidelines, each recommendation is categorized on the basis of existing scientific data, theoretic rationale, applicability, and possible economic benefit. The recommendations are evidence-based wherever possible. However, certain recommendations are derived from empiric infection control or engineering principles, theoretic rationale, or experience gained from events that cannot be readily studied.

The analysis of surgical LAF systems has resulted in specific national standards in many countries. Examples are the UK Health Technical Memorandum (HTM 2025) in the United Kingdom and territories and the German VDI Standards, both of which have resulted in LAF becoming a standard of care regulated by those countries. In the United Kingdom, 1999 recommendations were made by the British Orthopedic Association (BOA) and the National Institute of Health and Clinical Excellence on the measures that can be taken to avoid PJI. The BOA views the availability of well-maintained clean air theaters as being vital for hospitals performing arthroplasty. Data from the United Kingdom National Joint registry show 98% of all hip arthroplasties are carried out in operating rooms equipped with LAF technology. Current rates of 0.3% in Sweden and 1.4% in the United Kingdom are now accepted as the true risk of infection associated with joint replacement [48].

Ultraviolet Light National and International Standards and Guidelines

Although not recommended by the CDC, UVL is still currently being used by approximately 5% of US surgeons but has not become regulated or gained widespread popularity in the United Kingdom or Europe.

Discussion

The prevention of infection in orthopaedics is a comprehensive issue. One of the main goals of modern surgery is to avoid a postoperative infection and this can only be accomplished by a surgeon's thorough understanding of the factors that may contribute to infection. Although perioperative antibiotics have contributed considerably to decreased surgical site infection rates, it cannot be expected prophylactic antibiotic treatment will compensate for mistakes made in operative protocols, inadequate operative techniques, shortcomings in the operating room environment and equipment, or insufficient preparation of patients. The present low incidence of PJI can only be maintained and improved on by identifying and correcting all factors that may lead to infection and using every method or technology that will assist in achieving that goal [16, 30, 37, 42]. The aims of this article therefore were to examine (1) the most recent evidence and experience of laminar air flow (LAF) and ultraviolet light (UVL) effectiveness; (2) the known financial and potential health costs of each; and (3) the national and international standards, regulation, and guidance.

The limitations of this study are that the literature provides data that are evidence-based wherever possible, but recommendations are also derived from empiric infection control or engineering principles, theoretic rationale, or experience gained from events that cannot be readily studied. Many of the studies available are not high-level prospective but often retrospective from one institution. Conclusions about CAT in the modern operating room remain controversial secondary to the difficulty of conducting a study large enough to define differences in PJI rates. The lack of a high level of evidence from a randomized trial is not, however, proof of ineffectiveness.

The cost analysis of LAF reveals that the expense of this technology has decreased substantially over the years as most technology does as it matures. Currently the cost of installation of LAF approaches the cost of treatment of one or two PJIs. Studies have demonstrated that although the cost of UVL is relatively inexpensive, the greater costs may need to be measured in potentially unacceptable human health costs to operative personnel. In contrast, the financial and human health costs of PJI specifically are a burden greater than the costs of CAT and can only be alleviated with strict compliance with current concepts in infection prevention and the continued development of advances in prevention.

This patient safety issue has reached national and international prominence and CAT standards and guidelines and surgical site infection registries have been implemented primarily in Europe and are in the early stages of development in the United States. With the trend toward pay-for-performance standards, increasing incidence of resistant organisms, and studies suggesting the incidence of PJI may be increasing, all potential infection

control measures need to be reconsidered for use. Newer evaluations in today's surgical environment are needed to maximize these technologies to become part of the multifactorial infection prevention effort. Surgeons are in the position to make even greater advances in reducing PJI and help steer the establishment of evidence-driven and consensus national guidelines that will be implemented in the future. Sights should be set on developing a definitive strategy for study of CAT and other prophylaxis technologies. This task could be facilitated by a CAT and prophylaxis infection data registration effort potentially facilitated by the newly established American total joint registry that would provide an evidence base for future analysis and refinement of surgical site prevention interventions.

Areas of future research for LAF should include the value of LAF technology for joint arthroplasty as well as surgeries other than joint arthroplasty. It should be determined whether particulate sampling can be routinely performed in lieu of microbiologic sampling for purposes such as determining air quality of clean environments. Furthermore, comparison of LAF technology to standards for new non-LAF construction or renovation should be completed to determine whether they are equivalent or complementary. Costs of all technologies typically decrease with time and guidance for the acquisition of effective LAF and non-LAF systems should be developed. Finally, the potential reverse isolation benefits of body exhaust suits and LAF in the face of surgery on a patient with a preexisting viral or bacterial infection needs to be evaluated.

Areas of future research for high-intensity UVL should include verifying the radiation levels and type required to obtain air sterilization and evaluating the healthcare personnel exposure in institutions with high-intensity UVL. If cause and effect between the high-intensity UVL and conditions similar to those identified in the NIOSH evaluation are identified, then reconsideration of the use UVL altogether may be needed to implement better operating room personnel protection. Concerns with the human costs of high-energy UVL air decontamination are real and must be considered if this technology is used.

Analysis of any independent variable that may reduce PJI such as LAF or UVL would require standardizing the independent variables that will be studied. If LAF or UVL technologies are studied as the independent variable, then standardization would include the current state-of-the-art technology of that independent variable, which would include technical specifications of the LAF technology being studied. Dependent variables will have to be controlled or standardized or equalized in such a study and would include modern technical specifications of traditional modern non-LAF operating rooms; prophylactic antibiotics route, type, and timing administration; patient comorbidities; skin preparations; incise barriers; surgical gowns; operating room equipment that may contribute to contamination; behavioral change in personnel relative to the used technologies; personnel etiquette and discipline; and elimination of other random vectors of wound contamination. A controlled prospective study large enough to provide adequate data for comparison should allow determination of cost-effectiveness of each infection control strategy.

Acknowledgments I thank Larry Suva, PhD, director of the University of Arkansas for Medical Sciences Center for Orthopaedic Research, and Susan Steelman, MLIS, Coordinator of Research & Clinical Search Services at the University of Arkansas for Medical Sciences, for their assistance in the preparation of the manuscript.

References

1. Aglietti P, Salvati EA, Wilson PD Jr, Kutner LJ. Effect of a surgical horizontal unidirectional filtered air flow unit on wound bacterial contamination and wound healing. *Clin Orthop Relat Res*. 1974;101:99–104.
2. Ayliffe GA. Role of the environment of the operating suite in surgical wound infection. *Rev Infect Dis.* 1991;13(Suppl 10): S800–S804.
3. Berg M, Bergman BR, Hoborn J. Ultraviolet radiation compared to an ultra-clean air enclosure: comparison of air bacteria counts in operating rooms. *J Bone Joint Surg Br.* 1991;73: 811–815.
4. Bozic KJ, Kurtz SM, Lau E, Ong K, Chiu V, Vail TP, Rubash HE, Berry DJ. The epidemiology of revision total knee arthroplasty in the United States. *Clin Orthop Relat Res.* 2010;468: 45–51.
5. Bozic KJ, Ries MD. The impact of infection after total hip arthroplasty on hospital and surgeon resource utilization. *J Bone Joint Surg Am*. 2005;87:1746–1751.
6. Brandt C, Hott U, Sohr D, Daschner F, Gastmeier P, Rüden H. Operating room ventilation with laminar airflow shows no protective effect on the surgical site infection rate in orthopedics and abdominal surgery. *Ann Surg*. 2008;248: 695–700.
7. Brandt C, Sohr D, Behnke M, Daschner F, Rüden H, Gastmeier P. Reduction of surgical site infection rates associated with active surveillance. *Infect Control Hosp Epidemiol*. 2006;27:1347–1351.
8. Brown AR, Taylor GJ, Gregg PJ. Air contamination during skin preparation and draping in joint replacement surgery. *J Bone Joint Surg Br*. 1996;78:92–94.
9. Bureau of Labor Statistics. Consumer Price Index (CPI) Inflation Calculator Available at: http://www.bls.gov/data/inflation_calculator.htm. Accessed April 26, 2010.
10. Charnley J. Postoperative infection after total hip replacement with special reference to air contamination in the operating room. *Clin Orthop Relat Res*. 1972;87:167–187.
11. Charnley J, Eftekhar N. Postoperative infection in total prosthetic replacement arthroplasty of the hip-joint, with special reference to the bacterial content of the air of the operating room. *Br J Surg*. 1969;56:641–649.

12. Del Pozo JL, Patel R. Clinical practice. Infection associated with prosthetic joints. *N Engl J Med.* 2009;361:787–794.
13. Dharan S, Pittet D. Environmental controls in operating theatres. *J Hosp Infect*. 2002;51:79–84.
14. Dickson GH. Deterioration of theatre discipline during total joint replacement: have theatre protocols been abandoned? *Ann R Coll Surg Engl*. 2001;83:296.
15. Evans RP. Laminar air flow in the operating room: how effective is it in reducing infection? *AAOS Bull*. 2006:12–14. Available at: www2.aaos.org/aaos/archives/bulletin/jun06/fline7.asp. Accessed April 26, 2010.
16. Evans RP; American Academy of Orthopaedic Surgeons Patient Safety Committee. Surgical site infection prevention and control: an emerging paradigm. *J Bone Joint Surg Am.* 2009;91(Suppl 6): 2–9.
17. Fitzgerald RH Jr. Total hip arthroplasty sepsis: prevention and diagnosis. *Orthop Clin North Am*. 1992;23:259–264.
18. Gruenberg MF, Campaner GL, Sola CA, Ortolan EG. Ultraclean air for prevention of postoperative infection after posterior spinal fusion with instrumentation: a comparison between surgeries performed with and without a vertical exponential filtered air-flow system. *Spine (Phila Pa 1976).* 2004;29:2330–2334.
19. Hanssen AD, Osmon DR, Nelson CL. The prevention of deep periprosthetic joint infection. *Instr Course Lect*. 1997;46: 555–467.
20. Hart D. Bactericidal ultraviolet radiation in the operating room: twenty-nine-year study for control of infections. *JAMA*. 1960;172:1019–1028. Available at: http://jama.amaassn.org/cgi/content/abstract/172/10/1019. Accessed April 26, 2010.
21. Haslam KR. Laminar air-flow air conditioning in the operating room: a review. *Anesth Analg*. 1974;53:194–199.
22. Kurtz SM, Lau E, Schmier J, Ong KL, Zhao K, Parvizi J. Infection burden for hip and knee arthroplasty in the United States. *J Arthroplasty*. 2008;23:984–991.
23. Kurtz SM, Ong KL, Schmier J, Mowat F, Saleh K, Dybvik E, Karrholm J, Garellick G, Havelin LI, Furnes O, Malchau H, Lau E. Future clinical and economic impact of revision total hip and knee arthroplasty. *J Bone Joint Surg Am.* 2007;89(Suppl 3): 144–151.
24. Lidwell OM. Clean air at operation and subsequent sepsis in the joint. *Clin Orthop Relat Res*. 1986;211:91–102.
25. Lidwell OM. Ultraviolet radiation and the control of airborne contamination in the operating room. *J Hosp Infect*. 1994;28: 245–248.
26. Lidwell OM, Elson RA, Lowbury EJ, Whyte W, Blowers R, Stanley SJ, Lowe D. Ultraclean air and antibiotics for prevention of postoperative infection: a multicenter study of 8,052 joint replacement operations. *Acta Orthop Scand.* 1987;58:4–13.
27. Lidwell OM, Lowbury EJ, Whyte W, Blowers R, Stanley SJ, Lowe D. Effect of ultraclean air in operating rooms on deep sepsis in the joint after total hip or knee replacement: a randomized study. *Br Med J (Clin Res Ed).* 1982;285:10–14.
28. Lowell JD, Kundsin RB, Schwartz CM, Pozin D. Ultraviolet radiation and reduction of deep wound infection following hip and knee arthroplasty. *Ann N Y Acad Sci.* 1980;353:285–303.
29. Malik MH, Chougle A, Pradhan N, Gambhir AK, Porter ML, Ann R. Primary total knee replacement: a comparison of a nationally agreed guide to best practice and current surgical technique as determined by the North West Regional Arthroplasty Register. *Coll Surg Engl.* 2005;87:117–122. Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1963869/. Accessed April 26, 2010.
30. Mangram AJ, Horan TC, Pearson ML, Silver LC, Jarvis WR. Guideline for Prevention of Surgical Site Infection, 1999. Centers for Disease Control and Prevention (CDC) Hospital Infection Control Practices Advisory Committee. *Am J Infect Control*. 1999;27:97–134.
31. Meehan J, Jamali AA, Nguyen H. Prophylactic antibiotics in hip and knee arthroplasty. *J Bone Joint Surg Am.* 2009;91:2480–2490.
32. Memarzadeh F, Manning A. Reducing risks of surgery. *ASHRAE Journal*. 2003;45:28–33. Available at: http://orf.od.nih.gov/NR/rdonlyres/9EC84DBB-AC8D-409C-9783-025830F47D5A/12465/ReducingRisksofSurgery.pdf. Accessed April 26, 2010.
33. Miner AL, Losina E, Katz J, Fossel AH, Platt R. Infection control practices to reduce airborne bacteria during total knee replacement: a hospital survey in four states. *Infect Control Hosp Epidemiol.* 2005;26:910–915.
34. Nelson JP, Glassburn AR, Talbott RD, Mcelhinney JP. The effect of previous surgery, operating room environment, and preventive antibiotics on postoperative infection following total hip arthroplasty. *Clin Orthop Relat Res.* 1980;147:167–169.
35. Peersman G, Laskin R, Davis J, Peterson M. The Insall Award Paper. Infection in total knee replacement: a retrospective review of 6489 total knee replacements. *Clin Orthop Relat Res.* 2001;392:15–23.
36. Phillips JE, Crane TP, Noy M, Elliott TSJ, Grimer RJ. The incidence of deep prosthetic infections in a specialist orthopaedic hospital: a 15-year prospective survey. *J Bone Joint Surg Br.* 2006;88:943–948.
37. Pulido L, Ghanem E, Joshi A, Purtill JJ, Parvizi J. Periprosthetic joint infection: the incidence, timing, and predisposing factors. *Clin Orthop Relat Res.* 2008;466:1710–1715.
38. Report of an Ad Hoc Committee of the Committee on Trauma, Division Medical Sciences, NAS-NRC. Postoperative wound infections: the influence of ultraviolet irradiation of the operating room and of various other factors. *Ann Surg*. 1964;160(Suppl): 1–192. Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1408730/pdf/annsurg00941-0002.pdf. Accessed April 26, 2010.
39. Ritter MA, Olberding EM, Malinzak RA. Ultraviolet lighting during orthopaedic surgery and the rate of infection. *J Bone Joint Surg Am.* 2007;89:1935–1940.
40. Rutala WA, Weber DJ; The Healthcare Infection Control Practices Advisory Committee (HICPAC). CDC Guideline for Disinfection and Sterilization in Healthcare Facilities, 2008. Available at: http://www.cdc.gov/hicpac/Disinfection_Sterilization/20_00reference.html. Accessed April 26, 2010.
41. Salvati EA, Robinson RP, Zeno SM, Koslin BL, Brause BD, Wilson PD Jr. Infection rates after 3175 total hip and total knee replacements performed with and without a horizontal unidirectional filtered air-flow system. *J Bone Joint Surg Am.* 1982; 64:525–535.
42. Sandiford NA, Skinner J. Mini-symposium: what's new in hip replacement. Basic principles, (II) the prevention of infection in total hip arthroplasty. *Orthopaedics and Trauma*. 2009;23: 8–16.
43. Sehulster L, Chinn RYW. Guidelines for environmental infection control in health-care facilities: recommendations of CDC and the Healthcare Infection Control Practices Advisory Committee (HICPAC). *MMWR Morb Mortal Wkly Rep.* 2003;52:1–42. Available at: http://www.cdc.gov/mmwr/preview/mmwrhtml/rr5210a1.htm. Accessed April 26, 2010.
44. Sylvain D, Tapp L. UV-C exposure and health effects in surgical suite personnel. CDC NIOSH Health Hazard Evaluation Report 2007-0257-3082. Available at: http://www.cdc.gov/niosh/hhe/reports/pdfs/2007-0257-3082.pdf. Accessed April 26, 2010.
45. Taylor GJ, Bannister GC. Infection and interposition between ultraclean air source and wound. *J Bone Joint Surg Br.* 1993;75: 503–504.

46. Taylor GJ, Bannister GC, Leeming JP. Wound disinfection with ultraviolet radiation. *J Hosp Infect.* 1995;30:85–93.
47. US Department of Health and Human Services. *Primary Containment of Biohazards: Selection, Installation and Use of Biological Safety Cabinets* (Washington: GPO, 1995). 2. BMBL Appendix A Primary Containment: Biological Safety Cabinets. Available at: http://www.cdc.gov/OD/ohs/biosfty/bmbl4/b4aa.htm#N_1. Accessed April 26, 2010.
48. Walenkamp G. Joint prosthetic infections: a success story or a continuous concern? *Acta Orthop*. 2009;80:629–632.