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State of the Science Review

Environment of care: Is it time to reassess microbial contamination of the operating room air as a risk factor for surgical site infection in total joint arthroplasty?

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In the modern operating room (OR), traditional surgical mask, frequent air exchanges, and architectural barriers are viewed as effective in reducing airborne microbial populations. Intraoperative sampling of airborne particulates is rarely performed in the OR because of technical difficulties associated with sampling methodologies and a common belief that airborne contamination is infrequently associated with surgical site infections (SSIs). Recent studies suggest that viable airborne particulates are readily disseminated throughout the OR, placing patients at risk for postoperative SSI. In 2017, virtually all surgical disciplines are engaged in the implantation of selective biomedical devices, and these implants have been documented to be at high risk for intraoperative contamination. Approximately 1.2 million arthroplasties are performed annually in the United States, and that number is expected to increase to 3.8 million by the year 2030. The incidence of periprosthetic joint infection is perceived to be low (<2.5%); however, the personal and fiscal morbidity is significant. Although the pharmaceutic and computer industries enforce stringent air quality standards on their manufacturing processes, there is currently no U.S. standard for acceptable air quality within the OR environment. This review documents the contribution of air contamination to the etiology of periprosthetic joint infection, and evidence for selective innovative strategies to reduce the risk of intraoperative microbial aerosols.

The general estimate for the cost of a periprosthetic joint infection (PJI) in the United States is approximately $100,000.[1] In 2017, Parisi et al, seeking to provide a more accurate assessment of the actual cost of a PJI, included in their estimate not only the cost to the health care system but personal liabilities such as time away from productive endeavors including work which results in lost wages. The authors found by using a 1-way sensitivity analysis that the cost of a single PJI was in the range of $389,307-$474,004.[2] In addition, multiple studies have documented that PJI is associated with a mortality rate between 2% and 7%.[3,4] It has been suggested that in selective patients the 5-year survival rate with a PJI is worse than with many cancers.[4] Although approximately 1.2 million arthroplasties are performed in the United States each year, this number is anticipated to increase in part because of the aging of the U.S. population, exceeding 3.8 million annually by the year 2030. Using current metrics, the projected (total) cost burden associated with PJI in the United States will approach $1.6 billion by the year 2020.[5] The following review will focus on the potential impact of microbial aerosols on the etiology of device-related infections, specifically PJI.

Data sources

A search to identify published peer literature on microbial aerosol contamination of the intraoperative environment was undertaken. Different search strategies identified studies and reports from PubMed, MEDLINE, Cochrane Database of Systematic Reviews, and INAHTA. The literature search involved a broad free text search with no restriction to language. Although abstracts were not considered in the search, technical engineering reports were considered in the development of this manuscript.

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Evidence supporting the association between airborne microbes and surgical site infection

Over the last 20 years several peer-reviewed publications have presented evidence that airborne microbial populations can play a role in the etiology of surgical site infection (SSI), especially in procedures involving implantable biomedical devices, such as prosthetic joints.

Of course, traditional epidemiologic dogma suggests that risk strata of possible pathogens begins with the patient's microbiome, followed by skill of the perioperative team and sterility of surgical instruments, and finally, the environment of care in the operating room (OR), including air. However, contamination of an implanted device often presents as a stealth event, where the host immune system is unaware that contamination has occurred because the native immunologic response is primarily directed against the device itself and not the presence of any residual contamination. Once an organism adheres to the surface of a device it may actually downregulate its metabolism, multiplying at a slower rate, which further shields the host from noticing the presence of a microbial pathogen.[6] This process has been well documented in late-onset vascular graft infections, where the impact of bacterial contamination may not present with symptoms until weeks or even months postimplantation. By this period of time, the microbial pathogen is often enmeshed within a biofilm, having achieved a critical density, which eventually elicits a host response to the device-associated infection[7,8] Therefore, surgical procedures involving an implant are at significant risk after intraoperative contamination from even a minimal microbial inoculum.[9,10] The traditional presentation of a postoperative infection in a clean surgical wound requires a microbial burden approaching 10^5 colony forming units (CFU), whereas in the presence of a foreign body the contaminating burden which results in infection is significantly reduced (10^1-10^2) CFU.[6,11]

The importance of airborne transmission as a mechanism for intraoperative microbial contamination and infection is a considerable source of debate and controversy.[12-16] The convective air flow within the OR can spread airborne particles, posing a potential risk for postoperative infection. These airborne particles include dust, textile fibers, skin scales, and respiratory aerosols, loaded with viable microorganisms (including *Staphylococcus aureus*) having been released from the surgical team members and patient into the surrounding air of the OR. These particles have been shown to settle onto surfaces including the surgical wound and instruments.[17-23] A study supporting this assertion documented the recovery of the same molecular strains of coagulase-negative staphylococci and *S aureus* recovered from OR air samples, originating from nasopharyngeal shedding by members of the surgical team during the same surgical cases.[24] The shedding of bacteria into the air by the OR team members can be enhanced by conditions including dermatitis and upper respiratory infections.[15,25,26] A study published in 1984 in the *Journal of Bone and Joint Surgery* documented that conversations within the OR during total joint arthroplasty enhanced microbial contamination of the OR air.[27] These findings have validated a more recent study, which documented that the barrier properties of the traditional surgical mask rapid decreases due in part to the accumulation of moisture within the fabric of the mask leading to nasopharyngeal venting along the edges of the mask.[24] Underscored the impact of contaminated air on postoperative surgical infection are the recent global reports of intraoperative wound contamination by *Mycobacterium chimaera*.[28] These infections, which continue to be reported, have been found to be the result of air contamination associated with a commonly used heater cooler unit in cardiothoracic surgical procedures, despite use of ultraclean air ventilation.[28]

Current OR standards for reduction of microbial aerosol

Studies conducted in the mid-1960s by Goddard initiated the dialogue regarding total air changes needed in ORs to minimize postoperative infection rates. Goddard's experiments suggested a quantifiable relationship between air change rates and bacterial count, noting that increasing air changes per hour from 20 to 25 reduced bacteria forming colony (cfu) units from 3.8 to 2.5 cfu/ft^3 of room air.[29] Current clinical guidelines including those from the Centers for Disease Control and Prevention and the Association of periOperative Registered Nurses place significant focus on reducing environmental contamination in the OR via cleaning and disinfection of hard and soft environmental surfaces, equipment, and skin and hands of patients and health care workers. Air contamination and air cleaning strategies are addressed from the perspective of limiting door openings (OR traffic), efforts to limit the number of individual in the room during a case, and adhering to specific engineering controls for air pressure (positive), air recirculation (15-20 air changes per hour), temperature, humidity, and and High Efficiency Particulate Arrestance (HEPA) filtration.[30,31] However, these guidelines do not address specific criteria for the quantitative reduction of viable microbial aerosols in OR air. Guidelines from ASHRAE have established air displacement standards and operational parameters for the air handling units (Table 1).[32] Not surprisingly, even with these required engineering and traffic control standards, there are numerous reports and studies linking airborne contamination directly to device-related procedures and specifically, orthopedic SSIs.[33-36]

There is currently no U.S. standard for air quality for the OR environment that is akin to the standards for maximum particle size limits (particles per cubic meter of air) in pharmacy clean rooms.[37] Within the international arena there are numerous quantitative parameters for air particle or bacteria levels in the OR. A technical paper from health care professionals in Australia proposes that OR air quality should meet European Union (EU) ISO 7 classification (Table 2).[38] In an era of biomedical device-related surgery, an EU ISO 7 classification would potentially represent an excessive number of both viable and nonviable particles that may in the course of the surgical procedure settle within the surgical wound. The EU is in the process of developing new air quality standards for the hospital environment, including ORs, which will include 3 classes based on patient risk. Specific limitations will be set, by class, on the allowable number of bacterial CFU within selective health care environments as indicated in Figure 1.[39] For example, the particle count or bacterial CFU limits in a compounding pharmacy clean room would be different from an OR where there are many more people, equipment, and movement within the environment. However, the goal of measuring air quality in the OR should include a more comprehensive approach, especially with the availability of real-time laser particle counting technology that can differentiate between viable and nonviable particulates, which could be beneficial in developing a mitigating risk strategy to prevent airborne device contamination during implantation. Under the EU–World Health Organization plan, the permissible levels of microbial contamination in general ORs (class II) would be <50 CFU/m^3, whereas orthopedic, cardiac, and transplant ORs would have permissible limits of <10 CFU/m^3 (class I). This strategy is more in line with what we

Table 1
Additional operating room design considerations per ASHRAE 170-2008[32]

- Mean diffuser velocity 127-178 L/m^2
- Diffuser concentration to provide an airflow pattern over the patient and surgical team
- Diffuser array shall extend a minimum of 305 mm beyond the table footprint
- >30% of the diffuser array area used for nondiffuser uses such as lights

Table 2
USP 797 low- to medium-risk pharmacy clean rooms guidelines for microbial contamination of room air[38]

ISO 14644-1 clean room standards							
	Maximum particles per cubic meter						Federal Standard 209E Equivalent
Class	≥0.1 μm	≥0.2 μm	≥0.3 μm	≥0.5 μm	≥1 μm	≥5 μm	
ISO 1	10	2.37	1.02	0.35	.083	.0029	
ISO 2	100	23.7	10.2	3.5	0.83	.029	
ISO 3	1,000	237	102	35	8.3	0.29	Class 1
ISO 4	10,000	2,370	1,020	352	83	2.9	Class 10
ISO 5	100,000	23,700	10,020	3,520	832	29	Class 100
ISO 6	1.0×10^6	237,000	100,200	35,200	8,320	293	Class 1,000
ISO 7	1.0×10^7	2.37×10^6	1,020,000	352,000	83,200	2,930	Class 10,000
ISO 8	1.0×10^8	2.37×10^7	1.02×10^7	3,520,000	832,000	29,300	Class 100,000
ISO 9	1.0×10^9	2.37×10^8	1.02×10^8	35,200,000	8,320,000	293,000	Room air

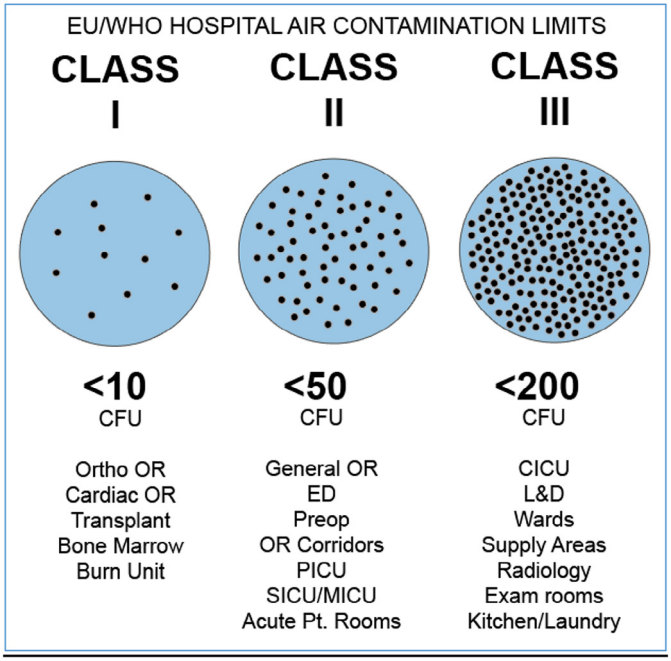

Fig 1. Propose EU-WHO standards for contamination of hospital room air: class I, <10 CFU; class II, <50 CFU; and class III, <200 CFU. Hospital OR fall within class I standards. 39 CFU, colony forming units; ED, emergency department; EU, European Union; Preop, preoperative; Pt., patient; OR, operating room pediatric intensive care unit (PICU); surgical intensive care unit (SICU); medical intensive care unit (MICU); cardiac intensive care unit (CICU) and labor and delivery (L&D). WHO, World Health Organization.

perceive to be risk stratification, recognizing that device implantation and immune status have a probable impact on development of a postoperative infection.

Currently, air sampling protocols are not standardized, and unfortunately it is difficult to compare results from studies which use different methodologies to assess microbial air quality. Traditionally, microbial air sampling in the OR (and health care in general) has involved either passive (settle agar plates) or active (cascade impactors or impingers) sampling strategies. However, it has been documented that different active air sampling devices show high variability, often giving different results in the same place at the same time.[40] Within the last 10 years the introduction of laser real-time bacterial enumeration has allowed investigators to differentiate between viable and nonviable airborne particulates. Although this technology is readily available, few health care institutions have incorporated real-time laser microbial enumeration into routine OR air sampling. There are multiple reasons for this omission, including (1) capital cost of the equipment; (2) lack of a standardized testing strategy; and (3) unfortunately, failure to recognized airborne microbial populations as playing a role in postoperative infections.

Although innovative microbial enumeration technology is providing a real-time analysis of the potential risk of intraoperative contamination, one cannot dismiss the relative value of traditional microbial culture methods. Dalstrom et al documented using a standard culture technique a time-dependent contamination of opened sterile OR trays, and found that "Culture positivity correlated directly with the duration of open exposure of the uncovered operating-room trays." The authors suggested that covering the surgical trays with a sterile towel significantly reduced the contamination risk.[41] This study has in part led to the recent practice of preparing a separate wound closure tray that is only opened when the surgeon is ready to close the case, thereby minimizing the risk of fascial and subcuticular wound contamination at closure.

Technologies to reduce the risk of viable particulate contamination within the OR

There are 4 selective processes for reducing air contamination: dilution, filtration, pressurization, and disinfection. Current SSI prevention guidelines strategies for reducing air contamination in the OR include dilution (15-20 air changes per hour), filtration (HEPA) and pressurization (positive), and the practice of limiting door openings and encouraging a reduction in OR traffic during surgical cases. In the practice of orthopedic surgery, multiple strategies have been used or proposed to reduce the risk of intraoperative contamination of the wound, including the use of surgical helmet systems (SHSs), ultraviolet (UV) plus heating, ventilation, and air conditioning (HVAC) systems, and ultraclean ventilation.

Surgical helmet system

Although SHSs are frequently used in joint replacement surgery, their role in preventing SSI remains controversial. The recent Centers for Disease Control and Prevention guidelines for prevention of SSI sought to resolve this dispute but were unable to reach a conclusion regarding the utility of such systems in reducing SSIs and hence could not make any recommendations on their routine use.[42] In a recent systematic review, the older Charnley-type body exhaust suits which are under negative pressure were reported to be effective in reducing deep infection rates and contamination in arthroplasty.[43] However, in contrast with the body exhaust suits, modern SHS designs were not shown to reduce contamination or deep infection during arthroplasty.[43] McGovern et al published a controlled experiment designed to investigate the effect of different surgical helmet or gown systems on counts of airborne particles measuring

≥0.3 μm, using a handheld particle counter. There was a significant reduction in particle counts with the hood/gown system (hood over helmet combined with an integral gown) versus gown alone ($P = .007$) and hood plus gown ($P = .037$). It was further determined that the fans in the helmets do not increase contaminants by blowing particles from the head area. Overall, a significant reduction in surgeon-originated contaminants was seen with the toga compared with both the hood and gown separate ensemble and gowns alone.[44] In another study, operating team members wore SHSs consisting of disposable gowns plus either a nonsterile squire-type disposable hood and triple laminar face mask, a sterilized helmet aspirator system, or no head cover. Both types of head covers resulted in low and comparable air contamination (means, 8 and 4 CFU/m^3, respectively) and surface wound contamination (means, 69 and 126 CFU/m^2/h, respectively). Omission of head covering resulted in a 3- to 5-fold increase in microbial air contamination, and an increase in the bacterial sedimentation rate in the wound area of 60-fold ($P \leq .0001$).[45] A study by Fraser et al in 2015 concluded that particle contamination occurs at the gown-glove interface in most commonly used positive-pressure SHSs, noting that this is something all orthopedic surgeons should be aware of as a potential source of intraoperative contamination. Although future studies are needed to clarify the link between particle contamination through this route and PJIs, the study concluded that surgeons should consider using gowning systems that minimize the migration of fomites through the gown-glove interface.[46] A recent study hypothesized that activation of the airflow in an SHS after complete gowning would lead to decreased contamination of the surgical environment. By using a fluorescent particle model, the maximal particle spread from a filtered-exhaust helmet and contamination of the surgical environment based on timing of airflow activation through simulated surgical procedures were evaluated. Helmet airflow analysis revealed particle spread >5 ft in all trials. Activation before gowning resulted in a significantly greater contamination in the control group compared with the experimental group ($P = .014$). The study conclusion was surgical gowning should be completed before activation of the airflow system.[47] In a recent study published in 2016, the authors found that the current positive-pressure SHS was found to be a potential risk for intraoperative contamination. Mechanistically, this was likely because of the buildup of positive pressure within the suit, which could aerosolize viable particulates via the unsealed areas around the surgeon's cuffs.[48] The finding of these various studies would suggest that the benefits of an SHS could very well be mandated by individual product choice, technique, and operator.

UV plus HVAC systems

UV disinfection as an adjunct to manual environmental cleaning is used increasingly in health care facilities to improve the quality of surface disinfection. Similarly, UV is being used with increasing frequency as an adjunct to standard engineering controls in ORs to clean the air to reduce the risk of microbial aerosols and thereby reduce the risk of infection. A wide spectrums of UV HVAC systems are currently available on the market.

Egg crate upper-room UV germicidal irradiation

This system was recently developed as an alternative to conventional upper-room UV germicidal irradiation using conventional louvered fixtures. Efficacy has been confirmed via experimental testing where airborne *Bacillus atrophaeus* spores were inactivated with the system.[49] However, no studies documenting the impact of this system to reduce risk of SSI rates are available for review.

HEPA and UV air recirculation system

The efficacy of this innovative system has been recently evaluated for reducing airborne microorganism present within a plastic surgery OR at an outpatient surgery center. The reactor system of the HEPA and UV air recirculation system uses C-band UV light focused on a reaction chamber filled with clear cylindrical silicate quartz crystals to decrease bacteria counts in the air. In the study, an air sampling impactor and agar media plates were placed in multiple locations in the OR and used to measure the number of CFU per cubic meter of bacteria in the air before and after use of the system. From the cultured samples obtained, there was a 53.4% ($P = .0163$) reduction in CFU count overall.[50] Further studies are warranted to assess the clinical benefit of this innovative technology.

UV-C, continuous, air purification system

Combining UV germicidal irradiation chamber and air circulating fans with an overhead ceiling light, this system uses UV-C light and filtration to draw in and treat environmental air. The system is designed to work constantly, providing 4 changes per hour for an $8 \times 10 \times 10$ ft^3 dimensional room. In a non–peer-reviewed 2016 study reported in McKnight's publication, a long-term care facility using this technology reported that in patient rooms without the system, infections rates per 1,000 patient days averaged 17.5. In rooms where the system was activated, infections per 1,000 patient days averaged 12.5, a statistically significant outcome. Additionally, the rooms with the system in place exhibited a 51% reduction in airborne bacteria.[51] However, future peer-reviewed published studies are warranted to assess the benefit of this technology as a feasible strategy for reducing the risk of intraoperative contamination and infection.

Ultraclean ventilation systems combining laminar airflow and high-efficiency particulate air filters

Ultraclean ventilation systems are predominantly used in clean prosthetic implant surgery. Several studies have demonstrated decreased air bacterial contamination with laminar airflow (LAF) using sedimentation agar plates placed in key areas throughout the OR. It is generally assumed that a reduction in airborne contamination with this system will translate into reduced orthopedic infections. However, apart from the original Lidwell Medical Research Council study, there are few clinical studies that validate the effectiveness of LAF systems.[52] However, one expert has rightly suggested that the "absence of a high-level of evidence from randomized trials is not proof of ineffectiveness."[53] Other investigators have concluded there is no benefit, and one report actually suggested an increased infection risk using laminar flow technology.[54-57] Two recent systematic reviews and meta-analyses failed to show an advantage with LAF compared with conventional turbulent ventilation in reducing the risk of SSIs in total hip and knee arthroplasties.[58,59] The authors of both of these studies concluded that LAF should not be regarded as a preventive measure to reduce the risk of infection and that it should not be installed in new ORs. The World Health Organization tackled this issue in their recent guidelines for preventing SSI. Based on the available scientific literature, the World Health Organization panels suggested ". . .that laminar airflow ventilation systems should not be used to reduce the risk of SSI for patients undergoing total arthroplasty surgery (conditional recommendation, low to very low quality of evidence)."[60] The likely source of this controversial issue resides in the difficulty of acquiring a true air barrier within the OR with the myriad of light, monitors, and personnel who pass repeatedly in and out of the LAF.[39] Although it appears that LAF may not be needed, the role of positive ventilation systems and the efforts to reduce the number of particulate matters in the OR cannot be questioned.

CONCLUSIONS

Microbial contamination of air in the OR is an underappreciated factor in the etiology of PJIs and infection after implantation of other selective biomedical devices. Current engineering controls and practice requirements for limiting traffic during cases have thus far resulted in failure to reduce the risk of microbial aerosols or intraoperative contamination of implantable devices during arthroplasty surgery. Furthermore, there is a general lack of understanding or even misunderstanding of how (and why) airborne microbial populations pose a significant risk to patients undergoing device-implant surgery. Future consideration should be given to institutional investment in innovative air purification technologies as an adjunctive strategy to enhance current engineering controls, in an effort to reduce the risk of PJIs. Future consideration should be given to ongoing research into OR air quality by testing the feasibility of HVAC-implemented designs according to ASHRAE 170 using simulated surgical procedures and equipment that mirrors activity during a typical orthopedic procedure such as arthroplasty. Traditional infection control strategies such as limiting OR traffic has had a marginal impact in reducing intraoperative microbial aerosols or the risk of implant-associated infections.

It is truly confounding that rigorous air quality standards are applied to the drug and computer chip manufacturing industries, whereas the same rigor has not been embraced to provide a safe and effective OR environment for surgical patients. To meet the future challenge of reducing the risk of PJIs and other implant-related infections, updated quantitative air quality standards for the OR (eg, those in development for the World Health Organization) are required that are based on state-of-the-art real-time microbial aerosol testing. If we are to have a measurable impact on reducing patient morbidity and mortality that is often associated with PJI, all surgical stakeholders must continue to evaluate and embrace innovative operative techniques along with evidence-based adjunctive risk reduction strategies, improving patient outcomes and preserving valuable health care resources.

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