Intraoperative sampling of airborne particulates is rarely performed in the OR environment because of technical difficulties associated with sampling methodologies and because of the common belief that airborne contamination is infrequently associated with surgical site infections (SSIs). In this study, investigators recovered nonviable (ie, lint) and viable (ie, microorganisms) particulates during vascular surgery using a personal cascade impactor sampling device. The predominant nonviable particulates recovered during intraoperative sampling were wood pulp fibers from disposable gowns and drapes. Several potential nosocomial pathogens (eg, *Staphylococcus aureus*, *Staphylococcus epidermidis*) and other drug-resistant isolates frequently were recovered from an area adjacent to the surgical field. The widespread presence of airborne particulates during surgery suggests that further studies are warranted to assess the role these particles may play in the development of SSIs or in dissemination of nosocomial pathogens within the OR and hospital environment.

More than 130 years ago, Joseph Lister, MD, influenced by the sentinel studies of Louis Pasteur, attempted to reduce air-
borne contamination within the OR environment by using carbolic acid sprays. His efforts resulted in an immediate decrease in both morbidity and mortality after surgical amputation; however, interest in airborne contamination as a vehicle for surgical site infection (SSI) rapidly decreased.1 By the early twentieth century, contact or hand contamination was viewed as the primary mechanism for acquisition of SSIs. Although researchers view contact contamination as the primary culprit in transmitting nosocomial pathogens in the hospital environment, significant time and monetary efforts have been directed toward designing airflow systems that reduce potential airborne bacterial populations in the OR and critical care environment.2

It is interesting that much effort and monies have been devoted to improving airflow in the OR. This is because it was well documented in the 1960s that multiple air changes were associated with decreased infection rate; however, most infection control practices focus on hand contamination as a preventive strategy to reduce nosocomial infections. This is because infection control policies focus on altering inappropriate behavior patterns (ie, tangible) that affect technique. It is much more difficult to control what floats (ie, intangible) in the air. To be completely fair, many, if not most, infections probably are caused by touch contamination, especially superficial SSIs. Our study demonstrates that there is a widespread presence of organisms like the staphylococci in the OR, which may contaminate a biomaterial surface and lead to other types of infections (ie, late onset). We should look toward reducing potential nosocomial aerosol contamination by developing more efficient masks, reducing traffic, or improving air-handling systems.

LITERATURE REVIEW

Studies have implicated bioaerosols in the transmission of nosocomial pathogens within the health care environment. The most widely transmitted pathogens include mycobacteria, viruses (eg, influenza, measles, chickenpox), Legionella, and saprophytic fungi (ie, Aspergillus). Far fewer studies have documented the role of aerosolized bacterial populations in patients' acquisition of nosocomial infections. Two separate studies, however, have linked the aerosol dispersion of Staphylococcus aureus with human disease. In the first study, a colonized OR technician was linked to 11 separate SSIs.3 In the second example, a cross-connection between an isolation room and intensive care unit ward was responsible for an outbreak of methicillin-resistant S. aureus infections.4 These studies suggest that pathogens such as S. aureus may be transmitted as an aerosol within the hospital environment, producing nosocomial infections. Unfortunately, researchers' past efforts to identify airborne microbial populations in the OR environment have focused on static environmental sampling techniques, using study intervals when the fewest personnel are present in the OR.

Airborne microorganisms are not the only particles present in the modern surgical environment. The extensive use of disposable nonwoven gowns and drapes, coupled with the presence of woven reusable materials in the OR, has resulted in the release of large amounts of inert material called lint, which adheres to walls, floors, instruments, and other critical surfaces.5 Precise quantitative data for nonviable (ie, lint) and viable (ie, microorganisms) particulates during the intraoperative period have been lacking due to limitations in sampling strategies and appropriate methodology. In this study, researchers measured both lint and airborne microbial populations during major surgical procedures using a personal cascade impactor to determine the intraoperative level of these particulates in a vascular surgical suite.

METHODS

Researchers studied 28 sampling periods in a vascular surgical suite to determine intraoperative lint levels. Each sampling interval lasted 3.5 hours to eight hours with a mean surgical time of 4.2 hours, and involved a total of 38 major vascular surgical procedures. Researchers studied two groups to ascertain the role of disposable fabrics (eg, drapes, gowns, packaging materials) on intraoperative lint generation. In one group (n = 15 sampling intervals), researchers asked all OR personnel to wear gowns and scrub attire constructed of wood pulp polyester. In addition, substitutions were made so that shoe covers, drapes, and sterilization pack and tray materials matched gown and scrub attire fabric during the sampling period. In the second group (n = 13), OR personnel used gowns, scrubs, drapes, sterilization pack and tray materials, and other items manufactured with 100% polypropylene fabric during the sampling period. Although fabric-specific compliance was 100% in both groups for drapes, OR personnel's overall compliance in wearing either wood pulp polyester or 100% polypropylene gowns and scrubs was 80% to 87%, respectively, within each study interval.

Particulate (lint) analysis. A personal cascade impactor may be configured as a four-, six-, or eight-stage device. In this study, researchers used the sampling device with six stages for recovery of both lint and microbial populations. Researchers attached individual samplers to a personal sampling pump that contained a rechargeable battery pack. Before each sampling
Period, researchers carefully calibrated all impactors and sampling pumps to an airflow rate of 2 L per minute. Researchers chose a sampling pump for this study that had sufficient vacuum capacity to maintain the preselected flow rate over the duration of the sampling period, even as backup pressure increased with particulate loading. The principle of particle capture with the impactor is depicted in Figure 1. Room air enters the sampler through the top (ie, cowling), moving downward through the various stages. Each stage is positioned so that air pulled through the sample slit strikes the base of the next stage, which causes the air to rebound and then continue downward to the next level. When the sampled air strikes the stage, a debris zone (ie, lint line) is created that contains particulate material (Figure 2). The sampling stage slit size decreases at each successive level, resulting in the deposit of smaller-sized particles on a disposable Mylar substrate. A total of two 34 mm-diameter Mylar substrates were used per sampling device, with one positioned on stage two and another positioned on stage three. Previous pilot studies conducted in our laboratory documented that loading the Mylar substrates between two stages was sufficient to capture the major airborne lint particulates (ie, wood pulp polyester, cotton, or 100% polypropylene) present during the intraoperative sampling. After each sampling interval, researchers removed the Mylar substrates from the impactor and determined lint levels by gravimetric analysis using a microbalance, comparing combined pre- and post-sampling weights.

Figure 1 • Airflow enters the air sampling device, cascading down through successive stages. A Mylar substrate inserted between each stage captures particulates.
Figure 2 • Light microscope image shows debris field (ie, lint line) on a Mylar substrate after four-hour sampling in unoccupied (ie, control) OR at 90 times magnification.

Figure 3 demonstrates the positioning of the impactors in the vascular OR. Two devices were stationed on IV poles adjacent to the surgical field (ie, approximately 0.5 m from the surgical field), and two devices were placed at the periphery (ie, approximately 4 m from the surgical field) of the room next to the air intake vents. In the wood pulp polyester group, researchers evaluated a total of 61 and 59 separate Mylar sheets from devices positioned approximately 0.5 m and 4 m, respectively, from the surgical field. Researchers evaluated a total of 59 and 58 Mylar substrates at 0.5 m and 4 m, respectively, from the surgical field in the 100% polypropylene group. Total intraoperative lint levels were expressed as micrograms (µg) of lint per cubic meter (m³) of sampled air. Researchers placed the impactor devices into position 15 to 30 minutes before room setup and removed them after the procedure was completed.
After gravimetric analysis, researchers submitted selected Mylar substrates to the electron optics laboratory for scanning electron microscopy (SEM) to identify the predominant fiber recovered during intraoperative sampling in both groups. To capture airborne particles, researchers also touched 31 carbon-coated SEM aluminum stubs containing an adhesive to inert surfaces (eg, cabinets, monitors, instrument carts) after terminal cleaning of the room. These samples were randomly obtained throughout the study to determine what fibers were present in the room after cleaning.

**Intraoperative microbial recovery.** Intraoperative microbial recovery during vascular surgery was evaluated using a personal cascade impactor with modifications. Researchers placed a 0.45 µm filter between the second and third stages of the device. Researchers calibrated and positioned the air samplers as per lint analysis. Researchers obtained a total of 75 intraoperative airborne samples for microbial analysis from both study groups (ie, wood pulp polyester, n = 38; 100% polypropylene, n = 37). The mean sampling interval was 3.5 hours. Figure 4 shows the sampling technique researchers used to recover intraoperative airborne microbial populations using the personal cascade impactor. After each sampling period, researchers completely disassembled the device and placed the components in 70% alcohol for 10 minutes. Researchers aseptically assembled the impactor, with an 0.45 µm membrane filter in place, in a laminar flow biological hood, wrapped it in sterile gauze, and stored it until they placed it in the OR. After sample collection, researchers removed the filter, placed it on the surface of trypticase soy agar supplemented with 5% sheep blood, and incubated the sample for 48 hours at 35° C (95° F). Researchers identified individual colonies by standard methods and performed susceptibility studies on selected isolates. Microbial quantitative recovery was expressed as colony forming units (cfu) per m³ of sampled air.
Intraoperative controls. Researchers performed several controls during the study. To determine baseline lint levels in the vascular OR, researchers placed sampling devices in the unoccupied vascular OR, which were run continuously for eight hours. The rooms were sealed off during this period, and no personnel were allowed to enter. Researchers performed control studies on four consecutive nights. To evaluate aseptic preparation of the impactors for airborne microbial recovery, researchers chose a total of 16 devices at random and unwrapped and placed them in a laminar flow biological hood. The devices ran for four hours, after which researchers removed and cultured the filters as per intraoperative samples. A final control was performed to determine baseline microbial recovery from the vascular OR. Microbial sampling was performed for four hours on four consecutive nights using the personnel cascade impactors while the OR was empty; researchers removed and cultured the filters as previously described.

Statistical analysis. Researchers analyzed the differences in total lint concentrations and microbial recovery between wood pulp polyester and 100% polypropylene groups using an unpaired Student's t test. In addition, researchers used a one-way analysis of variance (ANOVA) to determine whether differences in lint and microbial recovery existed between devices positioned adjacent to or 4 m from the surgical field.

RESULTS

Figure 5 depicts the mean nonviable (ie, lint) particulate recovery in the wood pulp polyester and 100% polypropylene groups at 0.5 m and approximately 4 m from the surgical field. The mean lint concentrations recovered adjacent to the surgical field were 128.8 µg/m³ and 35.7 µg/m³, respectively, for the wood pulp polyester and 100% polypropylene groups (P < .01). At approximately 4 m from the surgical field, researchers detected lint concentrations of 117.3 µg/m³ and 42.1 µg/m³, respectively, from wood pulp polyester and 100% polypropylene groups (P < .01). There was no significant difference in lint recovery from either the adjacent or peripheral sampling sites within each study group.
Figure 5 • Recovery of nonviable (ie, lint) particulates in wood pulp polyester and 100% polypropylene groups, adjacent to and distant from the surgical field; control sampling was conducted overnight in the same, but unoccupied, OR.

Lint particulates captured on Mylar substrates during intraoperative sampling resulted in the creation of a primary impaction field (ie, lint line). Figure 6 is a scanning electron micrograph of a lint line from the 100% polypropylene group viewed at 100 times magnification. A higher magnification of this debris field shows the individual fibers to be representative of wood pulp polyester, not 100% polypropylene. Control samples obtained after overnight sampling in the unoccupied vascular OR revealed baseline lint levels to be 20.3 µg/m³ and 16.6 µg/m³, respectively, at 0.5 m and 4.0 m from the surgical field. Although the scrub and gown wearing compliance (ie, 80%) in the wood pulp polyester group was slightly lower compared to the 100% polypropylene group (ie, 87%), differences in compliance did not appear to influence the overall findings of the study.
Figure 6 • (A) Low-power scanning electron micrograph shows debris (ie, lint) field on Mylar substrate from 100% polypropylene group (magnification, 100 ×); (B) higher magnification of debris field reveals that the fibers actually are wood pulp (magnification, 690 ×).

Table 1 presents SEM findings for the Mylar substrates and random touch preps taken from various OR surfaces. Wood pulp was the predominant fiber recovered in both study groups. Scanning electron microscopy analysis of 28 out of 31 random touch preps revealed wood pulp to be the predominant fiber obtained from counters, cabinet tops, monitor panels, and other surfaces in the OR (Figure 7). Fibers suggestive of 100% polypropylene were observed in two out of 44 (ie, 4.5%) Mylar substrates from group two and in three out of 31 (ie, 9.7%) random touch prep samples.

<table>
<thead>
<tr>
<th>Study groups</th>
<th>Wood pulp</th>
<th>Predominant fibers</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>100% polypropylene</td>
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<tr>
<td>Group 1** (n = 44)</td>
<td>44/44*</td>
<td>0/44</td>
</tr>
<tr>
<td>Group 2† (n = 44)</td>
<td>42/44*</td>
<td>2/44</td>
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<tr>
<td>Random touch preps‡ (n = 31)</td>
<td>28/31*</td>
<td>3/31</td>
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* Fibers representative of cotton also were observed in 18 of 44 group 1 samples, 13 of 44 group 2 samples, and 21 of 31 random touch preps.

** Group 1—wood pulp polyester.

† Group 2—100% polypropylene.

‡ Obtained using adhesive carbon-coated studs after terminal cleaning of OR and observed in a scanning electron microscope.
Table 1 SCANNING ELECTRON MICROSCOPIC ANALYSIS OF POLYESTER FILM SUBSTRATES OBTAINED DURING INTRAOPERATIVE SAMPLING (N = 88) AND RANDOM TOUCH PREPS (N = 31)

Figure 7 • (A) Touch prep obtained during control sampling from surface of supply cart shows fibers suggestive of wood pulp; (B) touch prep obtained from back surface of monitor during control sampling shows fiber (center of micrograph) suggestive of 100% polypropylene (magnification, 650 ×).

Microbial recovery. Researchers observed no significant difference in the intraoperative qualitative or quantitative microbial recovery between the wood pulp polyester and 100% polypropylene groups. Intraoperative microbial recovery in the vascular OR is presented in Figure 8. *Staphylococcus epidermidis* was recovered in 100% of air samples collected adjacent to the surgical field and from the periphery of the room. *Staphylococcus aureus*, an organism of known nosocomial virulence, was recovered from 73.3% of the air sampling sites at 0.5 m and 90.6% of the sites at 4 m in the OR. *Burkholderia cepacia* and *Stenotrophomonas maltophilia*, two nosocomial pathogens that express multiple-antibiotic resistance, were recovered 22% and 43% of the time, respectively, from air samples collected adjacent to the surgical field. Other miscellaneous gram-negative microorganisms, including *Acinetobacter* spp and *Enterobacter* spp, were recovered from 15% of the intraoperative air sampling sites at 0.5 m and 37% of the sites at 4 m. Miscellaneous gram-positive bacteria (eg, *Corynebacterium, Bacillus*) were recovered in more than 90% of samples from both sampling sites. *Candida* (ie, yeast) was found in 10.6% of air samples collected adjacent to the surgical field.
Control studies to validate aseptic preparation of the devices revealed no nosocomial contamination; a total of two colonies of *Bacillus* and one colony of *Micrococcus* were recovered from three of 16 control filters. A second control involved positioning four devices in the vascular OR while no staff members were present (ie, overnight for four consecutive nights). No staphylococci, gram-negative nosocomial pathogens, or yeast were recovered in cultures during these control studies. The quantitative microbial recovery from control and study groups is presented in Table 2. Control sampling in the unoccupied vascular OR demonstrated a low microbial threshold; however, in the presence of OR personnel, the total colony-forming units increased from fourfold to twelvefold.

**DISCUSSION**

The use of disposable gowns and drapes has been associated with increased lint levels in the OR environment. Although
there has been some discussion about the effect of linting in the health care environment, few studies have measured lint levels during the intraoperative period. The personal cascade impactor originally was designed to be worn by workers at risk for exposure to high levels of particulates (ie, silicone, wood, coal dust) in the workplace. The first application of this device in the surgical environment occurred during an effort to determine the level of OR personnel's intraoperative exposure to blood-containing aerosols. Using aerosolized hemoglobin as a marker for blood exposure, investigators were able to precisely quantify the upper and lower exposure thresholds for a number of surgical procedures.

In this study, air sampling studies with the personal cascade impactor demonstrated that the use of disposable gowns, scrubs, and surgical draping constructed of wood pulp polyester was associated with significant linting compared to items made from 100% polypropylene. It is interesting to note that elevated lint levels also were detected when 100% polypropylene fabrics were used in the study group; however, SEM analysis of the Mylar substrates revealed these fibers to be composed of wood pulp and not polypropylene. Baseline lint levels (ie, < 25 µg/m³) were detected in the unoccupied vascular OR. These findings suggest that where there has been a high dependency on wood pulp-based disposable items, a background level of lint can be detected, which is dispersed into the air upon increased OR activity. In addition, SEM analysis of random touch prep samples taken from various OR surfaces throughout the study documented the presence of abundant wood pulp and cotton fibers, even after terminal cleaning of the room.

More than 20 years ago, routine environmental sampling for nosocomial pathogens in the OR was discontinued due to

* the inadequacy of the sampling strategies to recover significant numbers of potential microbial pathogens,
* difficulties interpreting the importance of recovered isolates and their role in nosocomial infection, and
* the common belief that contact was the primary causal mechanism for dissemination of nosocomial isolates within the hospital environment.

Although current infection control practices emphasize contact as the major mechanism for the spread of nosocomial infections, there continues to be an ongoing interest in airborne sources of infection in the hospital environment. These are primarily related to the spread of multidrug-resistant tuberculosis, aerosol spread of saprophytic fungi in the transplant population, and the potential spread of multidrug-resistant microorganisms in health care facilities.

To date, the largest investigation of airborne microbial populations was conducted by the National Research Council, which sponsored a multihospital trial of the effectiveness of ultraviolet (UV) light in reducing the SSI rate. Although the investigators were able to document a decrease in total airborne microbial counts in UV-equipped ORs, a concomitant reduction in the overall SSI rate was not observed. An inherent problem complicating researchers' efforts to validate the importance of airborne microorganisms in SSIs has been the failure to establish a relationship between quantitative recovery and wound sepsis. This study was not conducted to prove a relationship between airborne microbes and SSIs; however, it has been proposed that wound contamination is proportional to the level of airborne contamination. The clinical significance of this supposition likely depends on intrinsic (eg, patient risk factors) and extrinsic (eg, antibiotic prophylaxis, surgical technique, patient comorbidities) variables. Studies conducted in ultraclean ORs suggest that airborne bacterial levels exceeding 10 cfu/cm³ increase the risk of biomedical device contamination.

Previous efforts to recover microbial populations in the OR environment have relied almost entirely on the use of passive settling plates or bioaerosol samplers, often positioned in empty ORs. Under these conditions, few nosocomial microbial pathogens have been recovered. In this study, total microbial (ie, threshold) counts in the unoccupied (ie, control) vascular OR were < 5 cfu/m³ and involved harmless commensal Bacillus and Micrococcus isolates. Total intraoperative mean microbial counts in both experimental groups were greater than the 10 cfu/m³ threshold and, in one case, the count was greater than 20 cfu/m³ adjacent to the surgical field. The results of this study suggest that Staphylococcus aureus, Burkholderia cepacia, Stenotrophomonas maltophilia, and other gram-negative microbial populations may be present during the intraoperative period in numbers exceeding 10 cfu/m³. Furthermore, the results demonstrate that quantitative and qualitative recovery of these microorganisms is directly related to the activity level within the OR. It is important to note the ubiquitous presence of Staphylococcus epidermidis, which was recovered in 100% of the sampling intervals. Staphylococcus epidermidis has emerged as the second most frequent organism associated with SSIs and the most frequent cause of biomaterial-associated infections.

The results of this study demonstrate that during the intraoperative period, when personnel are present in the OR, high
levels of nonviable and viable airborne particulates are detected throughout the OR environment. The etiology of the nonviable particulates is related to the use and movement of disposable drapes, garments, and packaging materials. This study does not address the etiology of the microbial aerosols; however, given the significant increase in microbial recovery associated with occupancy of the surgical suite, the increased bacterial recovery must be related to shedding from personnel in the room (ie, surgeons, nurses, ancillary staff members, the patient). In addition to the multidrug-resistant gram-negative isolates recovered in this study, 15% of the recovered staphylococcal isolates expressed antibiotic resistance, including methicillin-resistance. Although previous reports have demonstrated the presence of resistant microbial populations (eg, S. aureus) in the OR, this is the first study to document a diverse intraoperative nosocomial population with high quantitative recovery.

The clinical relevance of these findings poses some interesting questions.

* Does the presence of these airborne microbial populations effect the SSI rate?
* Can data such as this influence current practice patterns as the presence of personnel and activity level (ie, traffic) increases particulate burden in the OR?
* Does the traditional surgical mask play a sentinel role in facilitating the dissemination of nosocomial pathogens in the OR?

In this study, researchers did not observe any SSIs in vascular patients during the defined sampling period. Unfortunately, the etiology of SSIs is multifactorial and depends on a myriad of intrinsic and extrinsic risk factors, making it extremely difficult for researchers to assess the clinical relevance of nosocomial aerosol in the OR without conducting a large, prospective (eg, multiple facility) investigation. The presence of documented nosocomial pathogens, expressing multiple patterns of antimicrobial resistance in the OR, does belle some concern. In surgical suites where biomedical devices are implanted, infectious complications often are late onset, presenting weeks to months postoperatively. Organisms most often associated with prosthetic vascular graft infections were the most common pathogen recovered in this sampling. As staphylococcal and streptococcal microbial populations are not generally perceived as being transmitted in aerosolized form, skin contact with the prosthetic device at the time of implantation usually is viewed as the most plausible mechanism of graft contamination. Airborne contamination, however, may be a factor in late onset biomaterial infections. The presence of such diverse airborne microbial nosocomial populations in the vascular surgical suite suggests that prosthetic grafts and other implantable devices should not be left exposed to room air (ie, uncovered) for long periods of time before insertion. By using touch prep techniques, combined with aerosol sampling, OR personnel now can quantitate this risk.

It also is evident that room activity and traffic patterns play an important role in the generation of airborne particulates. Anecdotal and recently published observations suggest that increased activity within the OR is associated with an elevated SSI rate; however, statistical data to support this supposition as a covariable with other documented risk factors clearly are lacking. Nevertheless, the stark qualitative and quantitative differences between airborne contamination in the busy OR, compared to the unoccupied control, confirms that unwarranted traffic only increases the potential nosocomial risks. These data should serve as a stimulus for perioperative nurses to review traffic patterns in the surgical suite, policies for personnel interfacing with public areas of the hospital, and architectural placement of doors, patient holding facilities, anterooms, and equipment storage areas. Furthermore, perioperative nurses also should consider the configuration of the surgical field within the surgical suite and the position of anesthesia care providers and their ingress and egress from the room during procedures.

The suggestion that OR staff members play an active role in contributing to the airborne nosocomial microbial burden may be a provocative, rather than novel, assertion. This comes at a time when wearing traditional surgical masks is viewed in some quarters as an outdated and useless exercise that provides little or no benefit in preventing SSIs. The reverse argument, however, may be more appropriate. Perioperative nurses should ask, “If the barrier properties of the surgical mask fail, allowing the release of nasopharyngeal microbial flora within the vicinity of the surgical wound, what is the effect on SSIs, especially in those procedures involving implantation of a biomedical device?” Microbial shedding of S. aureus from the nasopharynx in the absence of a mask has been linked to nosocomial outbreaks. Further studies of microbial shedding during the intraoperative period clearly are warranted to determine the efficacy of current masks in reducing the level of potential nosocomial pathogens (eg, S. aureus). Potential sources of shedding are from OR personnel at the surgical field, anesthesia care providers, and patients whose potentially contaminated airways are not routinely covered.

CONCLUSION

This study does not attempt to draw a relationship between high lint levels in the OR and the introduction of nosocomial
microbial populations; however, it would be prudent for perioperative nurses to consider methods to reduce the levels of airborne particulates that may serve as vectors to increase the transport of microbes in the OR environment. The recovery of high numbers of potential nosocomial pathogens during surgical procedures indicates that aerosols need further study. Currently, infection control policies and procedures focus on combating the contact dissemination of nosocomial infections within the hospital environment. It is evident from this study that we must look more closely at the symbiotic relationships that may exist between aerosolized microbial populations and contact mechanisms of dissemination and acquisition of nosocomial pathogens in the surgical patient.

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NOTES


