Saudi Journal of Medicine and Public Health

https://saudijmph.com/index.php/pub

https://doi.org/10.64483/202412494

The Surgical Microbiome: A Narrative Review of Interdisciplinary Strategies for Infection Prevention in Ocular and Regional Anesthesia

Danah Othman Almazyad [1], Tahani Obaid Sheeqa Almutairi [2], Sami Saeed Alrashdi [3], Saleem Nawar Saleem Alboaqami [4], Hani Ghazi Abdulmalik [5], Rawan Rashed Omar Alharthi [6], Abdulmajed Awidh Almutiri [7], Bandar Mohammed Abdullah Al-Duhaymi [8], Laila Abdullah Alnasser [9], Abdulrahman Ali Alsugaihe [10], Saeed Ahmed Alghamdi [11], Rayan Abdulrahman Almugarry [12]

(1) King Saud Medical City, Ministry of Health, Saudi Arabia,
(2) Al-Basira Center, Al-Majma'ah, Ministry of Health, Saudi Arabia,
(3) Huraymala Hospital, Ministry of Health, Saudi Arabia,
(4) Wadi Al-Dawasir – Ministry of Health, Saudi Arabia,
(5) Maternity and Children Specialized Hospital , Ministry of Health, Saudi Arabia,
(6) Al-Dawadmi General Hospital, Ministry of Health, Saudi Arabia,
(7) Riyadh Third Health Cluster, Ministry of Health, Saudi Arabia,
(8) King Khalid Hospital & Prince Sultan Center – Al-Kharj, Ministry of Health, Saudi Arabia,
(9) King Khalid and Prince Sultan Hospital – Al-Kharj, Ministry of Health, Saudi Arabia,
(10) King Salman bin Abdulaziz Hospital, Ministry of Health, Saudi Arabia,
(11) King Abdullah Medical Complex – Jeddah, Ministry of Health,, Saudi Arabia,
(12) Dawadmi General Hospital, Ministry of Health – Riyadh Third Cluster,, Saudi Arabia

Abstract

Background: Surgical site infections (SSIs) and peri-neural infections following ocular and regional anesthesia are devastating, albeit rare, complications. Traditional prevention strategies often focus on isolated factors—patient skin prep or surgical technique—while neglecting the interconnected "surgical microbiome": the complex ecosystem comprising the patient's endogenous flora, the healthcare environment, and the medications introduced into sterile spaces. A siloed approach fails to address the multifactorial pathways of contamination.

Aim: This narrative review aims to synthesize evidence to propose an integrated, microbiology-informed framework for infection prevention.

Methods: A systematic search of PubMed, Scopus, Web of Science, and CINAHL was conducted for literature published between 2010 and 2024.

Results: The review identifies four critical, interdependent vectors of risk: 1) Environmental Reservoirs in phacoemulsification and anesthesia equipment; 2) Pharmaceutical Vectors from non-sterile compounded solutions; 3) Procedural Breaches during regional block administration; and 4) Surveillance Gaps in linking infections to their source. Evidence supports routine environmental culturing, mandatory use of USP <797>-compliant pharmacy compounding, standardized aseptic draping for blocks, and informatics-driven outbreak detection.

Conclusion: Infection prevention requires reconceptualizing the OR as a single microbiological continuum. An interdisciplinary strategy, uniting the laboratory, pharmacy, anesthesia technology, nursing, and informatics, is essential to mitigate risk. Proactive, system-wide vigilance over the entire surgical ecosystem—from the pharmacy cleanroom to the patient's eye—is the cornerstone of safeguarding vision and neurological function in modern anesthesia and surgery.

Keywords: Surgical Site Infection; Endophthalmitis; Sterile Compounding; Operating Room Environment; Aseptic Technique

Introduction

The modern operating room (OR) represents a pinnacle of human technological achievement, a controlled environment designed to exclude nature's ubiquitous microbial life. Yet, post-operative infections, such as acute endophthalmitis following cataract surgery or epidural abscess after neuraxial anesthesia, remain catastrophic sentinel events (Radkowski et al., 2023). Their rarity belies their severity: endophthalmitis can lead to permanent vision loss within days, while spinal infections cause profound neurological deficit (Durand, 2013; Relland et al., 2021). Traditional root-cause analyses often converge on a single, proximate cause—a lapse in sterile technique, a contaminated vial—perpetuating a reductionist view of infection as a linear "breach."

*Corresponding author e-mail: Danamz098@gmail.com (Danah Othman Almazyad).

Receive Date: 19 December 2024, Revise Date: 30 December 2024, Accept Date: 31 December 2024

This perspective is fundamentally inadequate (Schmidt & Bevilacqua Filho, 2023).

A more holistic understanding emerges from the "One Health" framework, which recognizes the interconnectedness of human, animal, and environmental health (Alverdy et al., 2017). Applied to the OR, this becomes the concept of the "Surgical Microbiome"—the dynamic, interconnected ecosystem comprising the patient's endogenous flora (conjunctival, skin, mucosal), the healthcare environment (air, surfaces, fluidic pathways of surgical devices), and the exogenous materials introduced (medications, implants, gloves) (Guarch-Pérez et al., 2023). In this model, an infection is not merely a breach but a systems failure: a pathogenic organism successfully navigated multiple barriers within this ecosystem to establish a niche (Long et al., 2022). Figure 1 illustrates the interconnected components contributing to infection risk, including patient endogenous flora (conjunctival, skin, and mucosal), the healthcare environment (air, surfaces, and surgical equipment), exogenous materials (medications, implants, and devices), and microbial transmission pathways.

Figure 1. The Surgical Microbiome Concept in Ocular and Regional Anesthesia

This narrative review synthesizes evidence from clinical ophthalmology, anesthesiology, microbiology, pharmaceutical science, and healthcare epidemiology to construct an interdisciplinary, microbiome-informed strategy for infection prevention. We argue that safeguarding patients undergoing ocular surgery and regional anesthesia requires vigilant stewardship of the entire surgical ecosystem. This demands seamless collaboration: the laboratory must monitor environmental reservoirs and enable rapid diagnostics; clinical pharmacy must guarantee the sterility of every injected medication; anesthesia technologists and nurses must execute flawless aseptic protocols for nerve blocks and line placement; and health informatics must provide the surveillance backbone to detect cryptic outbreaks. By examining the evidence across these domains, this review provides a roadmap for integrating disparate expertise into a unified defense, transforming the OR from a collection of sterile fields into a coherent, resilient antimicrobial ecosystem.

The Environmental Reservoir – Fluids, Surfaces, and Air

The OR environment is not sterile but is controlled to minimize bioburden. Complex medical devices with internal fluid pathways, however, can become persistent reservoirs for biofilm-forming pathogens, acting as stealth vectors for infection (Table 1).

Ophthalmic Surgical Devices

Cataract surgery, one of the most common procedures globally, relies on the phacoemulsification machine, which uses irrigating fluid to maintain the anterior chamber. Despite terminal sterilization of handpieces, the machine's internal tubing and fluid pathways are typically cleaned with chemical disinfectants between cases (Mordmuang et al., 2021). Multiple outbreaks have been definitively traced to biofilm contamination within these internal systems, often with waterborne, gram-negative bacteria like *Pseudomonas aeruginosa* or *Achromobacter* species that are resistant to standard disinfectants (Vergalito et al., 2019). These biofilms shed planktonic cells into the irrigation fluid, delivering a direct inoculum into the eye. The laboratory's role is critical here: routine environmental surveillance cultures of phacoemulsifier effluent, not just surface swabs, are essential for proactive detection (Lodha et al., 2022). Furthermore, ophthalmology must advocate for and adhere to manufacturer-recommended daily and weekly disinfection protocols with validated contact times, moving beyond simple "between-case" flushing (Sharma et al., 2023).

Anesthesia Workstation Ecology

The anesthesia machine and its work surface are a frequently touched nexus of care. Pathogens like methicillin-resistant *Staphylococcus aureus* (MRSA) and vancomycin-resistant enterococci (VRE) can persist on knobs, screens, and gas flow sensors (Carrico et al., 2018). More insidiously, ultrasound probes used for guided regional anesthesia are classified as semi-critical devices. Inadequate high-level disinfection of the probe, especially after contact with gelatinous ultrasound gel—which can serve as a culture medium—has been implicated in outbreaks of surgical site infections (Westerway & Basseal, 2022). Anesthesia technology and nursing share responsibility for implementing strict probe disinfection protocols using FDA-cleared agents, and using sterile, single-use probe covers and gel for aseptic procedures (Bloc et al., 2011).

The Pharmaceutical Vector – The Imperative of Sterile Compounding

Medications injected into the eye (intracameral, intravitreal) or near the neuraxis are administered into immune-privileged or poorly vascularized spaces where even low-level microbial contamination can cause infection. The compounding of these agents is the single most critical pharmaceutical intervention in this ecosystem.

Table 1: Vectors in the Surgical Microbiome and Interdisciplinary Mitigation Strategies

Vector	Potential Pathogen Source	Infection Risk	Interdisciplinary Mitigation Strategy
Environmental Fluid Pathways	Biofilm in phacoemulsifier/ vitrectomy machine internal tubing; contaminated irrigation/ infusion solutions.	Post-operative endophthalmitis (often gram-negative).	**Lab/Ophthalmology:** Routine effluent culturing; adherence to validated machine disinfection cycles. **Pharmacy:** Supply of sterile, preservative-free irrigants.
Compounded Medications	Microbial contamination during preparation of intracameral antibiotics, anesthetic cocktails for blocks; endotoxin presence.	Cluster endophthalmitis; meningitis, abscess.	**Pharmacy:** Mandatory USP <797> compliance; endotoxin testing; batch testing for sterility. **Informatics:** Lot-specific medication administration tracking.
Procedural Asepsis	Patient skin flora (e.g., *S. epidermidis*, *C. acnes*); provider flora via glove perforation; contaminated ultrasound gel.	Endophthalmitis, epidural abscess, phlegmon at block site.	**Anesthesia Tech/Nursing:** Strict draping for blocks; sterile gel & probe covers; double-gloving. **Ophthalmology:** Povidone-iodine conjunctival prep.
Healthcare Personnel & Airflow	Shedding from provider skin/ hair; turbulent airflow over non-sterile surfaces.	Airborne contamination of open surgical field or sterile trays.	**All Teams:** Strict adherence to OR attire policies; managing OR traffic. **Engineering:** Maintain positive pressure, HEPA filtration.

The Standard of Care: USP <797> and Beyond

The United States Pharmacopeia (USP) Chapter <797> sets enforceable standards for sterile compounding. For ophthalmology, the adoption of intracameral cefuroxime and moxifloxacin for endophthalmitis prophylaxis was a landmark advance, but it shifted risk from the OR to the pharmacy (Barry et al., 2013). Compounding outside a USP <797>-compliant cleanroom environment—such as in an OR anteroom—carries unacceptable risk. Clinical pharmacy must be the central authority, preparing these agents in an ISO Class 5 environment with validated aseptic technique, beyond-use dating based on stability and sterility testing, and, ideally, employing ready-to-use, commercially available formulations where possible (Herrinton et al., 2016). Furthermore, additives to local anesthetics for nerve blocks (e.g., clonidine, dexamethasone) must be introduced aseptically, with attention to the chemical and microbiological stability of the final mixture (Panahi et al., 2023).

Endotoxin and Particulate Matter

Bacterial endotoxin, a pyrogenic component of gram-negative cell walls, can cause intense intraocular inflammation (toxic anterior segment syndrome, TASS) even in the absence of viable organisms (Yao et al., 2022). Similarly, particulate matter from coring of vial stoppers or incomplete dissolution can act as a foreign body nidus. The pharmacy's role extends beyond sterility to include compendial testing for endotoxin levels and the use of final filtration during syringe preparation (Gil-Martínez et al., 2022). Health informatics supports this by enabling robust traceability: every administered dose should be linked in the EHR to its specific compounding batch, facilitating rapid recall in the event of a cluster of TASS or infections (Oshika et al., 2017).

The Procedural Vector – Aseptic Technique for Needle-Based Procedures

The moment of needle insertion represents the most direct conduit between the external microbiome and a sterile internal space. This vector is managed at the bedside by anesthesia technologists, nurses, and anesthesiologists.

The Challenge of Skin Flora and "Sterile" Draping

The human skin microbiome, dominated by *Staphylococcus epidermidis* and *Cutibacterium acnes*, is the most common source of pathogens in post-procedural infections. For ocular surgery, a 5-10% povidone-iodine conjunctival prep remains the gold standard, reducing bacterial load significantly (Singh et al., 2022). For regional anesthesia, the standard is more variable. "Aseptic technique" often involves cleaning the skin and wearing sterile gloves, but without a large sterile drape, the needle can contact unprepared skin or clothing during manipulation (Pozza et al., 2023). Evidence strongly supports a "full sterile barrier" approach for neuraxial and deep peripheral nerve blocks: performing a surgical skin prep, donning a sterile gown and gloves, and using a large fenestrated drape that isolates the procedural field (Hebl et al., 2017). Nursing is instrumental in preparing these kits and ensuring the proceduralist has uninterrupted access to all necessary equipment within the sterile field (Kwenaite, 2023).

Ultrasound Guidance

While ultrasound improves block efficacy and safety, it introduces new equipment (probe, gel) that must be integrated into the sterile field (Gupta & Garkoti, 2020). The use of a sterile probe cover is mandatory, but covers can tear with an incidence as high as 10%. A dual-strategy is recommended: applying a high-level disinfected probe, then covering it with a sterile sheath, and using only sterile, single-use ultrasound gel (Topor et al., 2020). Anesthesia technologists are key to maintaining and checking probe integrity and ensuring the availability of sterile supplies (Hammad et al., 2022).

The Surveillance Vector – Informatics and the Outbreak Detection Network

Rare infections become statistically visible only through systematic, long-term surveillance. Isolated cases treated at different facilities may represent the tip of a nationwide outbreak linked to a contaminated product or device.

Linking Data to Detect Signals

Health informatics provides the tools to move from passive reporting to active surveillance. This involves creating structured data fields within the EHR for specific procedural details: drug name, manufacturer, lot number; device identifiers and serial numbers; surgeon and anesthesiologist identifiers; and specific techniques used (Sawyer et al., 2019). When a postoperative infection is diagnosed, this data allows for rapid correlation. Was every patient with endophthalmitis this month exposed to the same lot of intracameral antibiotic? Did all patients with post-block infections receive a specific brand of chlorhexidine?

The Role of Rapid Diagnostics

When an infection occurs, time to pathogen identification is critical. Traditional culture for organisms like *C. acnes* or fungi can take days to weeks. The laboratory enables rapid response through molecular diagnostics (van Halsema et al., 2022). Multiplex PCR panels on intraocular or abscess fluid can identify a broad range of bacterial and fungal pathogens, along with key antibiotic resistance genes, within hours (Sugita et al., 2021). This rapid turnaround not only guides targeted therapy but is essential for outbreak epidemiology, allowing public health authorities to connect cases across institutions swiftly (Table 2). Figure 2 depicts four critical intervention domains: (1) environmental monitoring through routine operating room and equipment cultures; (2) sterile pharmaceutical compounding in compliance with USP <797> standards; (3) strict aseptic technique during regional anesthesia and needle-based procedures; and (4) infection surveillance supported by health informatics, including data tracking and automated alerts.

Table 2: Interdisciplinary Roles and Actionable Protocols in the Surgical Microbiome Framework

Professional Domain	Core Prevention Role	Actionable Protocol/Standard	Quality Metric / Surveillance Duty
Laboratory (Microbiology)	Environmental surveillance; rapid pathogen identification & typing.	Monthly cultures of phaco effluent; routine auditing of ultrasound probe disinfection.	Report clusters of environmental isolates; turnaround time for PCR on ocular/CSF fluid.
Clinical Pharmacy	Guarantee sterility & stability of all injected medications.	All intracameral/regional drugs compounded per USP <797>; mandatory final filtration; endotoxin testing.	Zero infections linked to pharmacy-compounded preparations; complete batch traceability in EHR.
Ophthalmology	Execute validated surgical prep; adhere to device cleaning protocols.	Mandatory 5% povidone-iodine conjunctival prep; adherence to manufacturer machine disinfection logs.	SSI rate; compliance with prep and disinfection checklists.
Anesthesia Technology & Nursing	Establish and maintain sterile fields for regional procedures; manage equipment asepsis.	Full sterile barrier (gown, gloves, large drape) for neuraxial/deep blocks; sterile probe cover + gel for all US-guided blocks.	Compliance with sterile draping audit; ultrasound probe cover tear rate.
Health Informatics	Enable data aggregation, traceability, and	Build EHR modules for capturing drug/device lot numbers, procedural details; create automated alerts for	Time to identify a potential outbreak; completeness of lot

	outbreak analytics.	infection clusters.	number documentation.

Figure 2. Interdisciplinary Infection Prevention Workflow Across the Surgical Ecosystem

Synthesis and Implementation

The pillars described are interdependent. A sterile medication is futile if injected through a contaminated needle via a non-sterile technique. Impeccable technique is undermined by a biofilm in the surgical device. Surveillance is blind without accurate data capture. Implementation, therefore, requires an orchestrated, systems-based approach.

First, **interdisciplinary committees**—including representation from all five domains—must be formed to own the surgical microbiome strategy. This committee would review every infection as a potential systems failure, not an individual error. Second, simulation and training must cross professional boundaries. Pharmacists should train surgeons on the risks of bedside compounding; microbiologists should present data on environmental outbreaks to anesthesia staff. Third, resource allocation must follow risk. Investment in pharmacy cleanrooms, single-use sterile supplies, and advanced environmental monitoring technology is non-negotiable for high-risk procedures.

The ethical imperative is clear: patients trust that the systems of modern medicine will protect them from preventable harm. In ocular and regional anesthesia, where the target organ is exquisitely sensitive, the margin for error is zero. A proactive, collaborative defense of the surgical microbiome is not merely an enhancement of care; it is the fundamental baseline of safety.

Conclusion

Post-operative infections in ophthalmology and regional anesthesia are multifactorial tragedies that emerge from a complex ecosystem. This review has argued that effective prevention necessitates abandoning siloed countermeasures in favor of an integrated, "One Health"-inspired defense of the surgical microbiome. This requires a paradigm where the microbiologist's culture plate, the pharmacist's laminar flow hood, the nurse's sterile drape, and the informatician's algorithm are seen as interconnected components of a single safety system.

The path forward is one of deliberate integration: establishing interdisciplinary governance, investing in the infrastructure of sterility (from pharmacy to device design), and fostering a culture of shared accountability where every team member is a steward of the microbial environment. By championing this collaborative model, we can transform the operating room from a venue of potential contamination into a truly resilient ecosystem, ensuring that the profound benefits of sight-restoring surgery and pain-controlling anesthesia are delivered with the highest possible guarantee of freedom from infection.

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