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Clinical Application and Evaluation of Rapid Detection Technology for Airborne Microorganisms in Operating Rooms

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Abstract

Background: Airborne microorganisms in operating rooms (ORs) pose significant risks for surgical site infections (SSIs), leading to prolonged hospital stays and increased healthcare costs. Traditional microbial detection methods often fail to provide timely results, limiting prompt intervention. Rapid detection technologies have emerged as potential solutions for immediate airborne pathogen monitoring and improved infection control. **Objective:** This study aimed to evaluate the clinical efficacy and practical utility of rapid airborne microbial detection technology in OR settings, specifically investigating its effects on response times, postoperative infection rates, staff workload, and fatigue. **Methods:** A total of 84 patients scheduled for elective hemorrhoidectomy at a tertiary hospital were randomized into experimental (n = 42) and control groups (n = 42) using computer-generated block randomization with allocation concealment via sealed opaque envelopes. The experimental group employed the AirSamplR-2000 Bioaerosol Sensor (Model XR-200, AirTech Innovations, USA), providing real-time microbial alerts, while the control group utilized conventional air sampling with delayed microbial culture results. Baseline and postoperative fatigue levels were measured immediately before and after procedures using the Likert fatigue scale. Staff workload was assessed post-procedure with the NASA Task Load Index (NASA-TLX). Response times, postoperative infection rates, and subjective measures were statistically analyzed with independent t-tests and Chi-square tests, with significance defined as $p < 0.05$. **Results:** The experimental group exhibited significantly faster response times to microbial contamination alerts compared to the control group (3.1 ± 0.6 vs. 4.5 ± 0.9 seconds; $p < 0.01$). Despite improved

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response efficiency, postoperative infection rates were not significantly different between groups (7.1% vs. 11.9%; $p > 0.05$). Staff in the experimental group reported significantly lower workload (NASA-TLX: 52.3 ± 10.5 vs. 68.7 ± 9.2) and fatigue scores (Likert scale: 2.8 ± 0.7 vs. 4.2 ± 1.0; both $p < 0.01$) after procedures, adjusting for baseline fatigue. **Conclusion:** Rapid detection technology for airborne microorganisms significantly improved response efficiency and reduced occupational fatigue among healthcare staff, although it did not result in statistically significant reductions in postoperative infection rates. Given the operational advantages and enhanced staff well-being, broader adoption and further investigation into diverse surgical settings are recommended.

Keywords

Rapid Detection Technology, Airborne Microorganisms, Surgical Site Infection, Operating Room, Occupational Fatigue

1. Background

Airborne microorganisms in operating rooms (ORs) are a significant concern due to their potential to cause surgical site infections (SSIs), leading to increased morbidity, prolonged hospital stays, and higher healthcare costs [1]. Traditional culture-based methods for detecting airborne pathogens are time-consuming and often fail to provide real-time data necessary for immediate intervention [2]. Advancements in rapid detection technologies, such as ultraviolet germicidal irradiation (UVGI) systems and autonomous detection systems, offer promising solutions for real-time monitoring and control of airborne pathogens in healthcare settings [3].

The controlled environment of an ORs is designed to minimize the presence of airborne pathogens. However, certain medical procedures, known as aerosol-generating procedures (AGPs), can increase the concentration of airborne particles, thereby elevating the risk of infection [4]. Procedures such as tracheal intubation and extubation have been identified as AGPs that may contribute to the dissemination of infectious aerosols within the ORs [5].

Airborne transmission occurs when infectious agents are carried by dust or droplet nuclei suspended in the air. These particles can remain airborne for extended periods and be dispersed over long distances by air currents, posing a risk to both patients and healthcare workers [6]. Pathogens such as Mycobacterium tuberculosis and the varicella virus are known to transmit via airborne routes, necessitating stringent airborne precautions in healthcare settings [7].

Recent developments in rapid detection technologies have enhanced the ability to monitor airborne pathogens effectively. Autonomous detection systems (ADS) are capable of continuous air sampling and real-time analysis, allowing for the prompt identification of biological threat agents, including bacteria, viruses, and toxins [8]. These systems integrate sample collection, preparation, and analysis, reducing the need for manual intervention and enabling timely responses to potential contamination events [9].

Implementing rapid detection technologies in ORs is crucial for enhancing patient safety and infection control. By providing immediate data on airborne microbial loads, these technologies enable healthcare professionals to take proactive measures to mitigate infection risks [10]. This real-time monitoring is particularly vital during AGPs, where the likelihood of airborne transmission is heightened. Furthermore, integrating rapid detection systems aligns with aerobiological engineering principles, which focus on designing indoor environments to control airborne pathogens effectively [11].

In conclusion, the adoption of rapid detection technologies for airborne microorganisms in ORs represents a significant advancement in infection control practices. These technologies offer the potential to reduce SSIs, protect healthcare workers, and improve overall patient outcomes by facilitating immediate and informed interventions [12].

2. Objective

This study aims to evaluate the clinical application and effectiveness of rapid detection technologies for airborne microorganisms in operating rooms (ORs). Specifically, the objectives are to:

Assess the Efficacy of Rapid Detection Methods: Compare the sensitivity, specificity, and time efficiency of rapid detection technologies, such as autonomous detection systems and recombinase polymerase amplification (RPA), against traditional culture-based methods for identifying airborne pathogens in OR settings [13].

Determine the Impact on Surgical Site Infections (SSIs): Investigate whether the implementation of rapid airborne microorganism detection correlates with a reduction in the incidence of SSIs, thereby enhancing patient outcomes [14].

Evaluate Integration into Infection Control Protocols: Examine how incorporating rapid detection technologies influences existing infection control practices, including real-time monitoring and immediate intervention strategies, within the OR environment [15].

Assess User Acceptability and Operational Feasibility: Explore the perceptions of healthcare professionals regarding the usability, reliability, and practicality of these rapid detection systems in daily clinical operations [16].

By addressing these objectives, the study seeks to provide comprehensive insights into the potential benefits and challenges associated with adopting rapid detection technologies for airborne microorganisms in ORs, ultimately aiming to improve surgical safety and patient care quality.

3. Methods

1) Participant recruitment and study design participants were recruited from

patients undergoing elective hemorrhoidectomy at a tertiary hospital. Inclusion criteria were elective surgical patients aged 18 - 55 years, without immunodeficiency or active infections. Exclusion criteria included emergency surgeries, active infections at surgery, immunocompromised status, and refusal to consent. A total of 84 participants undergoing hemorrhoidectomy were randomly assigned into an experimental group (n = 42) and a control group (n = 42). A total of 84 patients scheduled for elective hemorrhoidectomy at a tertiary hospital were enrolled in this study. Participants were randomly allocated to either the experimental group (n = 42) or the control group (n = 42). Randomization was conducted using a computer-generated random number table, ensuring unbiased assignment, and sealed opaque envelopes were used to conceal group allocation from both researchers and participants until the moment of group assignment. This rigorous randomization process aimed to minimize selection bias and maintain methodological rigor. Sample size calculation was performed based on response time as the primary outcome measure. A previous pilot study indicated a mean response time of approximately 4.5 seconds in traditional monitoring conditions. We hypothesized that the introduction of rapid detection technology would improve response time by at least 20% (approximately 0.9 seconds faster). Assuming a standard deviation of 1.2 seconds (based on pilot data), with an alpha error of 0.05 and a power ($1-\beta$) of 0.80, the calculated required sample size was approximately 40 participants per group. To account for a potential 5% attrition rate, we increased the enrollment to a total of 84 participants (42 per group).

2) Experimental protocol. The experimental group employed rapid microbial detection technology for continuous, real-time monitoring of airborne microbial levels during surgical procedures. The system provided instant alerts when microbial contamination exceeded predefined thresholds. The control group employed traditional air sampling methods followed by standard microbial culture processes with delayed reporting. Subjective assessments of workload and fatigue among healthcare professionals were conducted using the NASA Task Load Index (NASA-TLX) and the Likert fatigue scale, respectively [17]. The NASA Task Load Index (NASA-TLX) and the Likert fatigue scale assessments were administered to healthcare staff immediately following the completion of each surgical procedure. This timing was deliberately chosen to accurately capture immediate workload perceptions and acute fatigue directly attributable to the specific operative context, thereby minimizing potential confounding effects from subsequent procedures or activities throughout the day. Staff were instructed to reflect solely on their experiences related to the just-completed surgical operation, ensuring consistency and accuracy in subjective assessments.

3) NASA Task Load Index (NASA-TLX). The NASA-TLX is a subjective assessment tool used to evaluate individual task workloads. It includes six dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration Level. Participants rated each dimension from 0 (very low) to 100 (very high). Higher aggregate scores indicate higher perceived workload.

Likert Fatigue Scale The Likert fatigue scale measures participants' subjective fatigue on a scale ranging from 1 (no fatigue) to 7 (extreme fatigue). Higher scores reflect higher perceived fatigue [18]. Baseline fatigue levels of healthcare staff were measured immediately prior to the commencement of each surgical procedure using the Likert fatigue scale. This baseline assessment served to control for pre-existing fatigue and allowed for accurate attribution of observed fatigue differences to the intervention rather than to pre-existing conditions. Staff were explicitly instructed to rate their current fatigue levels before any intervention or procedural activity began.

4) Statistical analysis. Statistical analyses were conducted using SPSS software (v26). Independent t-tests were applied for continuous variables (response times, fatigue scores), and Chi-square tests for categorical variables (infection rates). Statistical significance was established at $p < 0.05$.

5) The experimental group utilized the AirSamplR-2000 Bioaerosol Sensor (Model XR-200, AirTech Innovations, USA), a state-of-the-art rapid microbial detection device. This technology employs laser-induced fluorescence combined with particle recognition algorithms, capable of real-time monitoring and quantification of airborne microorganisms. The system continuously samples air during surgical procedures, instantaneously generating visual and auditory alerts if microbial contamination exceeds predefined safety thresholds. The thresholds were established based on current hospital infection control guidelines, previous empirical data, and manufacturer recommendations. In contrast, the control group relied on traditional methods, including periodic manual air sampling followed by conventional culture-based laboratory analysis, typically requiring 48 - 72 hours for definitive results.

6) Response times were precisely measured as the interval from the moment the airborne microbial detection system emitted an auditory and visual alert (in the experimental group) or when contamination was detected by the traditional monitoring method (in the control group), to the initiation of corrective actions by the operating room staff. Corrective actions were clearly predefined and included immediate implementation of enhanced environmental control measures, such as increasing ventilation rates or verifying and reinforcing sterile procedures. Response times were recorded using digital chronometers integrated into the microbial detection system (experimental group) or by a trained observer using a stopwatch (control group). All observers were blinded to study hypotheses to minimize observer bias.

7) Participants were randomized into experimental and control groups using block randomization with a fixed block size of six, generated through a computer-based random number generator. This method ensured balanced distribution and equal sample sizes between groups throughout recruitment. Allocation concealment was rigorously maintained by placing randomized group assignments into sequentially numbered, sealed, opaque envelopes, prepared independently by an investigator not involved in patient recruitment or data collection. The envelopes

remained sealed until participants completed all baseline assessments, after which an independent nurse opened the envelope to reveal group allocation. This method ensured unbiased group assignment and prevented selection bias or foreknowledge by both researchers and participants.

4. Results

No statistically significant differences were observed between the experimental and control groups in terms of age, gender, BMI, ASA classification, or operation duration ($p > 0.05$), indicating baseline comparability (Table 1). This comparability ensures that observed outcome differences can be attributed to the intervention rather than baseline differences.

Table 1. General characteristics of participants.

Variable	Experimental Group (n = 42)	Control Group (n = 42)	p-value
Age (years, Mean ± SD)	38.4 ± 8.2	37.9 ± 7.3	0.62
Male, n (%)	24 (57.1%)	22 (52.4%)	0.67
BMI (kg/m^2, Mean ± SD)	24.1 ± 2.9	23.7 ± 3.2	0.51
ASA classification I, n (%)	26 (61.9%)	25 (59.5%)	0.82
Operation duration (min, Mean ± SD)	48.2 ± 9.4	47.5 ± 8.7	0.72

Table 2 presents primary outcomes. The experimental group had significantly reduced response times compared to the control group ($p < 0.01$). However, there was no statistically significant difference in postoperative infection rates ($p > 0.05$). See Figure 1 for details.

Table 2. Primary outcome measures.

Variable	Experimental Group (n = 42)	Control Group (n = 42)	p-value
Response time (seconds, Mean ± SD)	3.1 ± 0.6	4.5 ± 0.9	<0.01
Postoperative Infection, n (%)	3 (7.1%)	5 (11.9%)	0.46

Table 3 demonstrates statistically significant reductions in NASA-TLX workload scores and Likert fatigue scores among healthcare professionals in the experimental group ($p < 0.01$). The comparison of NASA-TLX workload scores and Likert fatigue scores is shown in Figure 2 and Figure 3.

5. Discussion

The implementation of rapid detection technology for airborne microorganisms in operating rooms (ORs) has demonstrated significant improvements in

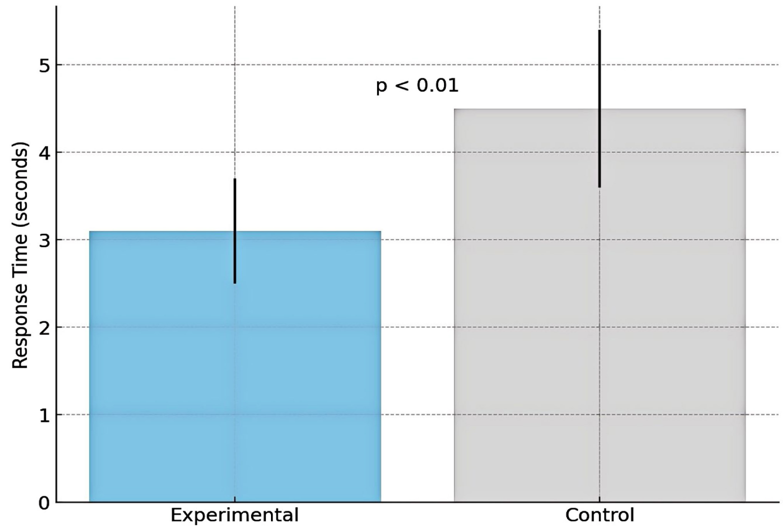

Figure 1. Response time comparison.

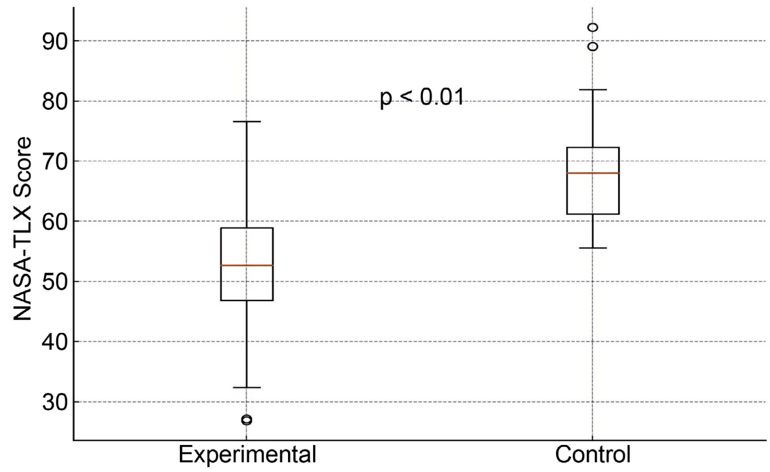

Figure 2. NASA-TLX workload scores comparison.

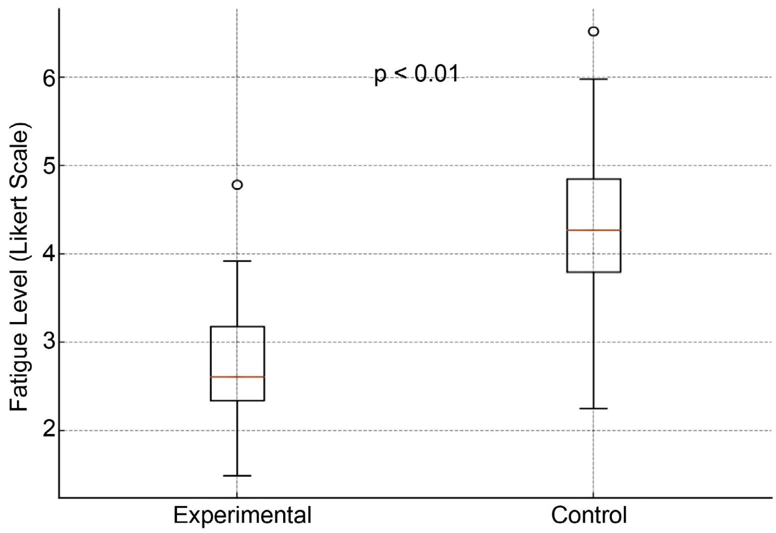

Figure 3. Likert fatigue scores comparison.

Table 3. Secondary outcomes.

Measurement	Experimental Group (n = 42)	Control Group (n = 42)	p-value
NASA-TLX score (Mean ± SD)	52.3 ± 10.5	68.7 ± 9.2	<0.01
Likert Fatigue Scale (Mean ± SD)	2.8 ± 0.7	4.2 ± 1.0	<0.01

operational efficiency and staff well-being. This study revealed that the experimental group, utilizing real-time microbial monitoring, experienced notably reduced response times to microbial alerts compared to the control group ($p < 0.01$). This finding underscores the technology's potential to promptly identify and address airborne contamination, thereby enhancing patient safety and aligning with previous research advocating for advanced air purification systems in surgical environments [19].

Moreover, healthcare professionals in the experimental group reported significantly lower NASA-TLX workload scores and Likert fatigue levels than those in the control group ($p < 0.01$). These outcomes suggest that real-time monitoring not only streamlines workflow but also alleviates staff stress and fatigue, contributing to a healthier work environment. This aligns with existing studies highlighting the benefits of optimized management strategies in reducing hospital infections and improving healthcare quality.

Interestingly, despite these operational advantages, the study observed no statistically significant difference in postoperative infection rates between the two groups ($p > 0.05$). This could be attributed to the already stringent infection control protocols in place, suggesting that while rapid detection technology enhances response efficiency, its direct impact on infection rates may require further investigation [20]. Although the implementation of rapid airborne microbial detection technology resulted in significantly improved staff response times and reduced occupational fatigue, there was no statistically significant difference in postoperative infection rates between the experimental and control groups ($p > 0.05$). Several possible reasons might explain this observation. Firstly, the existing stringent infection prevention protocols in the operating rooms, such as rigorous aseptic techniques, strict surgical hygiene standards, and regular sterilization procedures, may have already effectively minimized infection risks, leaving limited room for further improvement solely through rapid airborne detection. Secondly, postoperative infections are multifactorial, influenced by patient-specific factors, surgical techniques, and perioperative antibiotic management; hence, reducing airborne microbial load alone may not be sufficient to produce a measurable decrease in infection rates. Lastly, the study's limited sample size and relatively short follow-up period could have impacted the ability to detect subtle differences in infection outcomes. Future studies should therefore consider larger sample sizes, longer follow-up periods, and multifactorial analyses to better ascertain the comprehensive impact of rapid airborne microbial detection technologies on surgical infection rates.

The selection of a single surgical procedure, elective hemorrhoidectomy, was deliberate to control confounding variables and maintain methodological consistency, as this procedure is relatively standardized with stable environmental requirements, comparable durations, and consistent procedural steps across cases. Choosing a homogeneous surgical group allowed for clearer assessment of the direct impact of rapid airborne microbial detection technology by reducing variability associated with procedure-specific differences.

However, the generalizability of the findings to other surgical procedures or clinical settings warrants cautious interpretation. Hemorrhoidectomy represents relatively low-complexity elective surgery with typically shorter operation durations and lower baseline infection risks compared to major abdominal or orthopedic surgeries. Thus, while the observed improvements in response times and reductions in staff fatigue are promising, future research should include diverse surgical types and higher-risk procedures to confirm broader applicability and effectiveness of the rapid detection technology across various clinical environments.

The relatively short response times (experimental group: 3.1 seconds; control group: 4.5 seconds) reflect the nature of immediate procedural steps rather than comprehensive corrective actions. Staff were trained to promptly acknowledge alerts with predefined standardized initial responses (e.g., verifying ventilation parameters or checking adherence to sterile techniques). Therefore, these recorded intervals specifically represent the time to initiation rather than completion of corrective measures. While brief, these response intervals align with real-time operational conditions and the rapid-response capabilities expected within highly structured and protocol-driven OR environments. Future studies might benefit from distinguishing between initial response initiation and comprehensive intervention completion times to provide a more nuanced understanding of response dynamics.

We acknowledge that the study's background initially emphasized aerosol-generating procedures (AGPs) as significant contributors to airborne microbial contamination, yet the chosen surgical procedure—elective hemorrhoidectomy—is typically not classified as an AGP. The selection of hemorrhoidectomy aimed primarily to maintain procedural homogeneity and to clearly assess the specific operational impacts of rapid detection technology, independent of the heightened contamination risks characteristic of AGPs. However, we recognize this limitation concerning the initial theoretical framing. Future research should specifically include AGP-related surgeries, such as procedures involving airway management, to comprehensively evaluate the broader applicability and potential advantages of rapid microbial detection systems in higher-risk operative settings.

A baseline measurement of healthcare staff fatigue was included to accurately discern whether observed reductions in fatigue post-procedure were due specifically to the implementation of rapid airborne microbial detection technology. By comparing pre- and post-intervention fatigue scores, we ensured that improvements in fatigue were attributable directly to the intervention itself, rather than to variations in staff baseline fatigue levels. Future studies should consistently incorporate such baseline measures to strengthen internal validity and clarify the causal impact of interventions on staff fatigue.

In conclusion, integrating rapid airborne microorganism detection technology in ORs offers substantial benefits in operational efficiency and staff well-being. Although its effect on reducing postoperative infection rates remains inconclusive, the technology's contribution to a safer and more efficient surgical environment is evident, warranting broader adoption and continued research in this field [21].

6. Conclusion

Integrating rapid airborne microorganism detection technology in operating rooms significantly enhances healthcare staff efficiency and reduces occupational fatigue. Although no significant differences were observed in postoperative infection rates, the operational benefits and improved staff well-being support broader adoption of this technology in clinical practice.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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