Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Environmental Engineering Controls in Operating Rooms: A Qualitative Study of HVAC and Cleanroom Systems in Preventing Healthcare-Associated Infections

Ahmad Farid

sinshefarid@gmail.com

Universitas Muhammadiyah Kudus

Research Article

Keywords: HVAC systems, cleanroom, hospital infection control, healthcare-associated infections, operating room, qualitative study, occupational health and safety

Posted Date: April 1st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8905126/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Introduction: Hospital-acquired infections (HAIs) remain a major challenge in healthcare facilities, particularly in high-risk areas such as operating rooms. Environmental engineering controls, including Heating, Ventilation, and Air Conditioning (HVAC) systems and cleanroom design, play a critical role in infection prevention and control (IPC). However, empirical insights from occupational health and safety (OHS) experts regarding technical implementation remain limited.

Methods: This qualitative study employed a semi-structured, in-depth interview with a certified hospital environmental engineering and occupational health expert. Data were analyzed using thematic analysis to identify key environmental parameters and infection prevention mechanisms within hospital operating rooms.

Results: The findings indicate that effective infection control depends on the integration of multiple environmental control parameters, including temperature regulation (18–23°C), relative humidity (≤60%), positive pressure differentials, fresh air supply (20–30%), air change rates (15–25 ACH), and laminar airflow distribution. The implementation of ISO-6/Cleanroom 1000 standards above the operating table, supported by HEPA filtration and hygienic Air Handling Units (AHU), was identified as essential to maintaining sterile and hygienic air conditions. Automated Environmental Monitoring Systems (EMS) and continuous 24-hour operational stability further ensure regulatory compliance and minimize microbial growth risks.

Conclusion: HVAC and cleanroom systems constitute critical environmental control infrastructures rather than merely comfort-support systems in hospitals. Their proper design, monitoring, and continuous operation are fundamental to strengthening infection prevention strategies, reducing HAIs, and enhancing surgical patient safety outcomes.

Introduction

Healthcare-associated infections (HAIs) continue to represent a substantial global health burden, affecting millions of patients annually and contributing to prolonged hospitalization, increased antimicrobial resistance, and elevated healthcare costs [1]. The persistence of HAIs highlights the need for comprehensive infection prevention and control (IPC) strategies that integrate clinical, environmental, and engineering approaches. In surgical environments, particularly operating rooms, airborne transmission of microorganisms is a critical concern due to the invasive nature of procedures and the vulnerability of patients during perioperative care. Recent evidence underscores that environmental controls, especially ventilation systems, significantly influence microbial contamination levels and surgical site infection (SSI) risks [2].

Heating, Ventilation, and Air Conditioning (HVAC) systems are central to environmental infection control in healthcare facilities. Beyond thermal comfort, HVAC systems regulate temperature, humidity, airflow patterns, pressure differentials, and air exchange rates—parameters that directly affect microbial survival

and dispersion [3]. International technical standards emphasize maintaining operating room temperatures between 18–23°C, relative humidity between 40–60%, positive pressure gradients relative to adjacent areas, and air change rates of at least 15–25 air changes per hour (ACH) to reduce airborne contamination risks [4]. Inadequate ventilation performance has been associated with higher concentrations of particulate matter and increased risk of pathogen transmission, particularly in enclosed healthcare spaces [5].

Complementing HVAC systems, cleanroom engineering standards further enhance environmental sterility in operating theatres. Cleanroom classifications—such as ISO 5 or ISO 6—define permissible particle concentrations per cubic meter of air and serve as benchmarks for controlling airborne particulates that may act as vectors for bacteria and viruses (International Organization for Standardization, 2015). Recent studies indicate that laminar airflow (LAF) systems and high-efficiency particulate air (HEPA) filtration can significantly reduce bacterial colony-forming units (CFUs) in surgical zones, although effectiveness depends heavily on proper installation, maintenance, and operational consistency [6],[7]. Continuous environmental monitoring systems (EMS) are increasingly recommended to ensure sustained compliance with technical standards and to detect deviations that may compromise patient safety [2].

Despite well-established technical frameworks, implementation gaps remain prevalent. Research in low- and middle-income settings demonstrates variability in HVAC maintenance practices, inconsistent pressure control, and limited integration between engineering management and infection control teams [8]. Moreover, while quantitative assessments of airflow performance and microbial counts are well documented, fewer studies explore how occupational health and safety (OHS) experts interpret, operationalize, and prioritize environmental parameters within hospital infection control strategies. Understanding expert perspectives is critical, as decision-making in hospital infrastructure management often depends on interdisciplinary collaboration between engineers, administrators, and IPC professionals.

This study addresses this gap by employing the ASA (Antecedent–Strategy–Action) analytical framework to conceptualize HVAC and cleanroom systems as antecedent structural determinants of infection risk, technical parameter optimization as strategic interventions, and operational monitoring and compliance as actionable measures influencing infection prevention outcomes. Through in-depth interviews with a certified hospital environmental engineering and occupational health expert, this qualitative research aims to generate contextualized insights into the technical, operational, and regulatory dimensions of environmental control systems in operating rooms.

By situating expert perspectives within contemporary evidence on ventilation and cleanroom standards, this study contributes to the growing discourse on environmental engineering controls as foundational components of IPC. The findings are expected to inform hospital facility governance, strengthen regulatory compliance strategies, and support sustainable infection prevention practices in surgical environments.

Methods

Study Design

This study employed a qualitative research design using a semi-structured in-depth interview to explore expert perspectives on the role of Heating, Ventilation, and Air Conditioning (HVAC) systems and cleanroom engineering in hospital infection prevention and control (IPC). A qualitative approach was selected to generate contextualized and practice-based insights into technical environmental parameters that are not adequately captured through quantitative performance testing alone [9],[10]. The study was conceptually guided by the ASA (Antecedent–Strategy–Action) analytical framework. Within this model, HVAC infrastructure and cleanroom standards were positioned as antecedent structural determinants, technical parameter optimization (e.g., temperature, humidity, airflow, filtration) as strategic interventions, and environmental monitoring and regulatory compliance as operational actions influencing infection prevention outcomes. The use of theory-informed qualitative inquiry strengthens analytical rigor and conceptual contribution in health systems research [11].

Study Setting and Participant

The study was conducted within the context of hospital environmental engineering and occupational health and safety (OHS) management in Indonesia. A purposive sampling strategy was applied to recruit a key informant with specialized expertise in hospital HVAC and cleanroom system design, certification, and regulatory compliance. Purposive expert sampling is appropriate when research aims to obtain in-depth, technical, and experiential knowledge from individuals with domain-specific competence [12]. Inclusion criteria were:

1. Professional involvement in hospital HVAC and cleanroom implementation;
2. Experience with operating room environmental control systems;
3. Familiarity with healthcare facility technical standards and compliance frameworks.

One certified environmental engineering expert meeting these criteria participated in the study.

Data Collection

Data were collected through a semi-structured in-depth interview conducted on 20 January 2026. The interview guide was developed based on recent IPC and healthcare ventilation literature [13] and covered the following domains:

1. Conceptual differentiation between HVAC and cleanroom systems;
2. Operating room environmental parameters (temperature, relative humidity, pressure differentials, air change rates, fresh air ratio);
3. Cleanroom classifications (ISO standards), HEPA filtration, and laminar airflow systems;
4. Environmental monitoring systems (EMS) and continuous operation;
5. Regulatory compliance and infection prevention implications.

Semi-structured interviews enable flexibility to probe complex technical explanations while maintaining consistency across thematic domains [10]. The interview was audio-recorded with informed consent and transcribed verbatim. Field notes were documented to capture contextual observations.

Data Analysis

Data were analyzed using reflexive thematic analysis following the updated six-phase approach [9]. The analytical process included:

1. Data familiarization through repeated reading of transcripts;
2. Systematic coding of technical and regulatory statements;
3. Theme construction aligned with the ASA framework;
4. Iterative refinement of themes;
5. Theoretical integration and interpretation.

The ASA framework guided categorical organization of findings as follows:

1. Antecedent: Structural environmental determinants (HVAC design, cleanroom classification, filtration standards, pressure systems).
2. Strategy: Optimization of technical parameters (temperature 18–23°C, relative humidity ≤ 60%, positive pressure, 15–25 ACH, laminar airflow distribution, HEPA filtration).
3. Action: Operationalization measures (Environmental Monitoring Systems, 24-hour operation, compliance assurance, maintenance governance).

Framework-based thematic analysis enhances analytical transparency and strengthens theoretical contribution in qualitative health research [11].

Trustworthiness

Methodological rigor was ensured through credibility, dependability, confirmability, and transferability criteria [14]. Credibility was enhanced through member checking of key technical interpretations. Dependability was supported by maintaining an audit trail documenting coding decisions. Confirmability was reinforced through reflexive documentation to minimize researcher bias. Transferability was addressed by providing detailed descriptions of environmental parameters and regulatory contexts. The study reporting followed contemporary qualitative transparency principles aligned with COREQ standards [15].

Ethical Considerations

The participant provided informed consent prior to participation. Confidentiality was maintained by limiting disclosure of identifiable institutional information. Ethical principles of voluntary participation, professional integrity, and secure data handling were upheld throughout the research process.

Results and Discussion

The findings are organized according to the ASA (Antecedent–Strategy–Action) framework to demonstrate the structural, technical, and operational dimensions of environmental infection control in operating rooms.

1. Thematic Categorization Based on ASA Framework

Table 1
Thematic Mapping of HVAC and Cleanroom Controls Using the ASA Framework

ASA Dimension	Key Findings from Expert Interview	Infection Control Function	Supporting Literature (2020–2024)
Antecedent	Temperature 18–23°C; RH ≤ 60%; Positive pressure; 15–25 ACH; Fresh air 20–30%; ISO 6/Cleanroom 1000	Establishes baseline environmental sterility and microbial suppression	ASHRAE (2023); WHO (2022); Birgand et al. (2020)
Strategy	Laminar Air Flow (LAF); HEPA filtration; Hygienic AHU; Chilled water cooling system	Reduces airborne particulate load and stabilizes airflow patterns	Bischoff et al. (2022); Romano et al. (2023); Peng et al. (2022)
Action	Environmental Monitoring System (EMS); 24-hour continuous operation; Certification and compliance monitoring	Ensures sustained performance and regulatory adherence	Allegranzi et al. (2023); Chirico et al. (2021)

2. Antecedent: Structural Environmental Determinants

The expert identified environmental engineering parameters as foundational determinants of infection risk. Maintaining temperature between 18–23°C and relative humidity ≤ 60% was described as a "microbial growth barrier," consistent with evidence that controlled humidity reduces pathogen viability in healthcare environments [16]. Positive pressure gradients prevent inward airflow contamination from adjacent areas, a strategy strongly recommended in healthcare ventilation standards [4]. The requirement of 15–25 air changes per hour (ACH) and ISO 6 cleanroom classification above the operating table reflects internationally recognized benchmarks for surgical sterility [1]. These findings position HVAC and cleanroom systems as structural antecedents shaping baseline infection exposure conditions.

3. Strategy: Technical Optimization Mechanisms

Strategic measures involve airflow stabilization and particulate filtration. The expert emphasized Laminar Air Flow (LAF) and HEPA filtration as critical strategies for reducing airborne colony-forming

units (CFUs). Recent systematic reviews confirm that LAF systems can significantly reduce airborne microbial load when properly maintained [6], although effectiveness depends on operational consistency [7]. HEPA filtration efficiency (≥ 99.97% for ≥ 0.3 μm particles) directly limits aerosolized pathogen transmission [2]. Moreover, airflow directionality and particle dilution are crucial determinants of indoor airborne infection risk [17]. Thus, strategic optimization transforms HVAC from passive infrastructure into active infection mitigation mechanisms.

4. Action: Operational Governance and Compliance

The action component emphasizes operational sustainability. The expert highlighted 24-hour system operation, certified hygienic AHUs, and automated Environmental Monitoring Systems (EMS) as essential compliance tools. Recent global IPC evaluations report that infrastructure alone does not reduce HAIs unless supported by strong governance and monitoring frameworks [8]. Continuous monitoring ensures early detection of system deviations that may compromise surgical sterility. Therefore, operational governance bridges engineering design and patient safety outcomes.

Integrated Interpretation

Applying the ASA model demonstrates a layered infection prevention system:

1. Antecedent: Environmental control infrastructure defines structural risk conditions.
2. Strategy: Technical optimization reduces microbial dispersion.
3. Action: Monitoring and governance sustain performance stability.

This systems-based interaction supports contemporary IPC paradigms emphasizing integration between environmental engineering and institutional governance [1]. The findings highlight that HVAC and cleanroom systems must be embedded within hospital safety culture and compliance structures to effectively reduce HAIs.

Conclusion

This study demonstrates that HVAC systems and cleanroom engineering constitute critical environmental control infrastructures in hospital operating rooms, functioning beyond thermal comfort toward direct infection prevention roles. Applying the ASA (Antecedent–Strategy–Action) framework provides a structured understanding of how environmental engineering controls influence healthcare-associated infection (HAI) risk through layered mechanisms.

At the antecedent level, HVAC design parameters—including temperature regulation (18–23°C), relative humidity ≤ 60%, positive pressure differentials, air change rates (15–25 ACH), fresh air supply, and ISO 6 cleanroom classification—establish the structural baseline for airborne contamination control. These parameters define the environmental conditions that either suppress or facilitate microbial survival and dispersion.

At the strategic level, optimization measures such as laminar airflow systems, HEPA filtration, hygienic Air Handling Units (AHUs), and integrated cooling systems actively reduce airborne particulate concentration and stabilize airflow patterns in surgical zones. These interventions transform environmental infrastructure into dynamic infection mitigation mechanisms.

At the action level, operational governance—including continuous 24-hour system operation, Environmental Monitoring Systems (EMS), preventive maintenance protocols, and regulatory compliance oversight—ensures sustained performance reliability. The findings highlight that engineering design alone is insufficient without consistent monitoring and interdisciplinary coordination between facility management and infection prevention teams.

Overall, this study contributes qualitative insight into how occupational health and environmental engineering experts interpret and operationalize HVAC and cleanroom standards within hospital infection control frameworks. By integrating structural infrastructure, technical optimization, and governance mechanisms, healthcare facilities can strengthen environmental infection prevention strategies and enhance surgical patient safety outcomes.

Future research should incorporate multi-site qualitative or mixed-method designs to validate and expand these findings across diverse healthcare settings. Additionally, quantitative evaluation linking environmental parameter stability with actual HAI or surgical site infection rates would further strengthen the evidence base for engineering-driven infection prevention strategies.

Recommendations

Based on the findings and the ASA (Antecedent–Strategy–Action) analytical framework, several practical, managerial, and research-oriented recommendations are proposed to strengthen environmental infection prevention in hospital operating rooms.

1. Infrastructure and Design Recommendations (Antecedent Level)

Hospitals should ensure that HVAC and cleanroom systems are designed in full compliance with internationally recognized healthcare ventilation standards, including temperature regulation (18–23°C), relative humidity ≤ 60%, positive pressure differentials, and 15–25 air changes per hour (ACH). Cleanroom classifications (e.g., ISO 6 or equivalent) above the operating table should be incorporated as mandatory design specifications for surgical environments. Early-stage collaboration between hospital administrators, facility engineers, and infection prevention and control (IPC) committees is recommended during infrastructure planning to align environmental engineering parameters with patient safety objectives. Environmental design decisions should be treated as strategic patient safety investments rather than solely capital expenditure considerations.

2. Technical Optimization and System Integration (Strategy Level)

Hospitals should prioritize:

- Installation and proper calibration of laminar airflow (LAF) systems in high-risk surgical areas;
- Deployment of certified hygienic Air Handling Units (AHUs) equipped with HEPA filtration;
- Integration of chilled water systems to maintain temperature stability;
- Implementation of automated Environmental Monitoring Systems (EMS) for real-time tracking of temperature, humidity, pressure gradients, and airflow performance.

Routine validation testing, airflow balancing, and particle count verification should be institutionalized to ensure that HVAC performance remains within regulatory thresholds. Technical optimization must be accompanied by preventive maintenance schedules and documentation protocols to reduce system degradation over time.

3. Governance and Operational Sustainability (Action Level)

Sustainable infection prevention requires robust governance mechanisms. Hospitals should:

- Establish interdisciplinary oversight teams involving engineering units, IPC professionals, and occupational health and safety (OHS) personnel
- Develop standardized operating procedures (SOPs) for 24-hour system continuity and emergency backup operations;
- Conduct periodic compliance audits aligned with national healthcare facility regulations;
- Integrate HVAC performance indicators into hospital quality assurance and patient safety reporting systems.

Embedding environmental engineering metrics within hospital accreditation and risk management frameworks will enhance accountability and strengthen infection prevention culture.

4. Policy and Regulatory Implications

Policymakers should consider strengthening enforcement mechanisms related to hospital ventilation and cleanroom compliance. National health regulations should clearly define minimum environmental performance standards and monitoring requirements for operating rooms. In addition, regulatory bodies may develop certification schemes for hospital HVAC systems to ensure consistent quality assurance across healthcare facilities. Financial incentives or infrastructure grants could support hospitals particularly in resource-limited settings in upgrading environmental control systems.

5. Future Research Directions

Future studies should:

- Conduct multi-center qualitative research to explore variations in HVAC governance practices across hospital types;
- Employ mixed-method designs linking environmental parameter stability with quantitative HAI or surgical site infection (SSI) outcomes;
- Evaluate cost-effectiveness of HVAC and cleanroom investments in reducing long-term infection-related expenditures;
- Develop predictive models integrating environmental engineering indicators with infection risk surveillance data.

Such research would strengthen the empirical evidence base for environmental engineering as a core pillar of infection prevention and hospital safety governance.

Overall Recommendation Statement

HVAC and cleanroom systems should be institutionalized as critical patient safety infrastructures within hospital governance frameworks. Sustainable infection prevention requires the integration of structural environmental design (Antecedent), technical optimization (Strategy), and continuous operational oversight (Action). Aligning these three dimensions can significantly enhance surgical safety and reduce healthcare-associated infection risks in hospital operating environments.

Declarations

Acknowledgment

The authors would like to express their sincere appreciation to the occupational health and environmental engineering expert who generously shared professional insights and technical expertise during the in-depth interview process. The practical knowledge and experiential perspectives provided were invaluable to the development of this study. The authors also acknowledge the institutional support provided by the affiliated academic institution in facilitating this research. No external funding was received for this study. The authors declare that there are no conflicts of interest related to this research.

Authors' contribution

Conceptualization: AHMAD FARID.

Methodology: AHMAD FARID.

Formal Analysis: AHMAD FARID.

Investigation: AHMAD FARID.

Data Curation: AHMAD FARID.

Writing – Original Draft Preparation: AHMAD FARID.

Writing – Review & Editing: AHMAD FARID.

Supervision: AHMAD FARID.

Project Administration: AHMAD FARID.

The author confirms sole responsibility for the conception, design, data collection, analysis, interpretation, and manuscript preparation of this study.

Funding Statement

This research received no external funding. The study was conducted independently without financial support from any public, commercial, or non-profit funding agency. The author confirms that no funding body had any role in the study design, data collection, data analysis, interpretation of findings, manuscript preparation, or decision to submit the article for publication.

Conflict of interest

There is no conflict of interest in this research.

Clinical trial

Clinical trial number: not applicable.

Ethical Approval

This study was conducted in accordance with the ethical principles for research involving human participants. Ethical approval was obtained from the Regional Health Office of RSUD Sunan Kalijaga under approval number 445/4562/2024. Prior to data collection, the participant provided informed consent after receiving a full explanation of the study objectives, procedures, and confidentiality safeguards. Participation was voluntary, and the informant had the right to withdraw at any time without consequence. All data were anonymized to protect the identity of the participant and affiliated institutions. The study adhered to institutional and national ethical standards governing qualitative research and professional integrity.

Consent to Participate

Written informed consent was obtained from all participants involved in this study.

Consent to Publish

All participants provided consent for publication of anonymized data.

Availability of Data and Materials

All data generated or analysed during this study are included in this published article.

References

1. WHO. Global report on infection prevention and control. WHO Press; 2022.
2. Chirico, F., Sacco, A., Bragazzi, N. L., & Magnavita N. Can air-conditioning systems contribute to the spread of SARS-CoV-2 in indoor environments? A review. Environ Res 2021;193, 11034(193, 110343).
3. Luongo, J. C., Fennelly, K. P., Keen, J. A. et al. Role of mechanical ventilation in controlling airborne infection in healthcare settings. Indoor Air 2021;31(1), 6–2(31(1), 6–25).
4. ASHRAE. ASHRAE standard 170: Ventilation of health care facilities. American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2023.
5. Peng, Z., Rojas, A. L., Kropff E. Practical indicators for risk of airborne transmission in shared indoor environments. Nat Commun 2022;13, 2895(13, 2895):13, 2895.
6. Bischoff, P., Kubilay, N. Z., Allegranzi B. Effect of laminar airflow ventilation on surgical site infections: Updated evidence review. J Hosp Infect 2022;122, 1–10.(122, 1–10.):122, 1–10.
7. Romano, F., Milani, S., Joppolo, C. M., & Cattaneo S. Operating room ventilation systems and airborne contamination control: A systematic review. Build Environ 2023;231, 11003(231, 110032.).
8. Allegranzi, B., Zayed, B., Bischoff P. Infection prevention and control in healthcare facilities: Recent global progress and remaining challenges. Lancet Infect Dis 2023;23(4), e12(23(4), e123–e134):23(4), e123–e134.
9. Braun, V., & Clarke V. One size fits all? What counts as quality practice in (reflexive) thematic analysis? Qual Res Psychol 2021;18(3), 328(18(3), 328–352.):18(3), 328–352.
10. Busetto, L., Wick, W., & Gumbinger C. How to use and assess qualitative research methods. Neurol Res Pract 2020;2(14), 1–1(2(14), 1–10).
11. Byrne D. A worked example of Braun and Clarke's approach to reflexive thematic analysis. Qual Quant 2022;56, 1391–1(56, 1391–1412.).
12. Campbell, S., Greenwood, M., Prior S. Purposive sampling: Complex or simple? Research case examples. J Res Nurs 2020;25(8), 652(25(8), 652–661.):25(8), 652–661.
13. Birgand, G., Peiffer-Smadja, N., Fournier, S., & Lucet JC. Assessment of air contamination in hospital settings and implications for infection prevention. J Hosp Infect 2020;105(4), 58(105(4), 589–597.):105(4), 589–597.
14. Nowell, L. S., Norris, J. M., White, D. E., & Moules NJ. Thematic analysis: Striving to meet the trustworthiness criteria. Int J Qual Methods 2020;19, 1–13.(19, 1–13.):19, 1–13.
15. O'Brien, B. C., Harris, I. B., Beckman, T. J., Reed, D. A., & Cook DA. Standards for reporting qualitative research: A synthesis of recommendations. Acad Med 2020;95(1), 1–7(95(1), 1–7.):95(1), 1–7.

16. Spena, A., Palombi, L., Corcione, M., & Carestia M. Indoor air humidity and virus transmission risk. Int J Environ Res Public Health 2020;17(15), 55(17(15), 5524.):17(15), 5524.
17. Peng, Z., Rojas, A. L., Kropff E. Practical indicators for airborne transmission risk in indoor environments. Nat Commun 2022;13, 2895.(13, 2895.):13, 2895.