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Exploring Current Research Direction and Potential Ventilation Approaches in Hospitals' Operating Room: a State-of-the-Art Analysis

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This article reviews the current and potential trends in ventilation strategies within hospitals' operating rooms (ORs), with a specific focus on vertical downward ventilation systems meeting cleanroom criteria. It also explores potential innovations, including thermal-guided mobile air supply units and the possibility of localised exhaust systems mounted on operating tables. By evaluating existing ventilation systems and emerging technologies, this review aims to provide valuable insights into optimising surgical environments to ensure improved patient safety and outcomes. Vertical downward ventilation systems, currently widely deployed in modern ORs, adhere to stringent cleanroom criteria, maintaining sterile conditions by efficiently controlling air flow and minimising airborne contaminants. These systems utilise High-Efficiency Particulate Air (HEPA) filters and controlled airflow patterns to create a clean and controlled environment conducive to surgical procedures. While vertical downward ventilation remains the prevailing practice, the potential integration of thermal-guided mobile air supply units represents an exciting innovation. These units offer dynamic airflow control based on real-time temperature gradients within the surgical zone, potentially enhancing contaminant control and settlement rate. Also, the possibility of localised exhaust systems mounted on operating tables presents another avenue for improving ventilation efficiency. By efficiently capturing and removing contaminants generated during surgical procedures, localised exhaust systems have the potential to further reduce the risk of surgical site infections and improve overall cleanliness in the vicinity of the surgical site. This review concludes that combining a mobile air supply unit with thermal control capabilities, in addition to integrating it with a vertical downward ventilation airflow system, appears to be the optimal choice for reducing low concentrations near the patient's vicinity. By synthesising current practices with potential innovations, this review could assist healthcare professionals and facility managers in the evolving landscape of ventilation strategies in ORs. The adoption of advanced ventilation technologies and practices contributes to advancing surgical care and enhancing patient safety in healthcare settings. Future studies could consider integrating the Internet of Things (IoT) for automatic indoor air quality optimisation through ventilation control.

1. Introduction

An Operating Room (OR) is a specialised facility within a hospital where surgical procedures are conducted. It is an aseptic environment designed for surgeons to undergo surgery, with the aim of providing a safe and clean environment to the patient. Modern ORs are equipped with advanced medical technology, including surgical instruments, anaesthesia machines, and imaging equipment, to assist the medical staff in surgical procedures. A diverse array of surgeries can be carried out in modern operating rooms, which offer superior cleanliness

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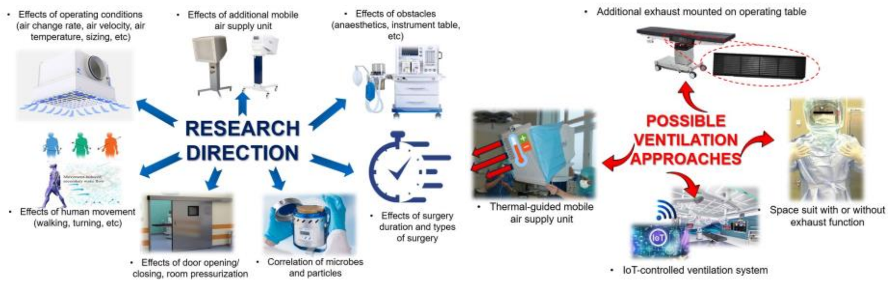
compared to traditional facilities. These surgeries span various specialities, including but not limited to general surgery, orthopaedic surgery, cardiovascular surgery, neurosurgery, plastic surgery, and ophthalmic surgery.
To determine the cleanliness of ORs, onsite microbes measurements were usually conducted. Tan et al. (2023) evaluated the microbial concentration for pre- and post-surgery in ISO Class 7 ORs and found that the microbes' increment could be up to 81 colony-forming units. Napoli et al. (2012) developed the correlation between two different air sampling approaches of measuring microbes' concentration and further proposed that both approaches could be integrated as routine surveillance programs. On the other hand, some studies measured the particulate matter concentration instead of microbes (Okoshi et al., 2022). This practice is due to the instantaneous measurement of particulate matter, which could reflect the contaminant fluctuation due to immediate activity, such as door opening/ closing. Another rationale for prioritising the measurement of particulate matter over microbes is the observed positive correlation between PM and microbial presence (Tan et al., 2022).
Common types of ventilation systems used in operating rooms (OR) include ceiling-mounted laminar airflow, horizontal laminar airflow, and turbulent mixing laminar airflow. Turbulent mixing airflow utilises a dilution principle, mixing fresh and contaminated air to dilute airborne contaminants. This system can ensure uniform temperature throughout the OR by supplying high-velocity air (up to 3.143 m/s), quickly equalising temperature differences (Cong et al., 2018). However, this mixing of fresh and contaminated air can result in up to a 20.1 % failure rate in removing airborne contaminants, potentially increasing the risk of surgical site infections (Francesco et al., 2020). Additionally, the high air velocity can affect the thermal comfort of surgical staff. Ceiling-mounted and wall-mounted laminar airflow systems both use unidirectional flow to sweep airborne contaminants to exhaust grills at air velocities ranging from 0.2 to 0.38 m/s (Lin et al., 2020). The main difference between horizontal and vertical airflow systems is the placement and direction of the airflow. Vertical laminar airflow diffusers are ceiling-mounted, directing air vertically, while horizontal laminar airflow diffusers are wall-mounted, directing air horizontally. Research indicates that unidirectional laminar airflow can reduce wound infections from 8.9 % to 1.3 % (Lin et al., 2020). Despite potential disturbances from obstacles like surgical lamps or personnel, vertical laminar airflow is generally preferred because it pushes airborne contaminants downwards to floor-level exhaust grills. In contrast, horizontal laminar airflow may interact with equipment, causing recirculation of contaminants. For optimal equipment ventilation, systems should ensure sufficient cooling to prevent overheating. For instance, surgical lamps could be equipped with built-in ventilation to dissipate heat, enhancing surgeon comfort during procedures. Room ventilation should address heat sources like surgical lamps, with vertical laminar airflow systems supplying air at velocities between 0.25 and 0.38 m/s to maintain temperatures between 20-25 °C, preventing bacterial growth.
To the best of the authors' knowledge, numerous ventilation strategies have been examined to enhance cleanliness in operating rooms. However, very limited studies have outlined the outcomes of each approach or identified future ventilation strategies worth exploring. The objective of this review article is to provide a comprehensive analysis of both current and potential trends in ventilation strategies within ORs, aiming to enhance patient safety and surgical outcomes. The contribution of this review lies in its exploration of emerging technologies and practices in OR ventilation, particularly focusing on thermal-guided mobile air supply units and the concept of localised exhaust systems mounted on operating tables. While established practices like vertical downward ventilation systems meeting cleanroom criteria are well-documented, the integration of these innovative approaches represents a significant advancement in the field. This review synthesises current research and potential future trends, revealing novel strategies poised to revolutionise OR ventilation and improve patient safety during surgical procedures.

2. Current research direction

This review article utilised the Web of Science (WoS) database to explore recent research articles. The WoS database, managed by Clarivate Analytics, is a web-based citation indexing resource recognised as the largest database encompassing high-impact journals across various disciplines (Wong et al., 2020b). An "advanced search" approach was conducted in the WoS database using the following search string: TS = ((operating room* OR operating theatre*) AND (ventilation* OR airflow* OR diffuser*)). The asterisk utilised within the search string acted as a wildcard operator, broadening the search scope by incorporating preceding words. This study focuses solely on articles published within the "past eight years", followed by meticulous manual screening.
Ventilation systems are essential for maintaining high air cleanliness and reducing the risk of surgical site infections. Among the various ventilation methods used in ORs, the vertical downward airflow approach has gained attention for its potential to effectively manage airborne contaminants and create a sterile surgical environment. This section aims to succinctly outline current ventilation practices in ORs, with a specific focus on the adoption and effectiveness of vertical downward airflow systems. The overall concept of recent research directions related to ventilation approaches is summarised in Figure 1(a).



(a) (b)

Figure 1(a): Evaluating the effectiveness of ventilation considering various aspects (Retrieved from Lapid-Gortzak et al. (2017), Kek et al. (2023)), Figure 1(b): Possible ventilation approaches to be further explored and enhanced in the future, retrieved from (Nakajima et al., 2017) and (Sadrizadeh et al., 2016)

Referring to Figure 1(a), it is evident that door openings in a closed room impact the particle concentration in the OR. A 1 min door opening increases the particle concentration from 15 Colony Forming Unit per m³ (CFU/m³) to 25 CFU/m³, taking approximately 4 min to return to 15 CFU/m³ (Sasan et al., 2018). Human movement, such as walking or turning, affects particle concentration in the OR. Research indicates that when a person walks at a speed of 0.25 m/s over a distance of 3 m, the average particle concentration is 113 CFU/m³. When the walking speed increases to 1 m/s, the average particle concentration rises to 143 CFU/m³. The studies show that when a staff member with bent forearms turns 90° clockwise, the particle concentration increases from 10 CFU/m³ to 40 CFU/m³ within 10 s (Kamar et al., 2020). The type of surgery being performed influences particle concentration in the OR. Research shows that during transplantation surgery, the particle concentration is 123 ± 60 CFU/m³, whereas during pediatric surgery, the concentration is 115 ± 30.3 CFU/m³ (Fu Shaw et al., 2018). Extensive research has been undertaken to minimise particle contaminants within operating rooms. One approach involves prescribing to change the air more than 20 times/h (ACH) in positive pressure operating rooms (modern type), which has been shown to decrease particle concentration and mitigate the risks of exposure during surgical incisions (Zhang et al., 2020). However, it's crucial to note that conventional operating rooms are typically engineered to operate with a higher ACH rate – set to an initial value of 25 ACH, as extended operation duration may lead to a decrease in this rate to approximately 20 ACH (Humphreys, 2021). A study also suggests that utilising physical partitions with heights of 0.3 to 0.9 m in the barn-integrated operating rooms could reduce the tendency of infection risks among the medical staff (Cheng et al., 2023). Table 1 tabulates the recent studies conducted in the operating rooms, mainly integrating the ceiling-mounted vertically downward ventilation system.

Table 1: Highlight of current research direction utilising the vertically downward ventilation strategies

Types of ventilation	Objectives	Findings	References
Vertically downward (Ceiling-mounted)	To examine the effectiveness of physical partition with different heights in reducing infection risks.	Mounting a physical partition on the supply air inlet significantly reduces the inhalation concentration for surgical staff.	(Cheng et al., 2023)
Vertically downward (Ceiling-mounted)	To evaluate the efficiency of operating room ventilation in reducing and eliminating aerosol particles during general endotracheal anaesthesia.	Particle concentration levels were notably elevated during intubation as compared to other sessions, potentially because of the disruptive impact of operating activities.	(Niu et al., 2024)
Vertically downward (Ceiling-mounted)	To investigate the impact of ACH and inlet area on airflow distribution, particle concentration, and thermal comfort.	Increased ACH enhances unidirectional airflow and prevents thermal plumes disruption. Excessively high ACH values do not enhance cleanliness but result in increased energy consumption.	(D'Alicandro and Mauro, 2023)
Vertically downward (Ceiling-mounted)	To evaluate the effectiveness of large diffuser versus multiple diffusers in reducing particle concentration in surgical zone.	The effectiveness of a single large diffuser is evident in its capacity to shield the surgical field and team from airborne particles emitted during surgery.	(Wagner et al., 2021)

3. Potential upcoming ventilation strategies

To further reduce the risk of patients contracting SSIs, several innovative ventilation strategies are proposed by researchers. For instance, one possibility is the use of equipment ventilation, personal ventilation, or room ventilation integrating the IoT approach. Figure 1(b) illustrates potential ventilation approaches that warrant further exploration and improvement. In the future, one potential approach could involve implementing vertical downward ventilation systems equipped with IoT sensors. These sensors would detect and provide real-time conditions to OR support staff in a control room. If airborne contaminant concentrations deviate from desired levels, the ventilation system will automatically adjust the air supply velocity within the range of 0.25-0.38 m/s. According to ASHRAE-170, the airflow velocity in an OR should not exceed 0.38 m/s. If the system cannot increase the airflow velocity further to remove contaminants, a warning will be displayed on the monitor screen advising the surgeon to either halt or quickly complete the surgery. Another approach involves mounting additional exhausts on the operating table to prevent airborne contaminants from interacting with the patient's open wound during surgical procedures by removing them from the table surface. Lastly, using surgical lamps equipped with ultraviolet germicidal irradiation (UVGI) could effectively eliminate airborne contaminants on the operating table by destroying the pathogens' structure. As exemplified by Kek et al. (2024), incorporating temperature control into the mobile air supply (MAS) unit effectively preserves a sterile environment around the patient. Their study also concluded that activating the MAS unit and subjecting it to a minor temperature increase to 23 °C consistently establishes an efficient barrier against particle penetration. A recent study also reveals that activating the localised exhaust positioned on both sides of the operating table reduces the overall particle settlement on the patient by 26 % in comparison to the standard ventilation system (Tan et al., 2024). Table 2 outlines the recent and potential ventilation approaches that could enhance the operating rooms' cleanliness.

Table 2: Possible ventilation approaches to be utilised in the operating room

Ventilation strategy	Objectives	Findings	Reference
Wearing air exhaust surgical body suits (space suit)	To explore how the discharge of air from space suits can decrease particle contamination in an operating room.	Space suit system could cause more contaminated air circulate in the operating room and potentially penetrate sterile instrument tray and the surgical field.	(Fu Shaw et al., 2018)
Incorporating MAS unit with thermal control	To examine the combined effects of thermal guided MAS unit, air curtain jet and local exhaust grilles in controlling particle dispersion and minimizing infectious particle settlement on patient.	By integrating temperature control using the MAS unit, it became feasible to diminish bacterial counts within the laminar airflow zone around patients, ultimately attaining a level of 0 BCP/m^3.	(Kek et al., 2024)
Wearing modern space suit	To evaluate the effect of wearing space suit and normal suit on airborne particle concentration.	By wearing space suits, medical personnel may inadvertently introduce additional contaminants into the operating field through simple motions.	(Nakajima et al., 2017)
Integrating localised exhaust on both sides of operating table	To evaluate the innovative air curtain and localised exhaust-based ventilation to improve particle removal efficiency in vicinity of surgical patient.	Installing the localized exhaust positioned on both sides of the operating table resulted in a 26% reduction in total particle settlement on the patient compared to the baseline ventilation system.	(Tan et al., 2024)
Incorporating Internet of Things (IoT) in ventilation system	To investigate the efficiency of automatic air quality enhancement in operating room by utilising IoT approach	IoT could assist in controlling the air quality system in the operating room and maintain the optimum operating condition.	(Yojana, 2021)

In general, the strategies outlined in Table 2 are still in the preliminary phase and require further investigation. The use of equipment ventilation (MAS unit) could create a localised area with a high-air cleanliness environment, provided that set-up conditions such as air velocity and air temperature are optimised. This approach could serve as an alternative instantaneous solution when the room's ventilation system fails to deliver the desired outcome. Conversely, personal ventilation is not recommended as it could increase contamination near the surgical zone and restrict the mobility of medical staff. Further clinical or experimental research is needed to confirm the functionality and practical application of this approach in the OR. Apart from the ventilation tactics, the application of ultraviolet germicidal irradiation (UVGI) technologies for disinfection and reduction of bacterial bioburden has been implemented across various hospital settings. Nevertheless, this method has not yet been extended to operating rooms and warrants further exploration.

4. Conclusions

This review article offers valuable insights aimed at enhancing patient safety and outcomes within surgical settings, considering the aspect of the ventilation system. Presently, vertical downward ventilation systems are prevalent in modern operating rooms, meeting stringent cleanroom standards to uphold sterility by regulating airflow and minimising airborne pollutants effectively. Although vertical downward ventilation remains the conventional approach, the introduction of thermal-guided mobile air supply units presents an innovative prospect. These units adjust airflow dynamically by introducing temperature gradients within the surgical area, potentially bolstering contaminant control and settling rates. Also, the incorporation of localised exhaust systems onto operating tables emerges as another avenue for refining ventilation efficacy. By swiftly eliminating contaminants produced during surgical procedures, localised exhaust systems hold promise in diminishing the tendency of surgical site infections and enhancing overall cleanliness within the surgical vicinity. In forthcoming studies, there is potential to investigate the integration of the Internet of Things (IoT) for the automatic optimisation of indoor air quality through ventilation control.

The insights from this review article are closely aligned with the United Nations Sustainable Development Goals (SDGs), specifically Goal 3: Good Health and Well-being and Goal 9: Industry, Innovation, and Infrastructure. Improving patient safety and surgical outcomes via advanced ventilation systems directly supports SDG 3 by enhancing health and well-being through better medical environments. The exploration of new technologies, such as thermal-guided MAS units and localised exhaust systems, embodies the innovation and resilient infrastructure advocated by SDG 9. Also, the potential use of the Internet of Things (IoT) for automatic indoor air quality optimisation demonstrates a commitment to modern, efficient, and sustainable medical practices. These advancements aim to reduce surgical site infections and contribute to the overarching goal of ensuring healthy lives and promoting well-being for people of all ages. Also, the current review offers valuable insights that policymakers can use as a reference for developing and updating regulations and guidelines to foster hygienic surgical environments.

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