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A systematic review of operating room ventilation

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ABSTRACT

Ventilation systems are the primary way of eliminating airborne pathogenic particles in an operating room (OR). However, such systems can be complex due to factors such as different surgical instruments, diverse room sizes, various staff counts, types of clothing used, different surgical types and duration, medications, and patient conditions. OR ventilation should provide a thermally comfortable environment for the surgical staff team members while preventing the patient from suffering from any extreme hypothermia. Many technical, logistical, and ethical implications need to be considered in the early stage of designing a ventilation system for an OR. Years of research and a significant number of publications have highlighted the controversy and disagreement among infection specialists, design engineers, and ventilation experts in this context. This review article aims to provide a good understanding of OR ventilation systems in the context of air quality and infection control from existing research and provide multidimensional insights for appropriate design and operation of the OR. To this end, we have conducted a systematic review of the literature, covering 253 articles in this context. Systematic review and meta-analyses were used to map the evidence and identify research gaps in the existing clinical, practical, and engineering knowledge. The present study is categorized into six research focuses: ventilation system, thermal comfort, staff work practice and obstacles, door operation and passage, air cleaning technology, emission rate, and clothing systems. In the conclusion, we summarize the key limitations of the existing studies and insights for future research direction.

1. Introduction

The history of surgical intervention is as old as the human race, and surgical site infections remain a deadly, costly, prevalent, and controversial topic, which has been referred to as the 21st-century challenge. Several research studies have linked postoperative complications to the risk of morbidity and mortality, increased length of hospitalization,

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patient dissatisfaction, a tremendous economic burden on patients and society, and permanent health conditions.

The primary source of airborne pathogenic particles in the OR environment is the surgical staff, and ventilation systems are the main tools used to eliminate such infection agents. In addition, ventilation systems should provide a thermally comfortable environment for the surgical staff team while preventing the patient from suffering any extreme hypothermia.

However, designing a general ventilation system for an OR is complicated. Different surgeries require different surgical instruments, diverse room sizes, various staff counts, different surgical duration, and medications. Many technical, logistical, and ethical implications need to be considered in the design stage of operating room ventilation. Many human factors need to be taken into account to achieve the desired outcome.

To overcome all OR challenges, interdisciplinary collaboration, and mutual understanding between ventilation experts and surgical staff are key factors in reducing infection rates.

Despite years of research and a significant number of publications, controversy and disagreement remain evident among the infection specialists, design engineers, and ventilation experts. There is still little or no general agreement on which type of ventilation systems should be implemented, which clothing system needs to be used, and what are the most critical factors affecting ventilation performance and efficiency. This is made it challenging, and in some cases impossible, to draw clear conclusions.

This literature survey aims first to summarize the most relevant research studies that have been conducted in six different main categories, which will be outlined below. It also aims to provide a critical reflection on the parts with enough research and widespread agreement; at the same time, we have tried to highlight the parts that need more research to clarify uncertainties.

We aim to present the most updated information regarding the engineering aspects of hospital OR ventilation and air quality and infection control. Our focus is on identifying how different factors affect OR ventilation performance and, thus, the contaminant level that may affect surgical site infections (SSIs). We have also considered other factors that may not directly contribute to the level of airborne particles, but indirectly affect the surgical staff performance. For example, in this regard we critically review the influence of different ventilation systems on staff thermal comfort, which may affect their performance during their demanding work in a given surgery.

However, we have limited our review to the engineering aspect of OR ventilation design and related air quality fields. The number of post-operative infections involves several clinical aspects (such as the susceptibility to infection of individual patient groups) that we have not considered in detail in this study.

Abbreviation list

ACH	Air changes per hour
BCP	Bacteria-carrying particles
CAP	Atmospheric pressure plasma
CFD	Computational fluid dynamics
CFU	Colony-forming units
C-UVC	Crystalline ultraviolet C
DV	Displacement ventilation
HEPA	High-Efficiency Particulate air
HVAC	Heating, ventilation, and air conditioning
LAF	Laminar air flow
OR	Operating room
PIV	Particle image velocimetry
PJI	Periprosthetic joint infection
PM	Particulate matters
SSI	Surgical site infection
TcAF	Temperature-controlled air flow
WHO	World Health Organization
ULPA	Ultra-low penetration air
UV	Ultraviolet
UV-C	Short-wavelength ultraviolet (type C)
UVGI	Ultraviolet germicidal irradiation

2. Methodology

Systematic keyword-based searches were conducted on PubMed, Scopus, Web of Science, IEEE, and Google Scholar to collect articles that were relevant to the research questions. Other national websites were also searched to cover relevant documents, standards, national reports, and guidelines. A comprehensive list of keyboards, i.e., “operating rooms”, “airborne contamination”, “bacterial load”, “door openings”, “traffic flow”, “air cleaners” and “clothing system” was used, including as Medical Subject Headings (MeSH). The subsequent articles were then imported into a reference manager. After deduplication, all records were examined by their titles, keyboards, and abstracts. Thereafter, a full-text reading was performed to apply additional exclusion criteria based on research quality, validity, and publication date. Six sub-topics were defined after a meta-analysis review on the remaining articles based on the research questions and context. An additional literature search was performed based on each sub-topic, and relevant articles were added to the article database. Finally, 262 articles were considered eligible for inclusion in the present review study. Fig. 1 depict the distribution of the articles cited in the present review study.

2.1. Operating room ventilation system

Since the landmark study by Charnley [1] reported a significant role of the Laminar Airflow (LAF) system in decreasing wound infections (from 8.9% to 1.3%), hospitals around the world have shifted from the use of conventional mixing to the LAF systems. Although the LAF ventilations appears to be superior compared to the mixing air distribution [2–4], the superiority of LAF or mixing ventilation is always controversial and a matter of debate among the experts. Nevertheless, current national and international standards recommended that LAF systems be installed in ORs [5–13]. A recent review of epidemiological studies showed no benefit in implementing a LAF compared to turbulent mixing systems [14]. However, the studies included in that review were questioned given that most of them utilized ventilation data from national

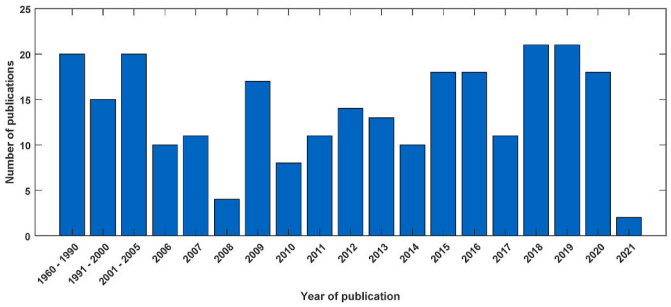


Fig. 1. The distribution of the cited articles in the current review study.

surveillance registries reported by surgeons or surgical departments. A recent validation study from the Norwegian Arthroplasty Register documented a significant misreporting rate associated with the surgeon reported ventilation data, thus questioning the validity of studies based on such data [15].

2.1.1. Turbulent mixing airflow ventilation

When mixing ventilation systems, clean air is supplied to the OR environment through the ceiling or vertical wall diffusers and extracted, usually at the floor level. Such systems mainly rely on dilution to remove the OR environment's contaminants, characterized by fully mixed and unstable airflow patterns throughout the entire OR. A tracer gas experimental study by Kuivjõgi et al. [24] demonstrated the inefficiency of mixing systems to dilute pollutants in the OR uniformly. Other influential factors (such as supply and exhaust locations, diffuser characteristics, room layout and dimensions, location, and size of contamination and heat sources) significantly impact the mixing systems [25,26].

2.1.2. Vertical (ceiling) airflow systems

Vertical (ceiling) LAF systems supply a large volume of air from the ceiling to the floor at relatively low velocities (0.2–0.3 m/s), which enables the LAF to swipe (a "washing" effect) airborne pathogens away from the surgical zone to the exhaust grills (Fig. 2), that are either located in the side-walls or ceiling. Recent studies have shown that the locating the exhaust in the ceiling can prevent the recirculation of airborne contaminants and contribute to the improvement of LAF ventilation design [27,28].

Air velocity at the ceiling diffusers is an essential factor and significantly influences the performance of LAF systems. Earlier measurements by Whyte et al. [30] showed that a supply velocity in the region of 0.3–0.35 m/s results in the lowest microbiological concentrations, although a higher velocity of above 0.3 m/s might affect the surgical staff's thermal comfort [31]. Based on a review of 16 national and international standards in 2006, there is a somewhat global consensus regarding appropriate supply air velocity (*0.20–0.*30 m/s) and High-Efficiency Particulate Air (HEPA) filtration efficiencies (99.5–99.7%) [32].

However, since the publication of the German hospital hygiene guideline [33], the minimum requirement for the total LAF airflow rate defined by DIN 1946-4 in ORs has increased more than threefold: from 2400 m^3/h in 1999–9200 m^3/h in 2008. Thus, the size of the LAF diffusers has increased by the same factor and the new guidelines require the size of the ceiling to be larger than 3.2 × 3.2 m^2; that is, a minimum supply velocity of 0.25 m/s. This trend has been followed by several other national/international guidelines in the past 10 years, as summarized in Table 1. In support of these revisions, several studies have shown that the implementation of large-size ceilings LAF (≥3.2 × 3.2 m^2) reduces the OR microbiological contamination compared to smaller-sized LAF systems [2,34–37] (see Table 2).

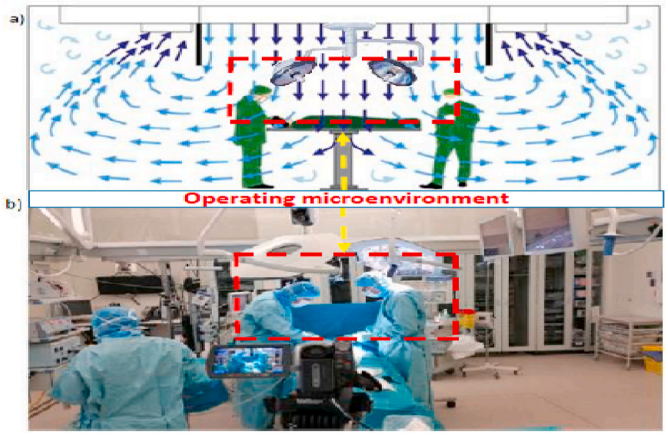


Fig. 2. (a) Schematic outline of airflow from a LAF unit, and (b) example of a vertical installed LAF in an OR of St. Olav's Hospital in Trondheim (dashed lines indicate the operating microenvironment) [29].

2.1.3. Horizontal and mobile LAF systems

The horizontal LAF system is either wall-mounted (lateral) or portable. Wall-mounted horizontal LAF systems are easy to install and maintain and inexpensive compared to ceiling LAF systems [38]. However, improper positioning of surgical staff can significantly reduce the performance of lateral ventilation systems [39].

The protected area under the LAF systems is usually occupied by medical staff, patients, and other required equipment. Thus, in some cases, the instrument table and other peace of medical equipment may remain unprotected. To resolve this issue, portable units were developed as an extension to the main OR ventilation and used to protect both the instruments and the surgical site [21,22]. The air supply device is located on a portable trolley so the supplied HEPA filtered air can be directed immediately onto the surgical site with relatively high velocities (0.4–0.5 m/s) [40], pushing potentially contaminated air forwards, away from the sterile zone. Mobile LAF units supply HEPA-filtered air directly to the operating microenvironment [21,22,41–44]. The protection area offered by mobile LAF units is significantly smaller than the vertical or wall-mounted LAF supply inlet [45]. However, unlike the ceiling LAF, the mobile LAF reaches the surgical site or instruments table directly without encountering obstacles such as surgical lights and bent surgeons.

While mobile LAF systems have attracted attention and their performance has been reported in clinical studies [21–23], wall-mounted horizontal systems have been relatively underreported, and there are no existing guidelines or requirements concerning the supply airflow characteristics such as inlet size or required air diffuser velocity. There are also no clinical studies showing the direct effect of mobile LAF systems on the SSI rate.

2.1.4. Displacement ventilation systems

Displacement ventilation (DV) systems introduce a low-momentum stream of cold and clean air at the floor level to displace the contaminated air toward the OR ceiling [46]. When the cold air meets a heat source in the operating microenvironment, due to the temperature difference and buoyant force, warmed and contaminated air moves upward to the ceiling, where it is exhausted out of the room. A major limitation of DV systems in hospital rooms such as ORs is the lock-up phenomenon. Previous studies have shown that pollutants can be trapped or locked at the breathing height at certain conditions due to the temperature stratification [47,48]. A clinical study by Andersson et al. [19] compared LAF and DV systems during planned and acute orthopedic implant surgery. The researchers found that LAF offers higher-quality air and a lower level of CFUs than the DV systems. In addition, recommendations on DV system characteristics have not been defined by existing national standards for OR ventilation systems [5–13].

2.1.5. Hybrid ventilation systems

Hybrid ventilation systems have been developed to combine two or more ventilation concepts to maximize performance and reduce operational costs. An example is a recently developed system, usually referred to as temperature-controlled airflow (TcAF) [20,49–51]. TcAF combined both LAF and turbulent mixing system in which the HEPA-filtered air was discharged toward the surgical zone with relatively colder air temperature (1.5–3 °C) compared to room temperature [49]. This small temperature difference subdivides the OR into two distinct zones, as depicted in Fig. 3.

At the same time, warmer air is dispersed from surrounding air showers, preventing stagnation zones in the periphery of the room and maintaining the temperature gradient that drives the central vertical

Table 1
Characteristics of OR air distribution systems.

	Airflow disitribution concept	Location of supply	Location of exhaust	Air supply conditions as reported in field studies			Air supply conditions as defined by national guidelines		
				Velocity (m/s)	Air changes per hour (ACH)	Diffuser size (m2)	Velocity (m/s)	Air changes per hour (ACH)	Diffuser size (m2)
Turbulent Flow Air distribution (TFAD)	The concentration of airborne contaminants is diluted by mixing the supply air with the contaminated OR air	Ceiling or wall-mounted	Wall mounted near floor	–	11.5–23.8 [2] 12 [3] 15.5–21.3 [16] 50 [17] 5.3–27.6 [18]	–	N/A	≥20 [5, 11]	N/A
Vertical Laminar Airflow (vLAF)	The unidirectional airflow swipes away the contaminants over the operating microenvironment	Ceiling-mounted	Ceiling and/or wall mounted near floor	0.25–0.38 [19]	26-178 [3] 80.5 [16] 58 [17] 15.1–59.9 [18] 67 [19] 100 [20]	2.4 × 2.4–3.2 × 3.2 [2] 3.8 × 1.2–5.18 × 3.83 [3] 3.2 × 3.2 [16] 3.6 × 3.6 [19] 2.75 × 2.75 [20]	#N/A	≥20 [5,11)	≥3.0 × 3.0 [6] ≥ 3.2 × 3.2 [7] ≥ 8 [10] ≥ 9 [13]
Horizontal Laminar Airflow (hLAF)		Wall-mounted	Ceiling and/or wall mounted near floor						
Mobile Laminar Airflow (mLAF)		In the vicinity of the operating table	Ceiling and/or wall mounted near floor	0.5–0.7 [21]	8.4 [22]	0.5 × 0.4 [19] 0.69 × 0.7 [21]	N/A	N/A	N/A
Displacement Ventilation Airflow (DV)	Cool air is supplied at floor level and is moved up displacing the contaminated air from the operating microenvironment	Wall mounted near floor	Ceiling or wall mounted near ceiling	0.09–0.15 [19]	21 [19]	–	N/A	N/A	N/A
Temperature-Controlled Airflow (TAF)	Combination of LAF (cool laminar airflow breaking convective currents in the operating microenvironment) and TFW (warm air maintaining temperature gradient)	Both cool and warm air is supplied from the ceiling	Wall mounted near floor	>0.25 [20]	47 [20]	–	N/A	N/A	N/A

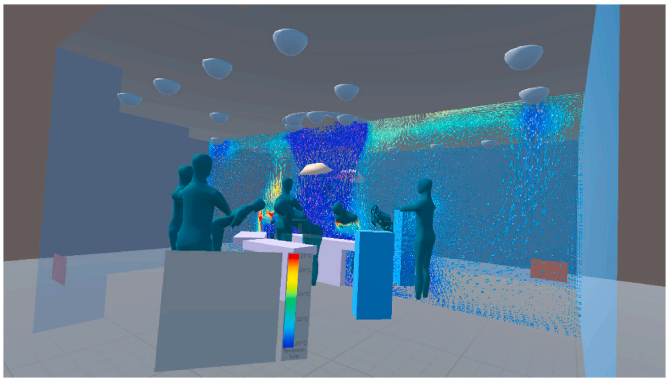


Fig. 3. Temperature-controlled ventilation system (KTH Visualization Studio – VIC).

flow of cooled air. In contrast to the LAF and mixing air distribution, the TcAF system has shown resilience to obstacles and thermal plums [52] and has been reported to be less demanding, in terms of airflow volume, and energy, than LAF and mixing systems [20,53]. In 2019, a clinical research study analyzed 1000 primary total joint arthroplasties before and after TcAF installation and confirmed a significant decrease in infectious complications, from 3.3% to 1.1% [54].

2.1.6. Comparison of the effect of different air distribution systems on airborne contamination rates and SSIs in ORs

ORs equipped with a 3.2 × 3.2 m^2 LAF systems exceeded the minimum DIN 19464:2008–12 standard supply requirements, reporting mean and median values close to one Colony Forming Unit (CFU)/m^3 (significantly lower than the limit value of 10 CFU/m^3 prescribed by standards). However, some studies have questioned the benefit of LAF systems and suggested that such systems not be used in infection-prone surgeries. A recent review article that summarized articles published between 1990 and 2016 [14] reported no advantage of using that ceiling LAF in total arthroplasty surgeries compared with conventional mixing systems. In addition, the new World Health Organization (WHO) guidelines state that LAF should not be used for orthopedic surgeries [55]. Bischoff's [14] research methodological approach has been recently debated: no LAF system differentiation or definition based on technical specifications, no or limited documentation of surgical clothing worn, and validation on the ceiling LAF systems was reported in the study [56]. Therefore, it remains unclear whether the ceiling LAF systems' inefficiency reported in Bischoff's study has been due to either insufficient size of the LAF ceiling diffuser in previously published studies and/or physical obstructions the air's unidirectional flow path. A recent Norwegian epidemiological registry study from 2020 assessed the impact of different ventilation systems on the risk of revision due to SSIs [57]. Based on 51 292 reported total hip arthroplasties, high-volume ceiling LAF systems reduced the risk of revision due to infection compared to mixing and horizontal LAF systems [57]. The question remains whether data reported in this study are conclusive enough for WHO to change its recommendations for ultraclean surgery. However, a recent study revealed a substantial misreporting rate in unvalidated surgeon reported ventilation data, clearly emphasizing the need for a reevaluation of WHO's recommendations [15].

The cost-effectiveness of LAF systems is also an important factor as they are expensive to install and maintain and have significant energy requirements [62]. The installation cost ranged from $60,000 to $90,

000 [63] and required a 34% increase in annual operating costs compared to a conventional mixing system [64], although the presented data (from 2004) might be outdated. Mixing systems might be less demanding in terms of supplied airflow rate and installation costs; however, such systems require clothing systems with a very high protective capacity, which could jeopardize staff comfort. Overall, infection prevention, by any means, in ORs, is still the most cost-effective solution [65–71]. In 2016, SSIs cost to the US healthcare system estimated to be $3.5 to $10 billion annually [72].

2.2. Thermal comfort and hypothermia

Infection control and patient safety are the main areas of focus when establishing hospital building codes and standards, and the concept of thermal comfort is a less addressed research component [73]. Thermal comfort is an intricate aspect that can cause severe problems if not correctly addressed, considering that several factors are present in an OR: different activity levels, different clothing levels, different health states (for the patient, surgeons, and other medical staff) and thermal preferences. A comprehensive review study on thermal comfort revealed the need to investigate the different thermal conditions required by different hospital occupants to satisfy their different thermal requirements [74]. Various research studies in healthcare environments have highlighted the impact of thermal environment conditions on OR staff productivity and efficiency, directly connected to their quality of work, the number of errors, and thus patient safety [75–82].

While thermal comfort is generally discussed for the OR personnel, hypothermia is a relatively common occurrence in the surgical patient due to the low metabolic rate or lack of clothing protection while the thermoregulatory system is put on hold due to anesthetic substances [76]. Patients' thermal comfort in hospitals can significantly differ from the thermal perception of a healthy person because of the physical disability, which affects the thermo-physiology, thermal sensation, metabolism, blood flow, and regulatory response [83]. A surgical patient is usually physically weak and may also experience anxiety, fear, and other negative feelings [76,84]. A moderate degree of perioperative hypothermia has been reported to significantly increase surgical patients' mortality rate [85–88]. Anesthesia can also lead to body temperature disorder [87,89], knowing that constant body temperature is the primary condition for a patient to maintain physiological functions. All of these studies indicate that the conditions leading to a patient's cold thermal stress are vast and difficult to assess and address. Along with the control of the environmental parameters, local measures are used to increase the patient's body temperature, such as heating blankets [90–92], warm infusion/irrigation fluid [93–95], heated inhaling oxygen [96,97], forced-air convective systems [91,98], and increasing the thermal properties of drapes covering patients in non-operation procedure area [99]. A comprehensive description of patient warming solutions is described in Ref. [100], but that study focused on risk mitigation of medical procedures rather than the patients' thermal comfort. However, the most commonly used solution to prevent hypothermia of the patient is the high ambient temperature in the OR, various values have been proposed: 18–28 °C [101], 24–26 °C [102], and 26 °C [103]. On the opposite side are surgeons, anesthetists, and other medical staff. According to Leslie et al. [104], a temperature above 23 °C is usually intolerable for the surgical team in the OR. Johnston and Hunter [102] reached similar conclusions and recommended a temperature between 20 °C and 22 °C for the medical staff. In agreement with these findings, Olesen and Bovenzi [105] recommended 23–24 °C for anesthesiologists, 22–24.5 °C for nurses, and 19 °C for surgeons.

On the other hand, the relative humidity reported in different studies has values between 30% and 60%. These limits ensure that the multiplication of certain microorganisms cannot take place. From a thermal comfort point of view, relative humidity of 30% may lead to problems for the medical staff related to the sensation of dryness and irritation of the skin and mucous membrane. The heterogeneity of values is significant and can also be observed in the standards, which recommend different temperature and relative humidity ranges, considering the primary surgery type (Table 3). OR temperature not only influences the thermal comfort and hypothermia, but also other important surgical procedures. For example, bone cement (polymethyl methacrylate) used in orthopedic surgeries is heat-sensitive. Any variation in temperature from the recommended temperature of approximately 21–23 °C affects the cement handling characteristics and setting time [106].

2.2.1. Factors that influence thermal comfort

In the first study of the thermal sensations of medical personnel in ORs, Wyon [79] indicated that surgeons and anesthetists differ from other OR staff in their thermal preferences. Due to their different activities, surgeons typically prefer a colder environment, while anesthetist prefer a warmer one. One of Wyon's conclusions was that variation in the clothing worn by different staff members might be the only way of resolving this difficulty. The patient, the surgeon, the anesthetist, and nurses might have different thermal requirements due to their activity. Other personal or external factors will directly impact the preferred temperature and make it different to the one imposed by standards [112]. Other studies have found similar results [81,113,114] for the medical staff categories, indicating this discrepancy. At the same time, more investigation is needed for the patients due to medical conditions that prevent them from evaluating thermal comfort. Dascalaki [115] stressed that surgeons in Greek hospitals, in warm climates, often experience sweating and thermal distress. However, opposite sensations were observed in the Netherlands (cold climate), which shows that the OR environment felt rather cold [116]. This variation shows that ORs' problem of thermal discomfort is common, independent of geographic location, standards, and other national practices. Besides the general environmental aspects, the key parameters that prevent the achievement of thermal comfort are mainly the individual factors, such as the different metabolic rate of individual members of the medical team and the types of clothing used for the activity performed [75,117,118].

According to WHO, various surgery types can be classified based on the degree of invasiveness; for example, the surgeries can be either invasive or open surgeries [119]. Open surgeries typically involve more staff and equipment, which includes different levels of metabolic rate and thermal requirements. Surgeons work particles usually vary depending on the surgical procedure. Thus, their metabolic rate has different values, according to different studies: a minimum of 1.5 met according to EN ISO 7730:2005 [120], from 1.2 to 2.2 met as mentioned in Ref. [81], or 1.6 met for surgeons and 0.69 met for patients [114].

There is general agreement among design engineers that the staff clothing systems directly impact thermal comfort. However, the main goal is to offer protection for the patient and the personnel [121]. The medical clothing is standardized in the medical procedure's function and can be specified according to the ANSI Standard AAMI PB70:2012 [122]. Thermal comfort is not adequately addressed in the AAMI standard, while the EN13795 [123,124] standards provide basic indications

Table 2
Clinical studies reporting incidences of deep SSIs after total arthroplasty surgeries for LAF vs. mixing systems in ORs [29].

Country (Study period)	LAF		Mixing		Information on LAF supply requirements for comparison with DIN 19464:2008–12 standard
	Total	SSI (%)	Total	SSI (%)	
UK [58] (2000–04)	212	0 (0.0)	223	9 (4.0)	N/A
Germany [59] (2000–04)	23 650	247 (1.0)	14 369	121 (0.8)	N/A
Norway [60] (1987–2008)	45 620	324 (0.7)	48 338	260 (0.5)	N/A
Denmark [61] (1995–2008)	72 423	517 (0.7)	8333	80 (0.9)	N/A

Table 3
OR temperature suggested by different standards.

UNI 11425:2011 [107] (Italy)	Winter ≥ 20 °C, ≥40% RH | Summer ≤ 24 °C, ≤ 60% R
NF S 90 351 [108] (France and Belgium)	19–26 °C, 45–65% RH
ASHRAE, Std 170, 9/05 [5] (USA)	17–27 °C adjustable, 45–55% RH
DIN 1946-4 [7] (Germany)	19–26 °C adjustable, RH as per DIN 13779
SWKI 99-3F [109] (Switzerland)	18–24 °C adjustable, 30–50% RH
GB 50333-2013 [110] (China)	Level I clean OR temperatures 21–25 °C
GOST R 52 539/2006 [111] (Russia)	18–24 °C ± 1 °C, min value 30% RH with 22 °C

on thermal comfort assessments. During surgical procedures in an OR, medical personnel wear multiple-use surgical gowns that should meet requirements (regarding thermal resistance, water – vapor resistance, air permeability, drapability) described in Medical Devices Directive 93/42/EEC [125], amended by 2007/47/EC, EN 13795–1:2019 [123] and EN 13795-2: [124]. Thermal insulation of surgical clothing ranges from 1 to 1.5 clo [81], 0.2–1.10 clo [114], or 0.42–1.1 clo [126], which will lead to an increase in skin temperature and relative humidity between skin and clothing layer and, thus, to thermal discomfort. Modern surgical clothing needs to satisfy several requirements: it should be comfortable, breathable, loose-fitting, keep users comfortable, and allow heat exchange between the body and the environment while limiting BCP release from the staff skin.

Besides personal aspects, several other environmental factors directly impact the thermal comfort of the medical staff and patients. Pereira et al. [127] found that the surgical lights have a significant influence on the thermal discomfort sensation of the surgeon, while Salonen et al. [128] emphasized the impact of the lighting systems on the thermal environment. For example, higher equivalent temperatures (the temperature of a uniform enclosure, with still air, in which a sizeable black body at 24 °C would lose heat at the same rate as that observed) were found in the upper part of the surgeon's and nurse's body because of the heat released by the surgical lights [127]. During operation, the surgeons carry out high-intensity work under the operating lamp wearing multi-layer clothes with a standing posture for hours, which can easily bring hot sensation and sweating to affect surgeons' mood and pollute the surgical field of vision [114]. Further study is needed of adequate lighting systems, which enhance the visual field and the thermal comfort.

Air distribution also has a substantial impact on the thermal sensation of the OR staff. For the LAF system, the velocity above the chest position is 0.15–0.26 m/s, similar to the velocity distribution with the mixing ventilation. The airflow distribution in the OR with LAF resembles a stratified airflow with decreasing velocity when it approaches the operating table. Turbulence intensity (the ratio of the standard deviation of fluctuating air velocity to the mean airspeed) directly impacts local discomfort sensation. Cao et al. [129] reported a higher air turbulence intensity for the mixing ventilation compared to that of LAF systems. Similar results have been identified in another research study, where, overall, most of the occupants in the mixing case were thermally dissatisfied, while the LAF case induces more thermal stress to the patient [24]. In hybrid ventilation systems such as TcAF, the colder air supplied in the surgical area may provide a thermal comfort condition for the active surgical team members, while OR periphery is kept warmer to satisfy the low activity level personnel [20].

In the context of OR thermal comfort, the main issue remains in the harmonization between the conditions of preventing the patient's hypothermia and satisfying the staff's thermal requirements.

Different technical solutions have been proposed for the surgical staff, such as cooling the surgical lights or replacing them with surgical lights with an integrated cooling mechanism or even local cooling clothing for surgeons [114,130]. Using modern LED lights in the ORs has also been proposed as a solution because they emit less heat. The clothing type, the contact area between clothing and skin surface, and the air layer all greatly impact the users' thermal comfort state, especially on the sweating mechanisms triggered [131,132]. Further studies are needed in order to look for new materials and cooling/heating solutions to satisfy individual thermal comfort requirements.

2.3. Staff work practice and obstacles

The performance of OR ventilation is influenced by several factors, including the presence of heat loads and obstacles in the OR environment (surgical lamps, medical equipment, personnel, etc.) [36]. Careful design and consideration of any airflow disturbance in the ORs are crucial to secure the air quality and provide a healthy environment to the patient and surgical team members [133–138].

A numerical study by Liu et al. [139] suggested using horizontal LAF airflow to overcome the blocking effects of surgical lamps on bacteria-carrying particles (BCPs) near a wound. The authors concluded that horizontal airflow is a better, than ceiling LAF, alternative to overcome surgical lamps' detrimental effects and other obstacles in an OR. Nevertheless, the system's effectiveness relies on the positioning of the patient's wound area and should be prescribed correctly according to the surgical procedure. A similar comparison between vertical and horizontal LAF was performed numerically by Sadrizadeh and Holmberg [140], who focused on active and passive sampling of BCP with various source strengths arising from the OR personnel. The conclusions were similar to that of Liu et al. [139]; that is, horizontal LAF provides reduced BCPs near the patient with the caveat of appropriate positioning of patient and OR personnel. The effect of surgical lamps on the BCPs is more critical for vertical LAF compared to horizontal LAF.

Recent research studies have also confirmed the detrimental effects of surgical lamps and obstacles on laminar airflow based ventilation in an OR and the corresponding impact on SSI [134,141,142]. Sadeghian et al. [134] conducted a CFD-based study to quantify the impact of surgical lamp design on the concentration of BCPs within the OR environments. They also offered an innovative solution to overcome the lamps' adverse effects, proposing a fan-mounted lamp design. The performance of the proposed design was evaluated considering the effect on BCPs contamination under mixing and LAF ventilation. Aganovic et al. [141] also performed experimental measurements on a LAF system in an OR, assessing the effect of obstacles, including surgical lamps and OR personnel. The authors concluded that the surgical lamps decreased the airflow velocity significantly and increased the risk of SSI; however, that study only measured the airflow speed and no particle concentration.

Several studies have investigated the detrimental effect of surgical lamps on the airflow from LAF [143,144]. However, they have mainly used the airflow visualization methods to demonstrate the impact of surgical lamps', without any quantitative values. Other studies have also quantitatively reported the airflow velocities using the particle image velocimetry (PIV) method [144,145]. The authors concluded that the airflow velocity behind the lamps is significantly lower than the ambient OR environment, resulting in an accumulation of airborne infectious agents. A research study by Wang et al. [146] examined the influence of the surgical lamp shape (closed-shape and an open-shape lamp) on the airflow and particle distribution in OR, supplied with both LAF and TcAF. The results show that the closed-shape lamp severely obstructs the airflow and results in high BCP concentration in the laminar airflow, whereas the open-shape lamp has a negligible impact on the particle dispersion. However, the TcAF exhibited less sensitivity to surgical lamp shape and obstacles.

Woloszyn et al. [147] conducted experimental measurements in a controlled chamber as well as CFD simulations and reported airflow velocity and SF6 concentration. The impact of the obstacles such as surgical lamps, equipment, and staff shows a similar lowering of the airflow velocity and the increase of tracer gas concentration in the lamp's vicinity. However, the effect of buoyancy was not considered and no measurements of SSI risk were performed either.

Surgical staff work practice is also another essential factor that has been discussed in several research studies.

Chow et al. [148] investigated the influence of the impact of surgeon bending movement on BCP distribution in the ORs, comparing a static standing posture of the surgical team with a periodic bending movement. The results confirmed that ventilation airflow can efficiently reduce the BCP level down to 1 CFU/m3 within the surgical zone in a static standing posture. However, the dynamic movement of surgical staff acts as an obstacle and can cause an excessively high BCP concentration in the critical surgical zone. Brohus et al. [149] also examined the influence of staff movements on BCP transport in an OR supplied with a LAF system. They introduced a relatively simple yet accurate numerical method to simulate two kinds of movement: a significant single event movement and continuous small-scale local movement. That study found that staff movements may impose savior damage to ventilation performance and increase the contamination level in the critical OR zones.

A similar study was conducted by Sadrizadeh et al. [135] to investigate the impact of surgeon posture on BCP level in a turbulent mixing OR. A mobile LAF as an extension to main OR ventilation was integrated and examined. The results showed that a combination of proper work practice and the use of a local LAF unit could significantly reduce the contamination level. That study highlighted that the proper outcome will be ensured only if OR personnel understand how the work procedures should be performed and how the ventilation system functions.

2.4. Door opening and passage

Door openings connect the ORs to less controlled and often more contaminated [150] spaces, such as corridors. ORs are usually, but not always, equipped to maintain positive pressure relative to adjacent spaces to prevent the entry of contaminants through gaps and cracks. Other types of ORs are kept in a relatively lower pressure compared to the OR environment. Such negative pressure ORs were established to accommodate a surgical patient with infectious/contagious diseases to ensure there was no air penetration from the OR to the hospital environment. Many medical and governmental organizations have published recommendations and standards that restrict door openings and foot traffic in the OR to reduce SSIs. The reasoning behind this is two-fold. First, door openings may defeat the positive/negative pressure and disrupt the ventilation airflow, allowing the dirtier air to enter/exit the OR. Second, the movement of personnel increases the shedding of airborne BCPs. In addition, the distraction caused by the door opening and traffic flow has been identified as a contributory factor to surgical mistakes [151–153]. Observational studies have investigated door openings and foot traffic during surgery and evaluated their impact on

Table 4
OR door openings and their effect on SSI.

Authors (year)	Type of surgery	Ventilation type	Door opening frequency [Openings/h]	Monitoring contamination/SSI?	Association between door openings and contamination?	Association between door openings and SSI rate?
Bediako-Bowan et al. (2020) [154]	Abdominal	Mixing[c]	59.3[a]	SSI	–	Yes
Birgand et al. (2019) [155]	Cardiac/ orthopaedic	LAF/Mixing	20.2	Particles/CFU	Yes/Yes	–
DiBartola et al. (2019) [156]	Orthopaedic	Unknown	27.0–34.8[a]	–	–	–
Roth et al. (2019) [157]	Cardiac	LAF	32.4	SSI	–	Yes
Alsved et al. (2018) [20]	Orthopedic	LAF/Mixing/ TcAF	2.1–5.6	CFU	No	–
Hamilton et al. (2018) [158]	Total joint arthroplasty	LAF	19.2–21.6[a]	–	–	–
Perez et al. (2018) [159]	Orthopaedic/ general	LAF	12.6–36.6[a]	CFU	Yes	–
Teter et al. (2017) [160]	Plastic surgery	Unknown	13.4	Particles	Yes	–
Bohl et al. (2016) [161]	Neurosurgery	LAF	46.2	SSI	–	No
Mathijssen et al. (2016) [162]	Hip revision	Mixing	3.3[a]	CFU	Yes	–
Elliott et al. (2015) [163]	Cardiac/general	Unknown	33–54	–	–	–
Mears et al. (2015) [164]	Joint Arthroplasty	Mixing[b]	16.6–37.3[a]	SSI	–	Unclear
Smith et al. (2013) [165]	Orthopaedic	LAF	37.2[a]	CFU	Yes	–
Andersson et al. (2012) [166]	Orthopaedic	Displacement	12.5[a]	CFU	Yes	–
Crolla et al. (2012) [167]	Colorectal	Unknown	–	SSI	–	Yes
Panahi et al. (2012) [168]	Total joint arthroplasty	LAF	41.4[a]	–	–	–
Young and O'Regan (2010) [151]	Cardiac	Unknown	19.2	SSI	–	Yes
Stocks et al. (2010) [169]	Joint Arthroplasty	Mixing	33.6[a]	Particles/CFU	-/No	–
Lynch et al. (2009) [170]	Multiple	Unknown	19–50	–	–	–
Scaltriti et al. (2007) [171]	Orthopaedic/ urology/general	Mixing[b]	56.4[a]	Particles/CFU	No/Yes	–

[a] Calculated based on values given in the article, either information on number of door openings/surgeries and the duration of surgery or openings/minute.
[b] The articles give information on the average ACH.
[c] Non-laminar.

OR environments and SSI risks. Table 4 summarizes the major findings of these studies (see Table 5).

2.4.1. Frequency of door openings

The frequency of OR door openings varies significantly among different studies. Different door opening frequencies can be attributed partly to the type and complexity of surgery [170]. The door opening frequency can also result from poor preoperative planning, as the most common reason for door openings during operation is to get supplies and equipment. Information exchange and communication are the second-largest reason for door openings [160,168], while social talk and coffee breaks are other important reasons [167]. Many such door openings are unnecessary and should be avoided. Alsved et al. [20] and Mathijssen et al. [162] reported a frequency of fewer than six times per hour, while the other studies listed above documented a frequency ranging from 12 to 60 per hour. In a multicenter study of 34 orthopedic and 25 cardiac procedures, Birgand et al. [155] found the median frequency of door opening to be 14.8 per hour in orthopedic procedures and 23.4 per hour in cardiac procedures. When OR doors were not allowed to be opened unless strictly necessary, Mathijssen et al. [162] reported a median number of eight door openings per case (3.3 per hour) during hip revision operations [162], which is low compared with other studies [151,166,168,170,172].

2.4.2. Association between door opening and OR contamination or SSI risks

Most of the literature (summarized in Table 4) has reported a statistical correlation between door openings and increased OR contamination, regardless of the ventilation system. Mathijssen et al. [162] suggested that a single OR door opening equipped with a mixing ventilation system contributed to a 5% increase in the odds of microbial contamination $\geq$20 CFU/m^3. In mixing ventilated ORs, Scaltriti et al. [171] found that door openings increase the CFU level, but reduce particle counts. However, a few studies have demonstrated contradictory evidence. Stocks et al. [169] did not detect any relationship between the traffic flow and the CFU level in ORs with mixing ventilation. Alsved et al. [20] found no significant correlation between the number of door openings and the CFU level at the wound area in three ORs supplied by LAF, mixing, and TcAF. A low level of corridor contaminations and the low number of door openings (2.1–5.3 per hour) might justify that study's result. A PhD work by Wang [173] studied different OR ventilations extensively and favored LAF over fully mixed systems in minimizing the contamination caused by door openings. Perez et al. [159] reported an association between increased CFU count and door openings only in the area outside the clean LAF zone. Smith et al. [165] also found that the CFU level was lower inside the LAF zone than the OR periphery, suggesting that LAF independently reduced the risk of contamination.

The impact of the door opening on the risk of SSI is highly controversial in the literature. Several studies have shown that door openings and corresponding foot traffic are directly associated with SSI rates [151,157,167]. Crolla et al. [167] noted a significant correlation between SSI development and a higher number of door openings in a cohort study of 1537 colorectal procedures. Roth et al. [157] recorded SSI occurrence within 30 days after cardiac surgery in LAF-ventilated ORs and demonstrated a positive association between increased door openings and SSI rates. However, this study was challenged by Yoshioka et al. [174] and Birgand et al. [175], who pointed out the potential methodological weakness in Roth et al.'s study, arguing that unmeasured variables could confound the relationship between the door openings and SSI. For instance, more frequent door openings may reflect a more severe or complicated level of the procedures, which by themselves impose more risk for SSI. In a randomized OR traffic trail, Bohl et al. [161] found no significant difference in the door traffic rate between SSI and non-SSI groups and questioned the benefit of restricting OR traffic in reducing SSI rates.

2.4.3. Airflow exchange and contaminant intrusion

Since statistical correlation does not prove causation, it is necessary to refer to engineering studies exploring the airflow behavior to understand the effect of door openings on the OR environment. The airflow through a doorway is driven by a complex combination of several factors, such as the temperature and pressure difference, the ventilation airflow, the personnel motions, and the door's movement itself. Early engineering studies adopted an analytical approach, which attempted to develop a formula to quantify the air volume exchange as a function of temperature difference [176–179]. Recent works have focused more on the containment failure in isolation rooms caused by door openings. Those studies used scale models [180–185], full-scale mock-ups [186–188], and CFD simulations [189–196]. The majority of such studies have concentrated on hinged doors and found that the hinged door's motion can cause an inter-zonal air transfer, which is referred to as the door swing pumping effect [181,184,189,192]. While hinged doors are common in hospital isolation rooms, modern ORs tend to use sliding doors. Analyses have shown that the gravity (or buoyancy)-driven flow dominates the air exchange through the doorway [194], and the difference between the two types of doors becomes insignificant when a temperature difference is involved [191].

Very few studies have explored the door-opening induced airflow in the ORs. Villafruela et al. [197] measured the transient airflow across the doorway caused by opening a sliding door in an empty OR with LAF ventilation. A small volume of air exchange between the OR and the corridor was detected, even under isothermal conditions. Those authors also noted that the human passage could induce a more significant air volume migration. Early numerical studies used static simulation to investigate the airflow and contaminant dispersion in the OR with an open door [198,199]. As the door cycle is short compared to the duration of surgery, it is the transient flow behavior that dominates the air exchange, and steady-state simulations are less likely to reflect the reality. The dynamic simulation by Balocco et al. [200] showed disruptions of the airflow inside the OR caused by the door opening and closing, as well as staff movements. Zhou et al. [201] simulated the interface airflow and contaminant penetration caused by sliding door openings in a LAF-ventilated OR. The results suggested that the OR and adjacent corridor's temperature difference played an essential role in determining the two-way airflow pattern and the contaminant intrusion. The simulation study by Sadrizadeh et al. [202] emphasized the cumulative effect of door openings and showed that frequent door openings could lead to a greater elevation of overall contamination in the OR.

The above-mentioned studies quantified the air volume exchange or focused on overall OR contamination. However, the risk of SSI is associated more with the local contamination close to the incision and instrument table. Thus, it is necessary to investigate the spread of contaminants within the OR and evaluate the airborne contamination at the surgical site. Wang et al. [203] simulated the transient airflow and BCP spread by sliding door openings in an OR with mixing ventilation. The results demonstrated that the airborne contamination at the surgical site could be drastically different under different thermal conditions even if the overall contamination were similar. The authors emphasized that the contaminant dispersion resulted from the airflow interaction across the doorway with the main OR ventilation. The findings of that study could partly explain the contradictory evidence in the literature regarding the association between the door opening and OR contamination.

2.5. Air cleaning technology and filters

2.5.1. Ventilation systems in ducts (or the ceiling)

OR ventilation systems are usually equipped with HEPA or ultra-low penetration air (ULPA) filters [204,205]. While the staff emits the vast majority of microbiological contamination that may initiate SSIs, these HEPA/ULPA ventilation systems ensure particle-free air supply to the OR. The role of filters becomes crucial if the OR air is partially

recirculated back into the OR environment. An air cleaning solution has also been used to supplement the HEPA-filtered ventilation systems to remove existing airborne particles within the ORs. Stand-alone air cleaners are usually developed by integrating a short-wavelength ultraviolet (UV–C) light (100–280 nm), known as ultraviolet germicidal irradiation (UVGI), and HEPA/ULPA filters [206–208]. However, in-duct air cleaning systems feature a bank of UVGI lamps installed inside HVAC exhaust or air supply ducts [209,210]. Several studies have reported the efficacy of UV-C in reducing the total and viable particle counts in highly controlled OR environments [211,212]. It has been reported that air filtration and disinfection units combining HEPA filtration and UV-C disinfection technologies may reduce the potential for patient infection. Evans [63] reviewed experience of LAF and ultraviolet light effectiveness, concluding that both LAF and ultraviolet light reduce the prevalence of periprosthetic joint infection. Evans also mentioned that many of the studies available do not take a high-level perspective, but are often retrospective from one institution. The challenge involves using UV lights because UV radiations damage human tissue, particularly skin, and thus cannot be used a given surgery in the OR's occupied zone [213].

Zhang et al. [214] conducted a comprehensive analysis of air purification methods in ORs located in China. The authors concluded that air cleaning technology is used in 81% of the investigated hospitals, of which 4% is central ventilation systems with integrated air purification devices. However, the authors did not discuss the efficiencies of the air purification devices implemented in the ventilation systems.

Ülgen and Tezer [215] studied the effects of ultraviolet radiation on the OR's airborne particles and microorganisms. A single 30 W low-pressure mercury lamp (234 nm) was mounted at the height of 234 cm and above the room entrance. The authors concluded that the effect of ultraviolet radiation on the microorganisms was significant in one location out of 15 measured locations in the OR [215].

Ereth et al. [216] studied the effect of an electrostatic field manipulation on airborne particulate matter in two live real-world OR settings and on pathogen survival in a microbiology laboratory. The authors concluded that the electrostatic field manipulation technology reduced fine and ultrafine particle counts by 95% during two different OR studies.

Prehn et al. [217] introduced cold atmospheric-pressure plasma (CAP) technology that enables the inactivation of microorganisms, including multidrug-resistant strains. The authors confirmed the decontamination potential of CAP by eliminating 89% of the tested microorganisms.

Stocks et al. [218] studied the use of a system that delivers a small field of local, directed air from a HEPA filter to reduce airborne particulate and airborne bacteria in the surgical field during total hip arthroplasty. The device consists of two components: a HEPA blower and a sterile nozzle. The nozzle is secured in immediate proximity to the surgical site and emits HEPA-filtered air to wash airborne particles away from the wound area. The authors concluded that the system is effective in reducing airborne particulate and BCPs.

2.5.2. Portable air cleaners

LAF systems provide a relatively small clean zone that is usually occupied by staff members and necessary medical equipment. Thus, some surgical instruments might remain outside the protected area. In order to overcome such issues, portable ultra-clean airflow units were introduced as an extension of the main ventilation system.

Curtis et al. [219] designed an experimental study to investigate BCP count variation related to OR foot traffic and to examine the efficiency of a crystalline UVC (C-UVC) filter unit. Three series of experiments were performed where a base case with no C-UVC unit was compared with a C-UVC unit placed four and 8 m from the door. The case study with the C-UVC unit of 4 m from the door had significantly lower particle levels than the base case (no C-UVC unit). In terms of BCP counts, the authors found no significant difference when the C-UVC unit was placed at a distance of four and 8 m from the OR doorway.

Cook et al. [220] compared the infection rate in a turbulent mixing OR with and without a supplemental HEPA – ultraviolet ventilation system. The results confirmed that the supplemental air decontamination unit might significantly reduce the overall risk of PJI. The validity of the results presented in that study is a matter of concern as the sample size might not be either statistically significant or clinically relevant.

There are different types of surgical smokes and odors in the OR, containing various malodorous and hazardous combustion byproducts that need to be removed from the surgical environment. Ha et al. [221] used a built-in-filter port to remove surgical smoke and found a significantly lower level of volatile organic compounds and aldehydes.

2.5.3. Personal protection technologies for the patient or surgeon

Personal protection technologies have been used in the ORs to reduce airborne contamination levels during a given surgery. Filtered exhaust hoods and suits are used to remove airborne contaminants shed by the surgical personnel. Evans [63] reviewed the most research evidence of body exhaust suits combined with air cleaning systems, concluding that the combined use of body exhaust suits and LAF reduces the prevalence of PJI. Evans also mentioned that many of the studies available are not high-level perspectives, but are often retrospective from one institution. Makovicka et al. [223] studied the impact of positive-pressure exhaust suits on personal protection for the surgeon and assistants compared to other types of protecting equipment. The results showed that the positive-pressure exhaust suits provided better personal protection than the other examined clothing systems and protective equipment. Hanselman et al. [224] studied the effect of filtered-exhaust helmet systems to limit intraoperative contamination, finding that the helmet airflow system's activation resulted in a substantial spread of BCPs from the helmet to the surroundings. The author recommends complete surgical gowning before activation of the helmet airflow system.

2.6. Emission rate and clothing systems

2.6.1. Characteristics of airborne particles in the ORs

The transport mechanisms of airborne bacteria from the human body are conducted to particles carrying these viable units. Skin scales are produced by the skin's friction with the clothing and transmitted with air into the room due to pumping effects. The size distribution of skin particles dispersed into the air during activity was discussed extensively in a research study by Mackintosh et al. [225]. The release rate of BCPs from an individual is dependent on several factors [226] and directly proportional to the number of staff presented in the OR [133]. Clothing systems are directly associated with source strengths (the mean BCP value emitted from one person per second – CFU/s) and have been discussed extensively in many clinical [227–230] and numerical [140,231] studies. It is generally agreed that a lower source strength resulted from a clothing system with a high protective capacity reduces the OR particle concentration.

Davies and Lidwell [232] and Hughes [233] found a correlation between the number of skin fragments and bacteria counts (between 400 and 1700 CFU). Tang et al. [234] determined the size distribution of airborne particles in conventional ORs in which t size distribution biological particles had the characteristic of a logarithmic normal distribution. The aerodynamic diameter ranged in size from 1.7 to 30.2 μm (average 7.2 μm). The two most frequently occurring germs, Staphylococcus Epidermidis and Micrococcus, were registered in a study by Pastuszka et al. [235]. The size of the viable particles with the most significant frequency was 3.3–4.7 μm.

Kim et al. [236] sampled the OR air and found Staphylococci in over 50% of all airborne germs. Although most CFUs were detected in a size range of 1.1–2.1 μm, viable particles in similar quantities were registered in all other size classes (0.65–7 μm and >7 μm). Nasir et al. [237] reported a size distribution of 3.3–4.7 μm in conventionally ventilated ORs, while a size range of 2.1–3.3 μm in ORs supplied by LAF

dominated. Airborne BCPs were also transported on saliva drops emitted during sneezing, breathing, or speaking activities. Although OR personnel wear face masks, this mostly catches larger saliva drops (>10 μm) produced when coughing or speaking loudly [238,239]. Measurements on the emission rates of respiratory droplets and the size distribution showed more than 80% of the particles were smaller than one μm, and more than 99.9% were smaller than five μm [240]. The mean values of the emission rates for breathing (134 particles/s), speaking (195 particles/s), and coughing (13 709 particles/cough) were measured.

The size distribution of exhaled saliva droplets and their correlation to the final droplets size have been recently investigated by Lieber et al. [241]. The equilibrium size correlates to 20% of the initial diameter for a relative humidity between 6 and 65%. For particles with an initial diameter of 50 μm and smaller the airborne lifetime is mostly independent of the relative humidity. These particles can stay airborne for 10 min and much longer with further decreasing initial size.

Pasquarella et al. [242] investigated the concentration of CFU in ORs at rest (12 CFU/m^3) and during operation (80 CFU/m^3). Landin et al. [243] found values of 0–38 CFU/m^3 with no correlation with microbiological level and the particle counts.

Woods et al. [244] estimated that microorganisms colonized only 10% of all human-emitted particles; however, Tarvainen et al. [245] reported a lower rate of 0.5–5%. Racoczy [246] reported numbers for the total emission of human-emitted particles of about 10^2 #/s up to 10^5 #/s, depending on the activity and clothing system. The value for a one-piece cleanroom suit with headgear and facemask with slight physical movement was given as 350 #/s. A recent investigation by Moschner [247] showed quite similar values. Table 6 summarizes research studies related to the size distribution of BCPs in OR environments.

Table 5
Effect of air cleaner technology to main types of pollutants.

Authors (year)	Capacity	Performance	Efficiency
Curtis et al. (2018) [219] On UVC units	UVC units are capable of significantly reducing the total and viable particle counts	Compared to controls, the cases with the C-UVC unit at 4 m had significantly lower particle levels.	Not mentioned.
Casagrande and Piller (2020) [40] On Mobile LAF	The Mobile LAF has a marginal impact on the distribution of the vertical velocity 1.4 m above the floor, except near and above the principal instrumentation table.	The local changes in the airflow pattern induced by the Mobile LAF might cause significant differences in the concentration of BCPs.	The portable air-cleaning device maintains sterile conditions on the principal instrumentation table over a range of flow rates of the general ventilation
Cook et al. (2019) [222] On HEPA + ultraviolet	The use of intraoperative supplemental air decontamination significantly reduced the overall risk of PJI.	The rate of PJI was documented to be 1.9% in the traditional group, and no infections were documented in the cohorts operated under UV-C air decontamination.	Not mentioned.
Hi et al. (2019) [221] On Gas filter + built-in-filter port	Built-in-filter ports have the potential to reduce the exposure of surgical smoke to surgeons and OR personnel	Built-in-filter ports significantly reduced the concentration of five volatile organic compounds and two aldehydes but not that of formaldehyde, acetaldehyde, and propionaldehyde.	Formaldehyde concentration decreased by 50% after filtration.

2.6.2. Influence of clothing on the microbial room air contamination

Surgical clothing acts as a filter to limit the number of particles released from the OR staff [249,250]. Thus, surgical team members must wear clothing systems suitable for their specific activities. Ljungqvist and Reinmüller [251] conducted a comprehensive examination of different ORs' clothing systems, finding that clothing systems are the most critical factor controlling the personnel source strength.

Two different types of gowns (disposable spun-bonded polyester gown and reusable woven polyester gown) were investigated by Lankester et al. [252]. However, Whyte et al. [253] found no difference between cotton and disposable gowns in the number of SSI.

Significantly fewer bacteria were measured on the disposable gown than on the reusable gown. Tammelin et al. [227,228] conducted a series of laboratory tests and reported no significant performance change with reuses.

Hottner [254] suggested that cleanroom clothes be worn in ORs and showed a reduction in particle emission. Air pressure under the cleanroom gowns (between the body and gown) is usually higher than the ambient air due to the cloth airtightness. Thus, the contaminated air can easily escape into the room through openings, so tight sleeves and collars are recommended.

During 30 min of simulated operations, Hubble et al. [255] measured the number of bacteria in ORs with LAF and conventional ventilation. In the conventional ventilated OR, no significant influence of the clothing was reported. In the LAF OR, by contrast, the number of BCPs increased if parts of the clothing were left (for example, no headgear, 15-fold increase; no mask, 4-fold; no mask and no headgear, 22-fold increase; cotton cloth, 6-fold increase compared to using both mask and headgear).

Mitchell et al. [256], Webster et al. [257], as well as Tunevall [258] reported no significant differences in BCP counts if the non-scrubbed staff were wearing face masks. Friberg et al. [259] found a significant reduction of the BCPs using headcover, while Humphreys et al. [260] suggested using headcover just for scrubbed staff near the wound field. A recent study by Stapleton et al. [261] examined the influence of change in the clothing regulation to long-arm, disposable jackets as well as covering of head, hair, ears, and facial hair with disposable heads in restricted and semi restricted areas. Results confirmed that such measures would potentially lower the SSI rate, although, no statistically significant change has been found.

The transmission of pathogens from the personnel's hands is a contact transmission, and the gloves' perforation was found to be the essential problem [262]. In contrast, Whyte et al. Report no significant increase in the number of BCPs with perforated gloves [253]. In addition, no influence of the ventilation was found for gloves. These results are summarized in Table 7.

The different clothing showed a different influence on the emission

Table 6
Summary of key factors of contamination strength in ORs.

Reference number	type of particle	Discovered size	Concentration	Remarks
[232,233,244,245]	Skin scales/ particles and bacteria	Data not provided	1:400 up to 1:1700 bacteria per skin sales, 10%, 0.5–5% colonized	Depends on the investigated situation
[234,235,242,243,248]	Airborne bacteria	1.7–30.2 μm	12 CFU/m^3 (rest), 80 CFU/m^3 (operation)	Measurements with Andersen cascade impactor in ORs
[240]	Particles	<5 μm	134–195 particles/s	Different activities

Table 7
A summary of key factors of clothing in ORs.

Reference number	Type of clothing	Performance	Remarks
[252]	Disposable spun-bonded polyester gown	Reduction of emitted bacteria	Different materials, as well as cuts, have to be investigated
[227,228]	Reusable woven polyester gown	Performance did not decrease significantly with the number of reuses	concerning the ventilation system, thermal comfort, and wearing comfort
[255–260]	Headgear and face masks	Controversially discussed, suggested for staff standing near the wound field	Connection with ventilation system necessary
[262]	Gloves	Perforated gloves critical	Not influenced by the ventilation system

of BCPs; however, thermal and wearing comfort have to be considered, as discussed in previous sections of the current review study.

3. Conclusions

It is hard to make technical recommendations based on what is summarized in the current study, other than that surgical site infections have a massive cost to both patients and society. SSI cost is associated with a significant economic burden in terms of an extended length of stay, increased treatment costs, patient disabilities, mortality, and morbidity. Most studies agree that a higher BCP level in the OR air is associated with a higher SSI rate, although there are still many uncertainties and controversies that need to be clarified.

The lack of a mutual understanding among design engineers is apparent as opposing conclusions are regularly drawn on the same topics. For example, several articles recommended the implementation of LAF ventilation, while others report a higher SSI rate in the presence of LAF systems.

Door opening and passage were also reported to harm OR cleanness and ventilation efficiency, while others registered limited or no effect on OR contaminant level.

However, clear consensus can be observed in other aspects, such as the positive impact of proper staff work practice or the beneficial effect of protective clothing to limit airborne particles' emission. Overall, precise laboratory measurements and advanced numerical simulations are required in order to clarify the mentioned controversies. It is even more critical to achieve clinically relevant and statistically significant results, as most previous research studies have suffered from insufficient sample size, replicability, validation, and verification.

The lack of a universal standard in this area is also evident and, in some cases, leads to opposite recommendations provided by different standards. Reducing SSI incidence requires an advanced and complicated interdisciplinary collaboration between design engineers, infection control specialists, surgical staff, and behavioral specialists. Thus, developing a mutual language among all involved disciplines is important and needs concrete dedication. In the context of OR ventilation, WHO recommendations are based on contradicting clinical studies underreporting/misreporting ventilation design characteristics that may be crucial to the ventilation systems' effective performance. Thus, data on ventilation design conditions must be reported when comparing different ventilation systems' influence on SSI rates in future clinical studies. More care should be given to the surgical microenvironment, where exposure to surgical incisions occurs. Currently, insufficient studies are dedicated to investigating the effect of ventilation solutions on surgical microenvironment quality.

The surgical lamp, surgical equipment, and surgeon posture constitute substantial disruptions of the ventilation airflow, especially in the LAF ventilation. The surgical lamps, specially closed-shaped, prevent the clean air from reaching the surgical site, weaken the washing effect, and even create a recirculation zone underneath the lamp. The contradictory evidence in the literature regarding the efficacy of LAF ventilation can be partly attributed to the surgical lamp's negative impact. Innovative designs of surgical lamps can, to a large extent, alleviate the detrimental effect on the unidirectional airflow.

In the context of airflow disturbance, the door opening is another important topic that has been discussed extensively in the literature. In LAF-ventilated ORs, a broad LAF diffuser coverage seems highly effective in reducing the LAF sensitivity to the door opening disturbances. In ORs equipped with mixing, however, preoperative planning and communication should be improved to reduce unnecessary door openings. Since the SSI incidence is complex and multifactorial, there is no clear evidence to demonstrate an association between door openings and SSIs. Depending on the studied surgery's SSI rate, thousands to tens of thousands of patients would be required in order to achieve statistically/clinically reliable results. Simply put, epidemiological studies on this topic have a statistical power problem.

The surgical staff are the primary source of BCPs, and clothing systems have been reported to be effective at minimizing the contaminants' release rate. Along with discussing ventilation performance, infection control, and clothing, thermal comfort represents one of the ORs' fundamental challenges. Air distribution strategies and specific environmental parameters, along with local solutions, need to be further investigated in order to offer optimal thermal comfort for all the medical staff categories and patients at the same time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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