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Surgical clothing systems in laminar airflow operating room: a numerical assessment

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Summary This study compared two different laminar airflow distribution strategies — horizontal and vertical — and investigated the effectiveness of both ventilation systems in terms of reducing the sedimentation and distribution of bacteria-carrying particles. Three different staff clothing systems, which resulted in source strengths of 1.5, 4 and 5 CFU/s per person, were considered. The exploration was conducted numerically using a computational fluid dynamics technique. Active and passive air sampling methods were simulated in addition to recovery tests, and the results were compared. Model validation was performed through comparisons with measurement data from the published literature. The recovery test yielded a value of 8.1 min for the horizontal ventilation scenario and 11.9 min for the vertical ventilation system. Fewer particles were captured by the slit sampler and in sedimentation areas with the horizontal ventilation system. The simulated results revealed that under identical conditions in the examined operating room, the horizontal laminar ventilation system performed better than the vertical option. The internal constellation of lamps, the surgical team and objects could have a serious effect on the movement of infectious particles and therefore on postoperative surgical site infections.

Abbreviations: AAS, active air sampling; BCP, bacteria-carrying particle; CFD, computational fluid dynamics; CFU, colony-forming units; LAF, (ultraclean) laminar airflow; OR, operating room; PAS, passive air sampling; SSI, surgical site infection.

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Introduction

Surgical site infections (SSIs) are the most common nosocomial infections that result from surgery. These infections contribute to higher patient mortality and considerably longer hospitalization and impose severe demands on healthcare services [1]. Patients who develop deep SSIs suffer from severe pain, insecurity and isolation [2]. The main cause of SSI is bacterial contamination that is suspended in the operating room (OR) air, mainly from infected skin squames that are shed by staff members. It is generally accepted that *Staphylococcus aureus* is the main relevant bacterial species found in ORs and is the most common cause of SSIs [3—5]. The postoperative infection rate generally depends on several factors, which include the level of airborne bacteria and the quality of the air within the OR. An appropriate ventilation system is the primary means for acquiring a safe and healthy indoor OR environment to preserve air quality and for diluting and removing airborne bacteria, anesthetic gases, and odors from the surgical zone. The OR ventilation system should also provide comfortable working conditions and an appropriate level of thermal comfort for the personnel to facilitate their work during an operation. There is a significant difference concerning the ability of various airflow systems to prevent bacterial emission into the OR surgical area.

The most common ventilation systems used in ORs today are ultraclean ventilation systems commonly known as laminar airflow (LAF) ventilation systems. Alternative methods include mixing and displacement ventilation, which differ from LAF systems primarily in terms of the methods used to supply and extract air.

LAF ventilation is an air distribution strategy for supplying air in a parallel manner through the OR. This is achieved by providing large volumes of air with a uniform flow field over the clean zone. The idea is to swipe away or wash out any microbiological contamination from the surgical zone and prevent bacteria-carrying particles (BCPs) from being encountered in the wound area. This ventilation system offers high air-change efficiency at a low supply-air velocity to control air contaminant transport. Depending on the configuration of the diffusers, it may be possible to introduce a single- or multi-zone area.

What remains unclear is which type of LAF ventilation system — that is, vertical or horizontal — is most appropriate to use during infection-prone surgeries. Several studies have been conducted that explored the relative merits of each LAF system [6—11].

Indoor obstacles, including surgical personnel, medical lamps and equipment, are considered to be the main factors that influence airflow patterns, and they can easily affect the unidirectional airflow pattern of a vertical LAF system [12,13]. It has been reported that the heads of OR personnel are sometimes positioned directly above the surgical site in the LAF stream from the ceiling down to the wound [14]. This can cause BCPs to fall directly into the wound. It has been shown that vertical LAF enhances BCP sedimentation by adding an inertial impaction factor [15].

To avoid these vertical airflow pattern disadvantages in ORs, a horizontal LAF has been suggested as an alternative [6,16]. A unidirectional lateral ventilation system will avoid obstacles, such as surgeons and medical lamps; however, it is very sensitive to internal staff member and equipment constellations that are present in ORs. The literature has discussed that improper positioning of OR surgical team members when horizontal airflow systems are utilized may increase infection rates [16].

The purpose of the present study was to assess and explore the performance of these two unidirectional ventilation scenarios in reducing the BCP concentration/sedimentation level in the surgical zone.

Materials and methods

The case study

The OR spatial arrangement, which has been used in other authors' previous work [17,18], was chosen as the physical model for the current study. The OR was designed for Nya Karolinska Sjukhuset, a hospital under construction in Stockholm. The OR dimensions were L 8.5 m × W 7.7 m × H 3.2 m, with the physical configuration shown in Fig. 1. The internal configuration of the OR personnel and other objects within the OR were appropriately arranged based on the DIN 1946-4 [19].

Ventilating air at a temperature of 20 °C was introduced to the OR with a total air volume flow rate of 2.5 m^3/s, which gave a nominal exchange rate of 47 h^{-1}. Ten surgical staff members were observed in upright stationary positions and mostly surrounded the operating table. A detailed validation of the airflow field was performed in terms of velocity and temperature [17] as well as particle distribution [20] between the numerical results and measured data. The agreements are within the limits required for engineering accuracy. However, the aspect was beyond the scope of the present study and is therefore not discussed here.

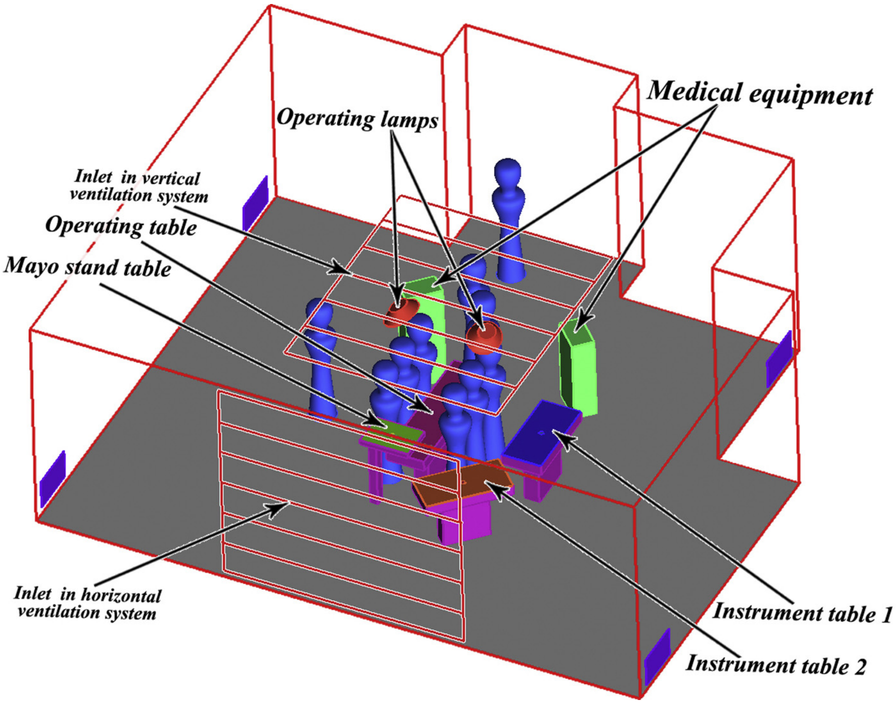

Figure 1 An isometric view of the operating room model.

Computational fluid dynamics

The indoor airflow complexity makes experimental investigation very difficult and expensive, especially in sensitive indoor environments such as ORs. Rapid advances in computer capacity have meant that the computational fluid dynamics (CFD) technique has become a powerful alternative for predicting the airflow field in enclosed environments. CFD is a branch of fluid mechanics that has been used extensively as a numerical tool to assess and visualize air movement, temperature distributions and particle concentrations [12,21—25].

Additionally, valuable predictions regarding infection situations, such as colony-forming units (CFUs), as well as ventilation systems, such as air velocity, temperature and humidity in discrete OR locations, have made it possible to clarify uncertainties during early design stages. Obtaining precise information can provide an important foundation on which to base design decisions.

The CFD technique typically has four main steps, which are described below.

Geometry: The first step is to define the geometrical configuration (computational domain) of the problem. For complex geometries, some degree of simplification is essential to focus on the parts of the room space that are most likely to be important. Hence, unimportant furniture and equipment may have to be ignored, and simple geometric representations of people are considered. In cases where the circuit interest is in the flow pattern detail or particle distribution near an object or a person, realistic feature modes should be considered [26].

Mesh: The spatial geometric space occupied by the fluid is then subdivided into discrete cells, which are known as a grid or mesh. The number of cells governs the accuracy of a solution. Optimal grids are often finer in areas where a large variation occurs in the flow field and coarser in regions with relatively little change. Particular attention is paid to the areas that contain the main flow, heat or particle sources in the domain. As the grid becomes finer, the calculations will become more accurate. However, because the element number increases, calculations become much more demanding in terms of simulation time and computing power. To minimize the grid resolution effect over the predicted results, variable grid densities are usually generated throughout the geometry to ensure that the results were appropriate and do not vary as the grid density increases; this is known as grid dependency. A systematic search for grid-independent results forms an essential part of all high-quality CFD studies. It is difficult to state a typical grid resolution. For example, the current calculations are run to resolutions of 5.2 million grid elements. When the resolution increases to this level, computational requirements extend beyond the capabilities of a single computer and a supercomputer is usually required.

Solve: Once the mesh has been chosen, the next key issue is to establish the physics that need to be included to calculate the airflow and properties. This involves specifying the fluid behavior and properties at the boundaries of the problem, that is, the inlet diffusers, exhaust grills and the particle sources. The fundamental basis of almost all CFD problems is the Navier—Stokes equation, a mathematical description of the momentum conservation (Newton's second law of motion). Areas of interest in infection control mainly relate to the transport, deposition and survival of bacteria-carrying particles. These factors must be considered along with the numerical models and approaches that are specific to the situation. The movement of airborne microorganisms released from staff members is generally characterized as discrete particles that are modeled using a motion equation. The equations are solved by an iterative method, which achieves high accuracy using a large repetition number. Here, the equations were solved using the *ANSYS Fluent 15.0* double-precision commercial solver.

Post-processing: CFD simulations do not end with the fluid flow and particle dispersal prediction. Benefiting from the prediction requires post-processing that gives users complete insight into the results of the fluid dynamics simulation. Thus, at the final stage, a post-processor software program is used to analyze and visualize the resulting solution. This is done using vector plots, line and shaded contour plots, 2D and 3D surface plots, particle tracking and animation for dynamic results.

There are limitations in the application of CFD techniques, such as grid-dependent solutions, slow or uncertain convergences, and the operator skill level (a skilled operator is necessary). However, those challenges are gradually being overcome by rapid advances in the computer system performance level and substantial improvements in the overall CFD software user-friendliness.

Bacteriological air sampling and simulation methods

In fact, the majority of atmospheric monitoring is carried out by passive air sampling (PAS) and active air sampling (AAS), as they have different purposes. PAS is the most primitive method for airborne microorganism sampling and is used to measure the viable particle settlement rate onto surfaces, while the AAS method provides information regarding the viable air particle volume concentration.

Because air sampling is typically performed during given surgical procedures, it involves ethical and logistical issues and cannot be rigorously studied. Furthermore, infection rate predictions in the design stage are not possible because the physical process is needed.

In the current study, both AAS and PAS approaches were numerically simulated to explore the OR BCP deposition and distribution. Due to different clothing system types, three different source strengths (the mean BCP value emitted from one person per second) — specifically, 1.5, 4 and 5 CFU/s — were considered for each staff member [27,28]. The particles were introduced into the OR from the head and neck of the OR personnel, and they were considered to have escaped the domain when they reached air exhaust outlets and their trajectories were terminated. Moreover, the particle trajectory calculations were terminated or were considered ''trapped'' after they hit a rigid surface and no rebounding was taken into account.

To mimic the AAS method, four slit samplers were placed over the operating table, mayo stands and instrument tables. OR air was drawn through the slit opening at a flow rate of 100 L/min for 10 min. This gives a total air volume of 1 m^3, and BCP counts were then explored as CFU/m^3. In this case, the OR was exposed to the amount of particles generated by the surgical team members during this 10-min period. To simulate the PAS approach, the surface areas of the operating and instrument tables were considered as settlement plates. Here, the OR was exposed to the amount of particles generated by the surgical team over 1 h and the results were explored as CFU/m^2 h. Sadrizadeh et al. [17,20] provided a more detailed explanation regarding the numerical calculation of the AAS and PAS approaches.

Recovery tests

Recovery tests are performed to determine the ability of the OR ventilation systems to eliminate airborne particles within a finite amount of time after a brief exposure to an airborne particulate challenge source [29]. The recovery time is the time, in minutes, for the particle concentration to decrease by two orders of magnitude. That is, the time it takes for each location to recover from 1000 times the target concentration to 10 times the target. The slowest recovery location in the cleanroom defines the room recovery rate as well as a particle concentration reduction by 99 percent within a specified time limitation of 25 min. Recovery performance can also be evaluated using the particle

Table 1 Air contamination by bacteria-carrying particles, expressed as the mean ± standard deviation, for three different source strength values in the horizontal and vertical LAF systems. (The CFD simulation results were based on the active air-sampling method.).

Source strength	LAF type	OT CFU/m^3, mean ± SD	MS CFU/m^3, mean ± SD	IT 1 CFU/m^3, mean ± SD	IT 2 CFU/m^3, mean ± SD	*P* value
5 CFU/s	Horizontal	15.15 ± 3.21	15.35 ± 3.11	9.19 ± 2.53	11.48 ± 3.22	0.43
	Vertical	33.93 ± 4.57	27.01 ± 3.57	11.28 ± 2.77	17.67 ± 3.51	0.32
4 CFU/s	Horizontal	11.32 ± 3.34	11.41 ± 3.21	7.12 ± 2.41	8.63 ± 2.58	0.37
	Vertical	29.30 ± 5.05	21.52 ± 3.83	8.32 ± 2.87	15.66 ± 3.08	0.31
1.5 CFU/s	Horizontal	4.51 ± 4.74	4.13 ± 3.18	2.48 ± 2.83	3.15 ± 3.01	0.21
	Vertical	10.21 ± 9.25	9.53 ± 8.78	4.02 ± 4.59	6.87 ± 5.86	0.19

LAF, laminar airflow; OT, operating table; MS, mayo stands table; IT, instrument table; CFU, colony-forming unit; SD, standard deviation.

concentration change rate by calculating the particle concentration decay curve slope.

In this study, based on DIN 1946-4 [19], the OR was exposed to 3500 particles/m^3 of air (0.5 μm). The time taken to reduce the particle concentration by two orders of magnitude was then calculated.

Results

The OR lateral and vertical ventilation strategy performance was examined by CFD calculations. Both active and passive air sampling methods were numerically examined to assess the particle concentration within the surgical zone. Three different source strengths were considered in relation to three different clothing systems. For both of the active and passive air sampling methods, the CFD simulation results are provided in Tables 1 and 2, and all three source strengths are included. The values are expressed as the mean ± standard deviation.

When the OR was supplied by a horizontal LAF ventilation system, the BCP counts over the operating table for the three source strengths were 15.15, 11.32 and 4.51 CFU/m^3. Once the vertical LAF system functions in the OR were evaluated, these values increased dramatically to 33.93, 29.3 and 10.21, respectively. The BCP counts over the tables were not the same because the airflow pattern was not fully mixed, although the same trend has been reported for other tables.

The BCP sedimentation results (CFU/m^2 h) that are provided in Table 2 reveal the same trend. More particles settled over the tables when the OR was supplied with the vertical ventilation system.

Fig. 2 shows the recovery test results for both of the examined LAF ventilation systems. The recovery time for the horizontal LAF system was 8.1 min,

Table 2 Bacteria-carrying particle sedimentation, expressed as the mean ± standard deviation, for three different source strength values in the horizontal and vertical LAF systems. (The CFD simulation results were based on the passive air-sampling method.).

Source strength	LAF type	OT CFU/m^2/h, mean ± SD	MS CFU/m^2/h, mean ± SD	IT 1 CFU/m^2/h, mean ± SD	IT 2 CFU/m^2/h, mean ± SD	*P* value
5 CFU/s	Horizontal	497.31 ± 62.5	184.36 ± 15.5	179.14 ± 11.9	666.54 ± 14.6	0.68
	Vertical	1892.69 ± 86.1	318.74 ± 65.4	366.41 ± 61.5	1064.81 ± 90.4	0.38
4 CFU/s	Horizontal	397.85 ± 16.1	147.49 ± 8.7	143.31 ± 5.9	533.23 ± 17.6	0.53
	Vertical	1514.15 ± 38.1	254.99 ± 12.7	293.13 ± 17.2	851.85 ± 20.6	0.50
1.5 CFU/s	Horizontal	150.21 ± 98.6	60.15 ± 30.2	57.81 ± 25.1	197.11 ± 19.5	0.39
	Vertical	571.80 ± 153.4	98.62 ± 42. 2	111.38 ± 50.1	312.91 ± 25.8	0.33

LAF, laminar airflow; OT, operating table; MS, mayo stands table; IT, instrument table; CFU, colony-forming unit; SD, standard deviation.

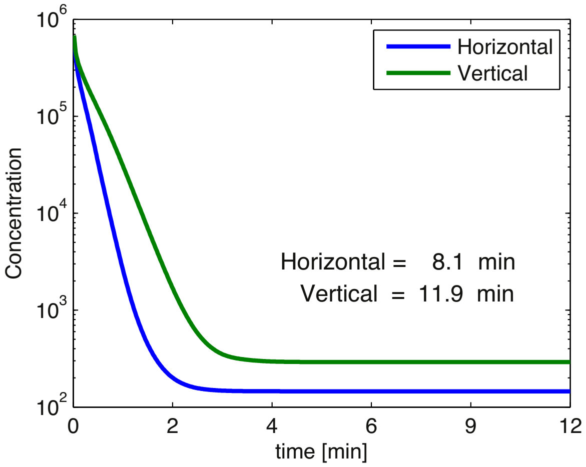

Figure 2 Recovery tests for the vertical and horizontal LAF systems (particle size: 0.5 μm).

while this time increased to 11.9 min in the vertical LAF scenario.

Figs. 3 and 4 display the CFD predicted airflow patterns over a vertical plane passing through the centerline of the operating tables. It is clear that medical lamps and the thermal plume that was induced by temperature differences between the environment and heat sources (e.g., the equipment, medical lamps and staff members) had no obvious influence on the horizontal LAF patterns (Fig. 3). Additionally, streamlines were straight and parallel from the air-supply diffuser to the surgical zone over the operating table.

When the OR was supplied with the vertical LAF system, reverse flows occurred in the marginal side of the surgical zone (Fig. 4).

Discussion

It is widely accepted that clean surgeries with a moderate or high risk of infection (such as orthopedic and implant surgeries) should be performed in an ultra-clean atmosphere. The accepted international definition of ultra-clean is air that contains less than 10 CFU/m^3 (AAS approach) and has a corresponding surface contamination rate of 350 CFU/m^2 h (PAS method) [9]. Based on the results provided in Tables 1 and 2, infection-prone surgeries can be performed safely in current ORs when they are supplied with a horizontal LAF system, especially when the staff is dressed in a clothing system that has a high protective capacity. This is in line with the results reported by Waaij et al. [30] in which the settling velocity was found to be stronger under vertical ventilation than with horizontal ventilation. Additionally, a proper clothing system has an obvious effect on reducing the source strength [31] and leads to lower surface and air BCP count concentrations that come into contact with the surgical area.

The recovery test results displayed considerably less recovery time in the horizontal ventilation case than in the vertical ventilation case. This result indicates that the horizontal ventilation strategy generates less turbulence than the vertical strategy. Quite strong eddies (see Fig. 4), which were generated by the vertical ventilation system, may trap the emitted particles for a long time, which means they cannot be evacuated from the surgical area.

When a horizontal ventilation system is employed, improper positioning of OR personnel may disrupt the unidirectional flow pattern.

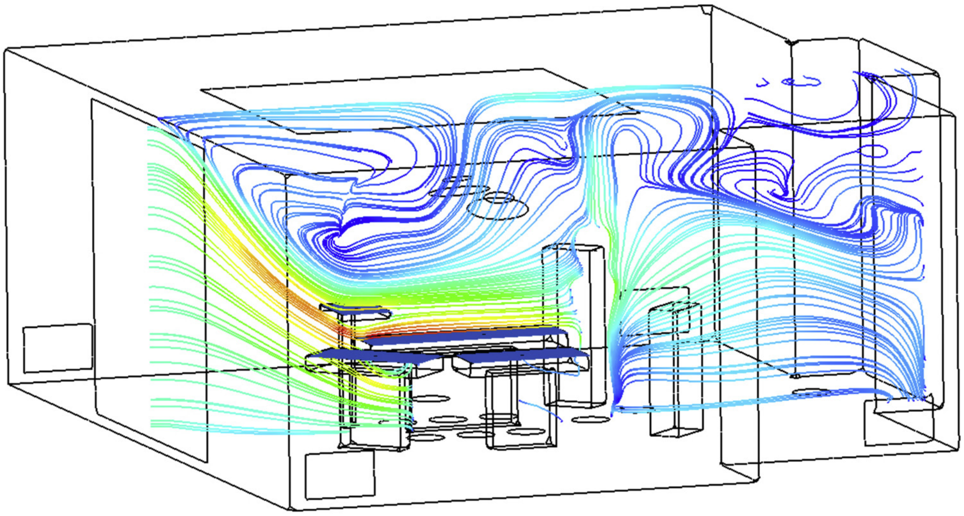

Figure 3 Velocity streamlines in an OR supplied by a horizontal LAF system.

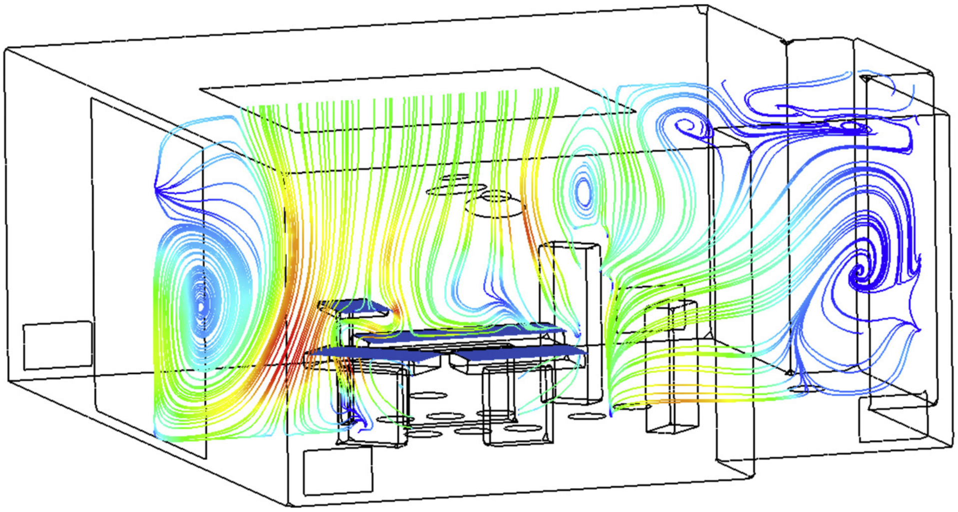

Figure 4 Velocity streamlines in an OR supplied by a vertical LAF.

To maintain a low CFU concentration surrounding the patient, especially in the area that is close to the surgical site, the direction of the patient should be prescribed correctly and the CFU sources (that is, the personnel) should be positioned downstream of the wound area. Because the flow is ventilated tangentially to the instrument tables and the surgical site zone (see Fig. 3), this ventilation system can greatly reduce BCP levels.

If a vertical LAF ventilation system is utilized, obstacles such as the surgeons' heads and operating lamps become increasingly important [13,32]. Currently, many medical devices that disturb the unidirectional downward flow are installed above the operating area, which can reduce the performance of the vertical LAF ventilation strategy. Moreover, the heat generated by medical devices and surgical team members has a remarkably negative effect on the vertical LAF systems.

There is a considerable stagnant area behind surgical lamps with large surface areas when they are interposed in the unidirectional down flow streams. This stagnant area may include a high bacteria concentration because it is usually close to the contamination source, such as a surgeon. Proper positioning of the lamp, as well as small surgical lamps, may be able to moderate the stagnant area and thus reduce the BCP concentration [33]. In a vertical LAF system, particle sources, such as surgeons, are always positioned upstream of the surgical area. This may cause the BCPs to be brought to the open wound site and may increase SSI susceptibility.

Conclusion

OR ventilation strategies have been identified as a key factor in the governing of airborne pathogenic particle dispersion. Obstacle positions, such as medical lamps, surgical staff and equipment, were found to be critical. The initial source strength of staff members due to different clothing systems is essential. Under identical conditions in our observed OR, the horizontal LAF system performed better than the vertical one. In ORs ventilated with a vertical LAF scheme, the need for small surgical lamps is more important, as the lamps may be positioned above the surgical site, which can cause a stagnant area with a high bacteria concentration. However, operating lamps and thermal plumes have little effect on the horizontal airflow pattern. Using clothing systems with a more protective capacity may reduce the surgical staff source strength, which can reduce the particle concentration within the OR. Our results indicate that with either horizontal or vertical ventilation, it is not possible to expect a microbiological air quality with the desired level of $<10\,\text{CFU/m}^3$ when using clothes that have a mean source strength of approximately 4 or 5 CFU/s.

If space constraints and workload considerations provide enough freedom to choose between two LAF systems, horizontal systems are a good option for OR ventilation. Moreover, horizontal systems are easy to install and maintain, comparatively inexpensive, and do not require a change of surgical lamps or pre-existing air-conditioning systems [34]. Additionally, more care should be given to the surgical team member work practices. Because the unidirectional LAF system performance is highly sensitive to the internal obstacle constellation, the designs of these ventilation systems are complex. Proper outcomes depend not only on overcoming technical complications but also on solving and incorporating human factors, such as OR personnel positioning and case-dependent furniture adjustments.

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Competing interests

None declared.

Ethical approval

Not required.

References

[1] Coskun D, Aytac J, Aydinli A, Bayer A. Mortality rate, length of stay and extra cost of sternal surgical site infections following coronary artery bypass grafting in a private medical centre in Turkey. J Hosp Infect 2005;60:176–9.

[2] Andersson AE, Bergh I, Karlsson J, Nilsson K. Patients' experiences of acquiring a deep surgical site infection: an interview study. Am J Infect Control 2010;38:711–7.

[3] Rizvi M, Rizvi MW, Shaheen, Sultan A, Khan F, Shukla I, et al. Emergence of coryneform bacteria as pathogens in nosocomial surgical site infections in a tertiary care hospital of North India. J Infect Public Health 2013;6:283–8.

[4] Hautemanière A, Florentin A, Hunter PR, Bresler L, Hartemann P. Screening for surgical nosocomial infections by crossing databases. J Infect Public Health 2013;6:89–97.

[5] Al Laham NA. Prevalence of bacterial contamination in general operating theaters in selected hospitals in the Gaza Strip, Palestine. J Infect Public Health 2012;5:43–51.

[6] Liu J, Wang H, Wen W. Numerical simulation on a horizontal airflow for airborne particles control in hospital operating room. Build Environ 2009;44:2284–9.

[7] Gastmeier P, Breier A-C, Brandt C. Influence of laminar airflow on prosthetic joint infections: a systematic review. J Hosp Infect 2012;81:73–8.

[8] Hansen D, Krabs C, Benner D, Brauksiepe A, Popp W. Laminar air flow provides high air quality in the operating field even during real operating conditions, but personal protection seems to be necessary in operations with tissue combustion. Int J Hyg Environ Health 2005;208:455–60.

[9] Friberg B, Friberg S, Burman LG. Inconsistent correlation between aerobic bacterial surface and air counts in operating rooms with ultra clean laminar air flows: proposal of a new bacteriological standard for surface contamination. J Hosp Infect 1999;42:287–93.

[10] Zoon WAC, van der Heijden MGM, Loomans MGLC, Hensen JLM. On the applicability of the laminar flow index when selecting surgical lighting. Build Environ 2010;45:1976–83.

[11] Diab-Elschahawi M, Berger J, Blacky A, Kimberger O, Oguz R, Kuelpmann R, et al. Impact of different-sized laminar air flow versus no laminar air flow on bacterial counts in the operating room during orthopedic surgery. Am J Infect Control 2011;39:e25–9.

[12] Chow TT, Yang XY. Ventilation performance in the operating theatre against airborne infection: numerical study on an ultra-clean system. J Hosp Infect 2005;59:138–47.

[13] Chow TT, Lin Z, Bai W. The integrated effect of medical lamp position and diffuser discharge velocity on ultra-clean ventilation performance in an operating theatre. Indoor Built Environ 2006;15:315–31.

[14] Hubble MJ, Weale AE, Perez JV, Bowker KE, MacGowan AP, Bannister GC. Clothing in laminar-flow operating theatres. J Hosp Infect 1996;32:1–7.

[15] Friberg B, Friberg S, Ostensson R, Burman LG. Surgical area contamination—comparable bacterial counts using disposable head and mask and helmet aspirator system, but dramatic increase upon omission of head-gear: an experimental study in horizontal laminar air-flow. J Hosp Infect 2001;47:110–5.

[16] Ahl T T, Dalén N, Jörbeck H, Hoborn J. Air contamination during hip and knee arthroplasties. Horizontal laminar flow randomized vs. conventional ventilation. Acta Orthop Scand 1995;66:17–20.

[17] Sadrizadeh S, Tammelin A, Ekolind P, Holmberg S. Influence of staff number and internal constellation on surgical site infection in an operating room. Particuology 2014;13:42–51.

[18] Sadrizadeh S, Tammelin A, Nielsen PV, Holmberg S. Does a mobile laminar airflow screen reduce bacterial contamination in the operating room: a numerical study using computational fluid dynamics technique. Patient Saf Surg 2014;8:27.

[19] DIN standard 1946-4. Ventilation and air conditioning – part 4: VAC systems in buildings and rooms used in the health care sector; 2008.

[20] Sadrizadeh S, Holmberg S. Effect of a portable ultra-clean exponential airflow unit on the particle distribution in an operating room. Particuology 2014, http://dx.doi.org/10.1016/j.partic.2014.06.002 [in press].

[21] Tang JW, Noakes CJ, Nielsen PV, Eames I, Nicolle A, Li Y, et al. Observing and quantifying airflows in the infection control of aerosol- and airborne-transmitted diseases: an overview of approaches. J Hosp Infect 2011;77:213–22.

[22] Walker JT, Hoffman P, Bennett AM, Vos MC, Thomas M, Tomlinson N. Hospital and community acquired infection and the built environment – design and testing of infection control rooms. J Hosp Infect 2007;65:43–9.

[23] Yam R, Yuen PL, Yung R, Choy T. Rethinking hospital general ward ventilation design using computational fluid dynamics. J Hosp Infect 2011;77:31–6.

[24] Chow TT, Kwan A, Lin Z, Bai W. Conversion of operating theatre from positive to negative pressure environment. J Hosp Infect 2006;64:371–8.

[25] Yuen PL, Yam R, Yung R, Choy KL. Fast-track ventilation strategy to cater for pandemic patient isolation surges. J Hosp Infect 2012;81:246–50.

[26] Martinho N, Lopes A, Gameiro da Silva M. Evaluation of errors on the CFD computation of air flow and heat transfer around the human body. Build Environ 2012;58:58–69.

[27] SIS-TS 39:2012 (E). Microbiological cleanliness in the operating room — preventing airborne contamination — guidance and fundamental requirements.; 2013.

[28] Tammelin A, Ljungqvist B, Reinmüller B. Single-use surgical clothing system for reduction of airborne bacteria in the operating room. J Hosp Infect 2013;84:245—7.

[29] 14644-3:2005 EI. Cleanrooms and associated controlled environments — part 3: test methods (ISO 14644-3:2005); 2006. p. 71.

[30] Van der Waaij D, Wiegersma N, Dankert J. Bacteriological evaluation of a mobile laminar cross-flow unit for surgery, under laboratory circumstances. J Hyg (Lond) 1976;76:1—10.

[31] Tammelin A, Ljungqvist B, Reinmüller B. Comparison of three distinct surgical clothing systems for protection from air-borne bacteria: a prospective observational study. Patient Saf Surg 2012;6:23.

[32] Zhao B, Yang C, Chen C, Feng C, Yang X, Sun L, et al. How many airborne particles emitted from a nurse will reach the breathing zone/body surface of the patient in ISO Class-5 single-bed hospital protective environments?—A numerical analysis. Aerosol Sci Technol 2009;43:990—1005.

[33] Whyte W, Shaw BH. The effect of obstructions and thermals in laminar-flow systems. J Hyg (Lond) 1974;72:415—23.

[34] Grounds MC. Laminar air flow vertical or horizontal? AORN J 1972;16:72—6.