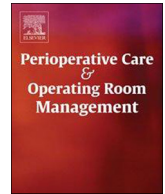




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Effects of forced air warming systems on the airflow and sanitation quality of operating rooms with non-laminar airflow systems

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ABSTRACT

Background: Previous studies have demonstrated that forced air warming (FAW) can be used safely in operating rooms with laminar airflow (LAF) ventilation systems. However, the effects of FAW on the airflow at surgical sites under non-LAF (nLAF) ventilation systems remain unclear, as nLAF systems generate outlet-to-inlet multidirectional airflows of the air conditioning system. Here, we evaluate the effects of FAW on the airflow and sanitation quality in surgical fields with nLAF ventilation systems.

Methods: The airflow speed and direction were measured using a three-dimensional ultrasonic anemometer. Sanitation quality was evaluated by measuring the amount of dust particles after the activation of air conditioning.

Results: FAW caused no meaningful airflow (> 10 cm/sec) and did not diminish the sanitation quality in the surgical field separated by the anesthesia screen. Above the head area, the upward FAW airflow was not counteracted by nLAF, which caused an upward airflow at the edges of the operating table, originating from outside of the operating table and the floor.

Conclusions: Sanitation quality was kept under FAW working even in an nLAF-equipped OR. According to the inlet/outlet layouts of nLAF, the upward FAW-induced airflow in the head area was not counteracted, and the upward airflow from the floor induced by the air conditioner outlet could be detected.

1. Introduction

In operating rooms (ORs), laminar airflow (LAF) systems create a homogenous airflow with very little turbulence from the air conditioner outlet to the inlet. Particularly, in ORs with a vertical LAF system, downward airflows from air-conditioner outlets on the ceiling are exhausted via air-conditioner inlets near the floor. Contrarily, non-laminar airflow (nLAF) systems do not produce homogenous airflows; then, a mixed or turbulent flow is passed into the OR, where air, aerosols, and particles can be homogenized. However, cost-effectiveness analyses found that LAF systems are more expensive compared to nLAF systems. Cacciari et al. reported that LAF systems increased building costs by 24% and annual operating costs by 36% compared to the respective nLAF system costs.¹ In a model calculation study performed by Merollini et al., LAF systems required an additional cost of AUD\$ 4.59 million per 30,000 hip arthroplasties.²

To ensure a low infection rate in an ultra-clean air environment, the usage of LAF as an air conditioning system has been recommended

when performing surgery.³⁻⁶ The rate of reoperation or wound infection after artificial joint surgery in an LAF-equipped OR was reported to be smaller than that in an nLAF-equipped OR.⁷ Contrarily, Lidwell et al. reported that the use of prophylactic antibiotics was a more effective prevention method for development of joint sepsis after surgery than ventilation systems in the OR (1.6% under ultra-clean air without antibiotics versus 0.8% under a conventional airflow system with antibiotics).⁴ Thus, perioperative prophylactic antibiotics are thought to be the most potent prevention factor for the development of surgical site infections (SSI). However, in gastrointestinal surgery, the effectiveness of prophylactic antibiotics varies among different types of surgery, and some studies reported that antimicrobial prophylaxis was not observed.^{6,8,9} Additionally, the efficacy of LAF for SSI prevention was demonstrated under the gastric or vascular surgeries.^{5,6}

On the other hand, LAF operating theaters, long operating times, high hospital care volume, antibiotic-laden cement, and forced air warming (FAW) systems have been reported as surgical risk factors for SSIs.¹⁰ Additionally, the global guidelines of the world health

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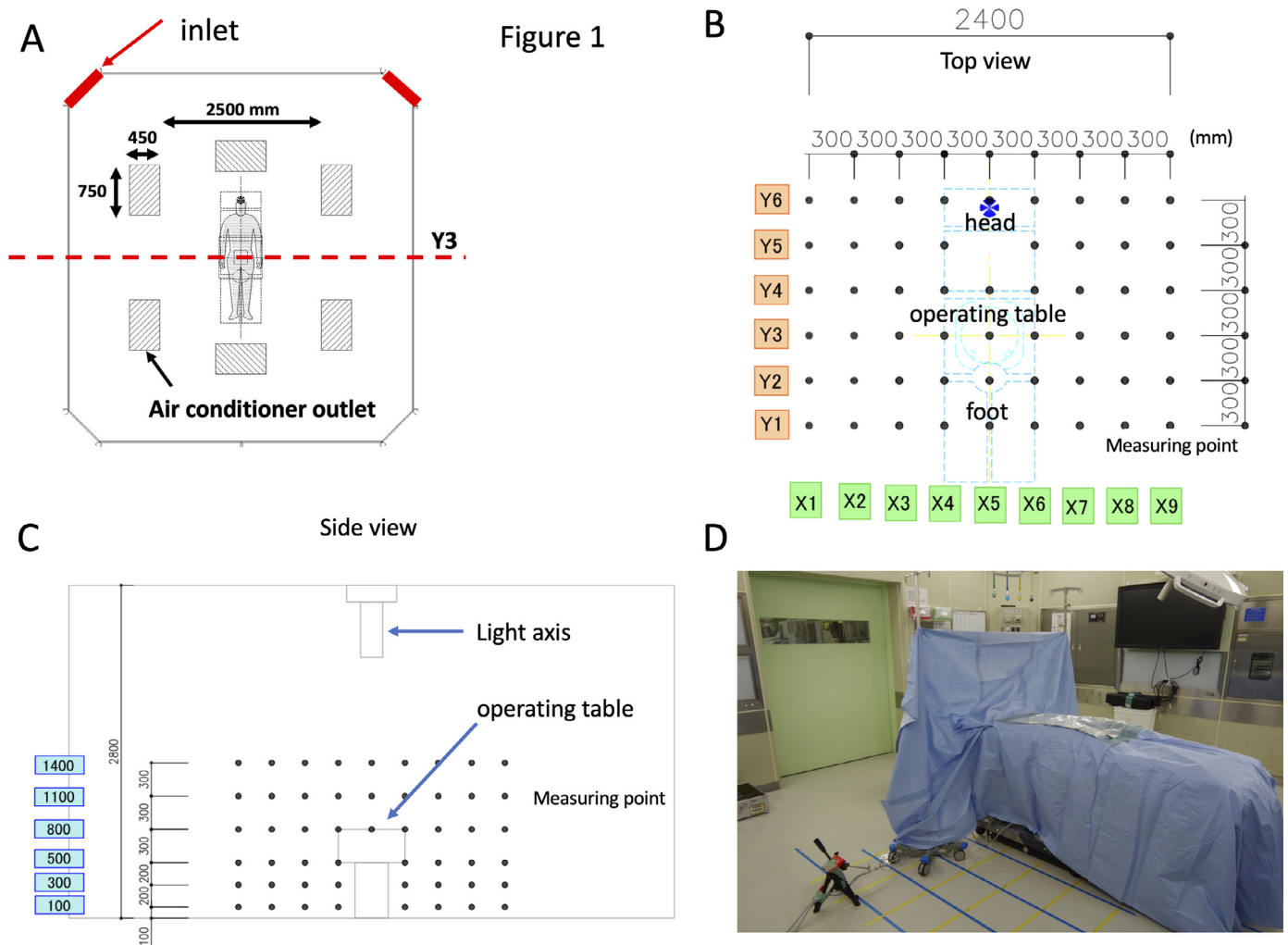


Fig 1. Experimental setup and airflow measurement points in the nLAF-equipped OR. (A) Top view. The slashed part indicates the air-conditioning outlet. (B) Top view of indicated measurement points. The floor was marked with tape every 300 mm. There were seven measuring points on the x-axis (X1–X9, with X5 in the center) and six measuring points on the y-axis (Y1–Y6). (C) Side view. There were four measuring points on the z-axis (100, 300, 500, 800, 1100, and 1400 mm from the floor). All measuring points were 300 mm apart. (D) An upper body manikin was placed supine on the operating table and covered with a warming blanket and a general surgical drape. The floor was marked with tape every 300 mm.

organization (WHO) for SSI prevention indicate that the use of LAF was not necessarily recommended for patients undergoing total arthroplasty surgery. These WHO 2016 guidelines were based on previous reports that showed that surgeries performed in LAF-equipped ORs resulted in increased SSIs and expenditures. This led to a reevaluation of the cost-effectiveness of this method and the risks of SSIs.^{2,11,12} It is expected that the number of ORs employing nLAFs will increase in the future. However, the benefit of using an LAF system for preventing SSIs remains controversial.

The safety of FAW systems is also controversial, although the active warming of patients during surgery is indisputably beneficial.^{13,14} In our previous study under an LAF system, the upward FAW airflow, above the head area, was completely counteracted by the LAF, and the FAW did not cause a meaningful airflow in the surgical site.¹⁵ However, the effect of the FAW airflow in an nLAF-equipped OR has not been reported to date. Therefore, we investigated the impact of FAW on the airflow and sanitation quality of an nLAF-equipped OR.

2. Methods

2.1. Airflow configuration

The study was performed in an OR within the Munakata Medical

Association Hospital, which is equipped with a vertical nLAF system. The airflow speed at the diffuser varies between 44 and 83 cm/s. The air is pre-filtered and then guided through ventilation ducts to the individual ORs. The OR used in the present study (height of 2.8 m, floor area of 27.9 m²) receives an airflow supply of 55 m³/min, resulting in 48 complete air circulation cycles per hour. The operating table (500 × 2080 mm) is surrounded by six air conditioner outlets (750 × 450 mm) that contain final point-of-use high-efficiency particulate air filters and two air inlets (Fig 1A).

We examined the airflow caused by FAW or nLAF in the presence of a surgical light, positioned above the operating table, via a three-dimensional measurement of the airflow direction and speed. A 3M Bair Hugger (Model 750; 3M Company, Maplewood, MN, USA) and a lower-body blanket (Model 585; 3M Company) were used as the FAW device, with the warming temperature set to 43°C. The air conditioning temperature in the OR was set to 25°C.

2.2. Three-dimensional measurement of airflow direction and speed

An upper-body manikin was placed in the supine position; a lower-body warming blanket was placed underneath it and was covered with a surgical drape (Fig 1D). A 3-dimensional ultrasonic anemometer (WA-790; Sonic Corporation, Tokyo, Japan) was used to measure the

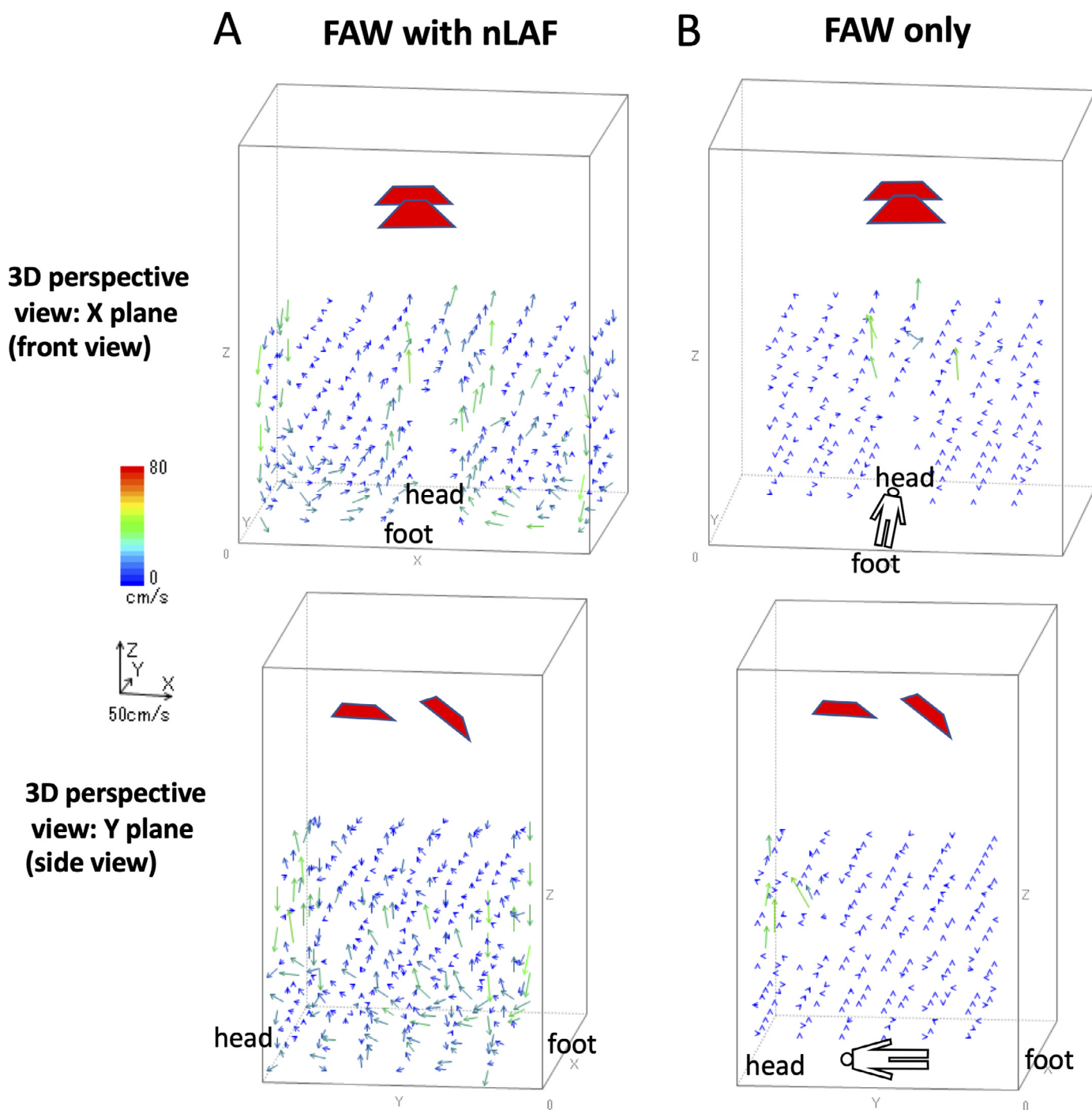


Fig 2. Three-dimensional schematic of the airflow direction and speed. Airflow caused by (A) FAW with nLAF and (B) FAW only. Top row: three-dimensional perspective view of the operating table from the feet. Bottom row: three-dimensional perspective view of the operating table from the side.

direction and speed of the airflow at intervals of 300 mm at 324 points ($9 \times 6 \times 6$): 9 points on the x-axis (in the right/left direction at 300 mm intervals with the cross-sectional point placed at point X4), 6 points on the y-axis (in the head or foot direction at 300 mm intervals with the head at point Y6), and 6 points on the z-axis [at 100, 300, 500, 800 (operating table height), 1,100 and 1,400 mm from the floor] (Fig 1B, C). A “meaningful airflow” is defined as an airflow under 10 cm/s.

2.3. Sanitation quality assessment

The sanitation quality was evaluated with a cleanliness recovery test during the use of the lower-body blanket. For this test, dust was

artificially generated in the surgical field with the nLAF turned off; then, the air conditioning was activated and the dust removal process was assessed.¹⁶ We performed measurements at the center and lateral edges of the operating table at the Y3 level (Fig 1B); three measurements were made at each height (800 mm and 1,500 mm) for 6 points. Using a particle counter (KC-03A; RION Co., Ltd., Tokyo, Japan), suction sampling was performed at a rate of 1 ft³/min to measure the number of dust particles with a grain size of $\geq 0.5 \mu\text{m}$. The air conditioning was turned on with an initial dust particle load of approximately 50,000 per cubic foot, and transitions in the number of dust particles were measured at 1 min intervals for 10 min. A comparison between the FAW running group [FAW (+)] and the FAW stop group

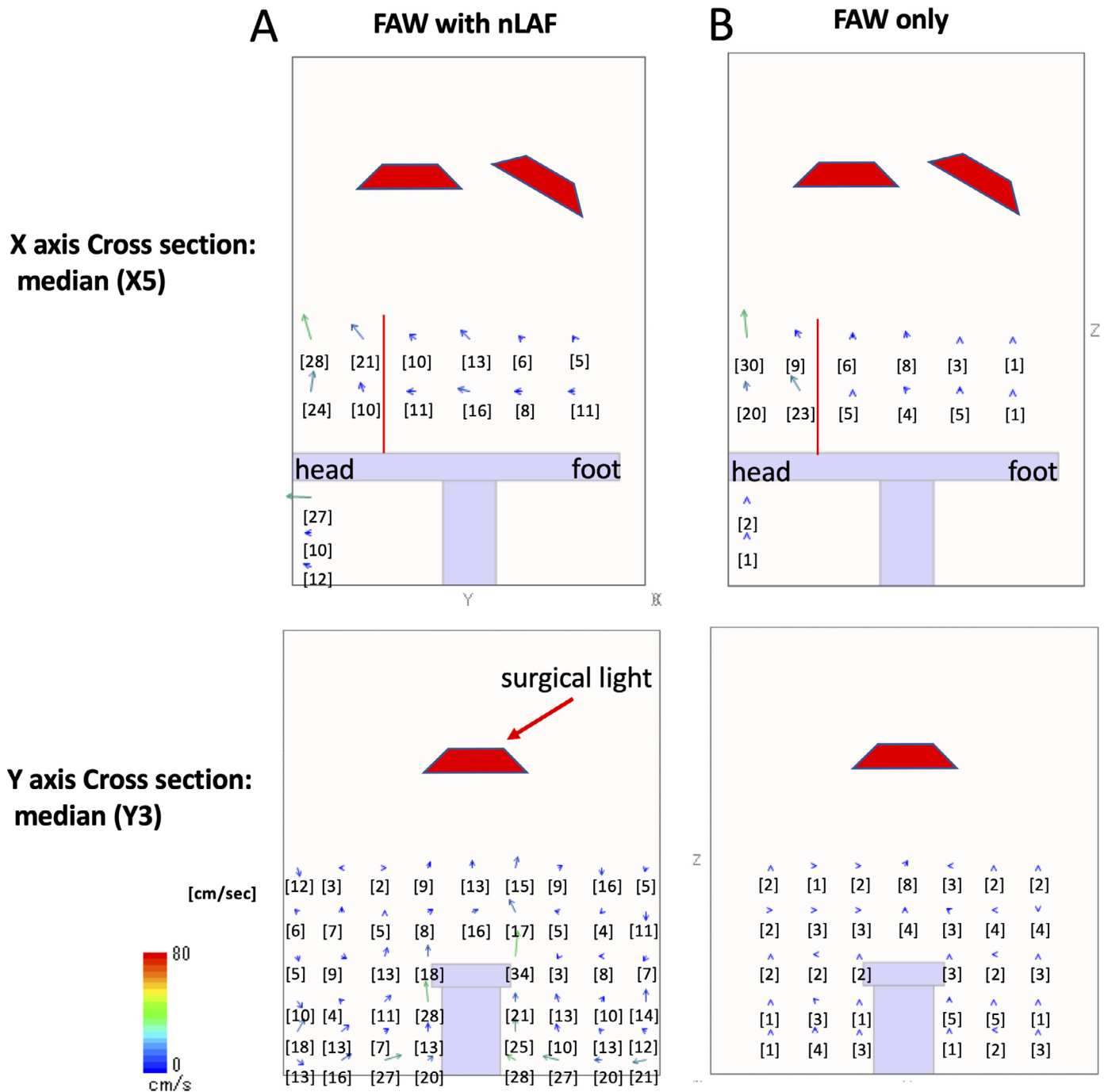


Fig 3. Airflow direction and speed at the cross section of the x-axis (upper: X5) and the y-axis (lower: Y3) caused by (A) FAW with nLAF and (B) FAW. The red trapezoidal shapes depict the surgical lights.

[FAW (-)] was performed.

2.4. Statistical analysis

The presented data are expressed as means and standard deviations. An unpaired t-test was conducted to compare the control levels between the FAW (+) and FAW (-) groups. A comparison between the two groups was performed via a two-factor repeated-measures analysis of variance (Fig 4B). The statistical analysis was performed using the Prism 6 software (GraphPad Software: La Jolla, CA, USA), where a p-value of $p < 0.05$ is considered statistically significant.

3. Results

3.1. Measurement of three-dimensional airflow by anemometry

Examination of the operating table from the right and foot sides showed that the nLAF-induced downward air current moved along the floor toward the operating table causing an upward air current on both sides of the table (Fig 2A). Contrarily, the FAW caused no meaningful airflow above or around the table (Fig 2B), except for the airflow around the head area.

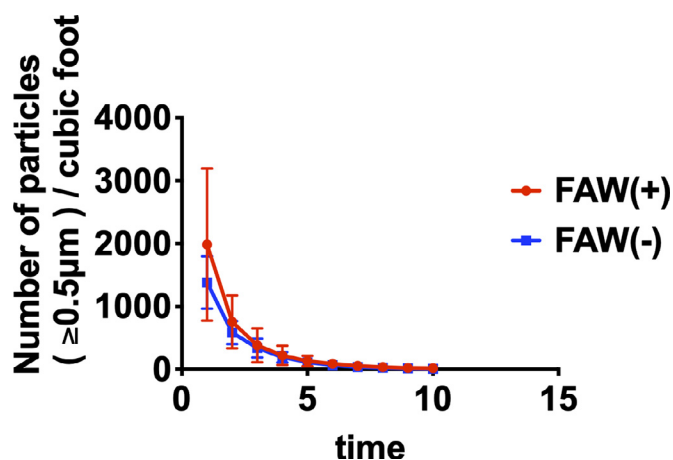


Fig 4. Comparison of cleanliness assessment between the FAW(+) and FAW(-) groups. Mean number of dust particles ($\geq 0.5 \mu\text{m}$) per cubic foot from 1 to 10 minutes. Red and blue data represent the FAW (+) and FAW (-) groups, respectively, with standard deviation indicated.

3.2. Measurement of cross-sectional airflow by anemometry

At the X5 point, an upward air current was detected directly above the manikin's head in the area separated by the anesthesia screen (9–30 cm/s) (Figs 3A and B, top row), regardless of the presence of the nLAF. The FAW caused no meaningful airflow above or around the operating table (Figs 3B, top and bottom row).

At the Y3 point, an air current (16 – 28 cm/s) was detected moving along the floor from the outside towards the operating table (Fig 3A, bottom row). An upward air current (18 – 34 cm/s) was detected at the edges of both sides of the operating table (Fig 3A, bottom row).

3.3. Cleanliness assessment

There was no significant difference in the number of dust particles per cubic foot before activation of the air conditioner, regardless of whether or not FAW was present [FAW (+): 52650 ± 1694 vs. FAW (-): 51289 ± 3667 , $p = 0.48$]. The number of particles per cubic foot 10 minutes after air conditioner activation was 17.2 ± 11.1 for FAW (+) and 9.8 ± 4.5 for FAW (-). There was no significant difference in the cleanliness recovery rate between the FAW (+) and FAW (-) groups (Fig 4).

4. Discussion

4.1. Airflow by FAW

This is the first study to investigate the FAW airflow under an nLAF system. It was found that FAW caused no meaningful airflow or disturbance of airborne cleanliness in the surgical field under the nLAF system. However, the FAW caused an upward air current above the head of the operating table, and nLAF could not counteract this upward air current. Our previous study revealed that the upward air current caused by the FAW was completely counteracted in the LAF-equipped OR, where the air-conditioner outlets were fully covered by the head area.¹⁵ In the OR used in this study, although vertical down airflow from the ceiling above the surgical field was not detected, the sanitary standard of the OR was adequate. This cleanliness in this OR could be mainly due to air circulation cycle times per hour.

4.2. Airflow by nLAF

The nLAF system used in this study created an upward air current on both sides of the operating table flowing along the floor, operating

table, and surgical drape. A downward air current from the air-conditioning inlets generated this upward air current on the ceiling. This phenomenon could be owing to the location or number of the air-conditioning inlets (Fig 1A). The OR used in this study has only two air-conditioning inlets in the corner of the room. Thus, the airflow from the ceiling creates neither a homogenous flow nor a laminar airflow and becomes stagnant. These results indicate the possibility of contamination of the surgical field from surrounding operating beds and the importance of the layout of the air-conditioner outlets.

4.3. SSI in ORs

Many interventions have been suggested to affect the micro-organisms in ORs. For example, infectious micro-organisms attached to microbial-laden dust, lint, squamous-cell skin, or respiratory droplets have been reported to float throughout ORs.^{17,18} Therefore, the removal of airborne particles and the maintenance of air quality in ORs is important for the prevention of SSIs. The use of shoe covers was reported to have no influence on the risk of SSIs or bacteria counts on the OR floor, and environmental surfaces are rarely implicated as sources of pathogens important in the development of SSIs.^{17,18} However, infectious micro-organisms can be attached to heavy objects lying on the floor. Recently, Guo et al. reported that coronavirus was more detected in the intensive care units (ICU) than in the general coronavirus disease ward and distributed on the floors (70%) in the ICU.¹⁹ Thus, situations in which the airflow is detected from the floor of the surgical site should be avoided. However, if the micro-organisms and bacteria are of considerable size, the contamination of large surfaces, such as floors, and the particle transfer throughout the surgical area should be measured and evaluated. The 0.5 micron size is the important standard size for determining if the environment is below or above the accepted level of particles for cleanroom standard. Additionally, most commonly bacteria size is over 0.5 micron, so particle size smaller than 0.5 is not critical issue, then we measured particles over the 0.5 micron. The sanitary standard of the OR used in this study was adequate, but potential contamination from the floor was expected because an air current from outside the operating table was detected at an airspeed between 16 and 31 cm/s. In almost all existing reports in which the air-conditioning type was found to be a risk factor for SSIs, the air-conditioning outlet layout or airflow in the OR was not discussed. If the airflow in the surgical field had been evaluated as a contributing factor, instead of the air-conditioning type, the conclusions in these reports might have been different.

4.4. Study limitations

A limitation of this study is that we could not evaluate the effect of upward airflows on both sides of the operating table and head area on the number of airborne particles in the surgical field. The detection of point-to-point particle movement is practically difficult because artificially generated dust particles are quickly diffused. Generating a fixed number of particles is also difficult. Belani et al. generated the illuminate neutrally buoyant detergent bubbles into the head area separated by anesthesia drape using by bubble generator and shifting bubbles were counted in the surgical site by photography.²⁰ They reported that the number of shifting bubbles into the surgical field originating from the head area was higher when the FAW was operative, but did not discuss the ventilation situation. However, the FAW-induced upward airflow detected in this study could possibly transfer the airborne from the head area to the surgical field or spread respiratory droplets to non-intubated patients. Nevertheless, further investigation is needed to address these concerns. Further, neither the operating staff nor the equipment around the operating table were included in this study. These factors could play a significant role on the airflow.

5. Conclusions

In this study, we demonstrated that the FAW caused no meaningful airflow (> 10 cm/sec) and did not diminish the sanitation quality in the surgical field. However, above the head area, the upward FAW-induced airflow was not counteracted by the nLAF system, which caused an upward airflow at the edges of the operating table, originating from outside of the operating table and along the floor. In ventilation systems similar to that of this study, particle transferring to the surgical field possibly occurred from the floor via the nLAF ventilation system or from the head area via FAW.

Declaration of Competing Interest

The authors report no conflicts of interest.

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