

A Novel Approach to Identifying How Equipment Disrupts the Airflow Patterns in the Operating Room

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Abstract: A decrease in the infection rates in the operating room (OR) is attributable to advances in sterile technique; heating, ventilation, and air-conditioning (HVAC) filtration; and limiting the number of people entering and leaving the OR. However, some infection complications after open heart procedures have been linked to the discharge fans of surgical equipment, most notably from the LivaNova 3T. We believe that surgical infection within the OR may also be due to other devices with internal fans. The purpose of this study was to 1) identify surgical equipment with an internal fan and see how they affect the airflow in an OR, 2) use the equipment to positively affect airflow to possibly reduce the risk of surgical site infections, and 3) bring attention to the HVAC system ability to exchange air throughout the OR. By

using a fog machine and multiple camera angles, we identified the devices that have an effect on the airflow. We saw that the direction of the intake vent of specific devices can change the direction of airflow and possibly help to remove air. Last, we showed how the current HVAC air exchange rate might not be enough to remove contaminated air within the OR. Understanding intake and discharge vents for all equipment is important because sterile contamination and wound infection may be minimized or mitigated completely by simply repositioning a few devices. **Key-words:** *Mycobacterium*, heater/cooler infections, sternal wound infections, surgical infections, airflow, vent exhaust, HVAC, return vents, intake vents, forced-air warm blowers. *J Extra Corpor Technol. 2021;53:130–6*

The hospital surgical department's heating, ventilation, and air-conditioning (HVAC) system has been extensively studied based on laminar airflow, doors opening and closing, movement of people, and use of filters or UV light (1–3,6,8,9,12,14–18). Every hospital is required to have the HVAC system validated annually. The Center for Disease Control (CDC) has specific infection control guidelines that cover how HVAC systems should be used within the hospital setting, especially air exchanges per hour (ACH). One important part of the CDC infection control guidelines is their statement that a hospital should prevent dust accumulation in the air duct grills and ventilation measures should “maintain ≥ 15 ACH, of which ≥ 3 ACH should be fresh air” (5). Other regulations, standards, or guideline recommendation agencies for HVAC properties and testing

include Testing, Adjusting, and Balancing Bureau (TABB); the American Society for HealthCare Engineering (ASHE); the American National Standards Institute (ANSI); and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). ASHRAE/ASHE/ANSI standards for operating rooms (ORs) are ≥ 20 ACH, of which ≥ 4 ACH should be fresh air (4).

However, the HVAC system is not the only area for possible contamination as noted by the FDA communication about the use of heater-cooler units (HCUs) in the OR and causing nontuberculous mycobacteria infections (7). The FDA recommends to “direct the exhaust vent away from the surgical field” as the rate of the HCU exhaust fan is strong enough to expel contaminants into the surgical field. The risk of infection from HCUs may be mitigated based on the design of the HCU or directing the exhaust outside of the OR (1,10,11). Also, the HCU is not the only source for possible contamination; forced-air warming blowers (FAWBs) are another source. FAWBs intake air directly from the ground level and force the air into a half body or full body blanket beneath or above the patient on the surgical table. Studies have shown that

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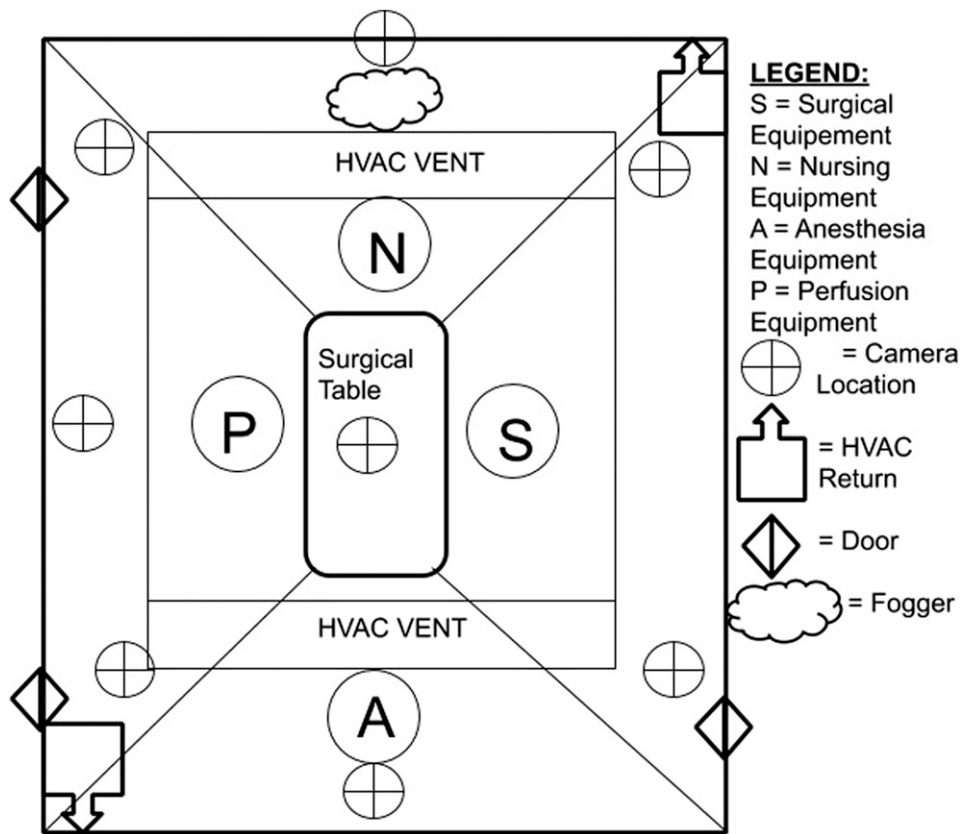


Figure 1. Outline of OR with how equipment was separated, camera locations, HVAC vents, and HVAC returns.

microbial buildup and emissions are very possible from these devices (1,12,13).

In recent news, the spread of SARS-CoV-2 (COVID) has made everyone take extra precautions to prevent contamination through constantly wearing a mask, wearing a face shield, social distancing, and self-quarantine. Hospitals have set up specific floors and strict ORs for COVID patients. We have become more aware of air transmission; however, we are not aware of the total number of devices that have internal fans and their potential to increase the risk of transmission, exposure, and surgical site infection when patients undergo surgical procedures.

We decided to study devices with internal fans and the HVAC unit in a single OR at our hospital to better understand airflow dynamics. Our hypothesis was that 1) identified surgical equipment with an internal fan affects the airflow in an OR, 2) the equipment can be used to positively affect airflow away from the surgical table and surgical area, and 3) the HVAC systems' exchange air rate is affected throughout the OR.

MATERIALS AND METHODS

All surgical equipment with an internal fan was placed in a positive pressure OR of the Bliss Wing at Hartford

Hospital located in Hartford, Connecticut. Figure 1 shows the location of cameras, room separation, and fogger. The room was separated into four groups: S = surgical equipment, N = nursing equipment, A = anesthesia equipment, and P = perfusion equipment. Table 1 has each device, listed in the groups in the following text: name, air flow rate in cubic feet per minute (CFM), and document I accessed to find whether or not the equipment has an internal fan.

Surgical equipment consisted of AtriCure Ablation and Sensing Unit (West Chester, OH), AtriCure ASU Switch Matrix, and O.R. Solutions, Inc. "Slush Maker" Model#ORS-1075HS (Chantilly, VA). All surgical equipment was placed perpendicular to the surgical table on the patient's right side.

Nursing equipment consisted of Olympus EVIS EXERA III CV-190, Olympus Optical Company high-flow insufflation unit UHI-2 (Japan), Olympus high-definition LCD monitor (Japan), Valleylab ForceTriad (USA), Valleylab Force FX-CS (China), and Arizant Healthcare Inc. Bair Hugger, FAWB Ref#77500 (Eden Prairie, MN). The FAWB unit was placed under the surgical table and attached to a half-body warmer on top of the surgical table, allowing air to flow directly up to the ceiling. The remaining equipment was positioned in a line perpendicular to the foot of the surgical table.

Table 1. Devices with internal fans and their corresponding airflow rate, if available.

Device	Rate (cfm)	Resource
AtriCure Ablation and Sensing Unit	Not available	IFU, OM
AtriCure ASU Switch Matrix	Not available	IFU, OM
O.R. Solutions, Inc. "Slush Maker" Model#ORS-1075HS	Not available	Not available
Olympus EVIS EXERA III CV-190	Not available	IM
Olympus Optical Company high-flow insufflation unit UHI-2	Not available	Specs.
Olympus high-definition LCD monitor	Not available	PB
Valleylab ForceTriad	Not available	BM
Valleylab Force FX-CS	Not available	UG, specs.
Arizant Healthcare Inc. Bair Hugger (FAWB)	48	SM
Belmont Instrument Rapid Infuser RI-2	Not available	OM
Philips EPIQ Diagnostic Ultrasound System	Not available	TM
CareFusion Alaris Pump model 8100	Not Applicable	UG
Edwards LifeSciences Vigilance II monitor	Not available	Specs.
CARESCAPE monitor 8850h CPU-CI	Not available	Tech. M.
3M Health Care 3M Ranger fluid warming unit	Not Applicable	OM
GE Medical Systems D19KT Display USE1921A	Not available	Tech. M.
Tripp Lite SMART700HG	Not available	OM
Datex-Ohmeda "Ventilator" S/5 Avance	High/Low	SM
CardioQuip Refrigeration Module for MCH-1000 (HCU)	Not available	OM
Cell Saver Elite	Not available	UG
Terumo Advanced Perfusion System 1	Not available	OM

IFU, information for use; BM, biomedical manual; OM, operating manual; UG, user guide/manual; IM, instruction manual; SM, service manual; Specs, specifications; TM, training manual; PB, product brochure; Tech. M., technical manual.

Anesthesia equipment consisted of Belmont Instrument Rapid Infuser RI-2 Ref#903-00037 (Billerica, MA), Philips EPIQ Diagnostic Ultrasound System Ref#989605488741, CareFusion Alaris Pump model 8100 (San Diego, CA), Edwards Lifesciences Vigilance II monitor Ref#VIG2 (Irvine, CA), CARESCAPE monitor 8850 CPU-CI (Mexico), 3M Health Care 3M Ranger fluid warming unit (St. Paul, MN), GE Medical Systems D19KT Display USE1921A Ref#2039143-001 (Freiburg, Germany), Tripp Lite SMART700HG, and Datex-Ohmeda "Ventilator" S/5 Avance Config Ref#1009-9002-000 (Madison, WI). The ECHO machine and blood warmer were placed parallel to the surgical table at the head of the table on the patient's left side. The remaining equipment was placed parallel to the head of the table on the patient's right side.

Perfusion equipment consisted of Terumo Advanced Perfusion System 1 with 4 roller pumps and system monitor Ref#801763 (Ann Arbor, MI), CardioQuip Refrigeration Module for MCH-1000 (M), HCU (Bryan, TX), and Cell Saver Elite (Braintree, MA). All equipment was perpendicular to the surgical table on the patient's left side. The HCU's four intake fans were facing the table. The cell salvage device airflow was facing the patient table.

Wing's Testing & Balancing Company, Inc., Branford, CT(19) used a Shortridge micromanometer for airflow and pressure measurements around the OR at two-time intervals, when all machines were off and when all machines were on. Airflow was measured at three different points in

each section during each interval, as seen in Figure 2. The calculation of ACH in Figure 3 was completed using the calculation from TABB in Figure 4.

Wing's Testing & Balancing Company, Inc.(19) used a Fogger ADJ VF1300 that creates smoke from a water-based American DJ Fog Juice at a factory set rate of 12,000 CFM equal to 1,500 feet per minute (FM) at 12 inches from discharge (ADJ). The fogger was set on top of a pole opposite to the anesthesia section. To capture the most views, we set up eight cameras around the room. The cameras consisted of the following: iPhone 10x, Canon PowerShot SX30IS, Samsung Galaxy S7, Canon EOS 7D, Huawei P20 Pro, iPhone 8, Nikon D7200, and Canon PowerShot A530. Fog was emitted for 3 seconds by remote control after everyone left the OR and the door to the OR had remained closed for 15 seconds. Video was captured at the following intervals: 1) baseline: no equipment was turned on, 2) surgical: only equipment was turned on, 3) nursing: only equipment was turned on, 4) anesthesia: only equipment was turned on, 5) perfusion: only equipment was turned on, 6) all surgical equipment was turned on, and 7) fogger moved opposite of surgical equipment, 8) fogger moved opposite of perfusion equipment, and 9) HCU was only moved so that intake vents faced the surgical table. In summary, a minimum of nine videos, 1 minute long, from each camera were taken, totaling 72 minutes of video recordings. The videos were edited to show only the fogger discharge and clearance, and labeled based on camera and captured interval.

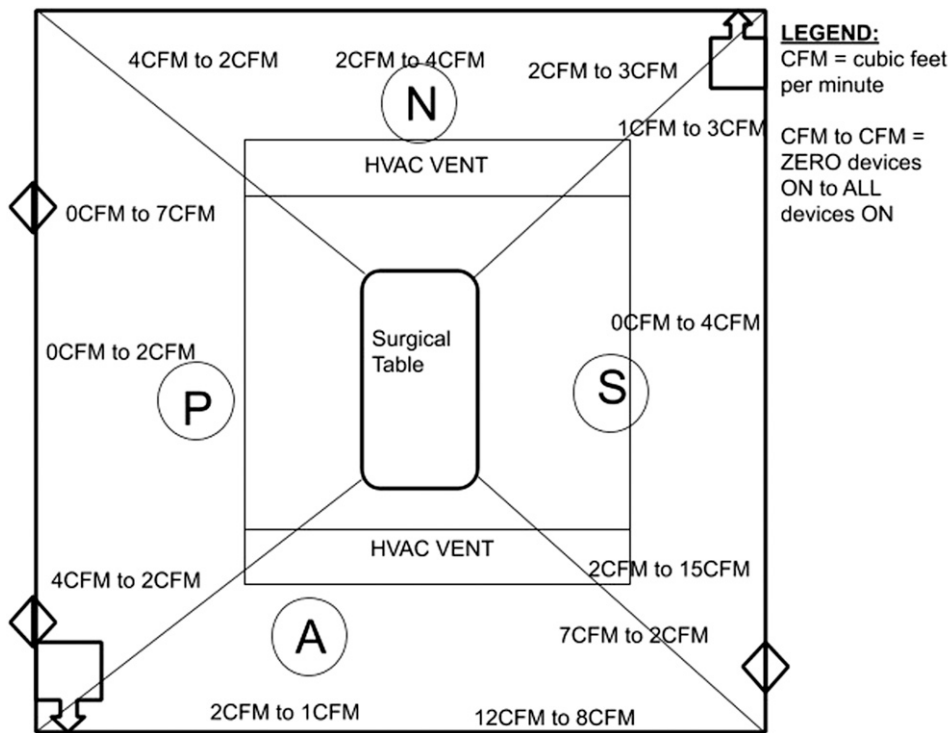


Figure 2. Change in airflow from baseline to all equipment on in each section of the OR. The perfusion and surgical areas where airflow was 0 CFM increased to 2–7 CFM when the devices were on, showing the effect internal fans have on the airflow within the OR. Most areas showed an increase in CFM; however, the areas where CFM decreased, mainly around the doors, depict how the internal fans compete against negative pressure from outside the OR.

RESULTS

The airflow rate in the room was tested at baseline and all surgical equipment turned on (Figure 2). The airflow rate changed based on equipment location and being turned on. We measured and calculated the OR to have a total of 1,651 CFM equal to 20.7 ACH (Figure 3). The fresh air exchange was later calculated for the entire hospital system of the operating department to be ≥ 4 ACH. The total CFM did not change when all equipment was turned on. The OR return vents were at zero CFM (surgical corner) and 148 CFM (perfusion corner), as seen in Figure 3. The airflow rate out of the room at the bottom of each door was roughly 500, 500, and 550 CFM (Figure 3). The HCU air rate was measured at the two intake vents for 50 FM and four intake vents for 82 FM. The HCU air rate measured at the discharge vents was 168 FM on the left and 159 FM on the right when facing the two intake vents. Table 1 shows all the OR equipment with internal fans and whether information is available on the airflow rate of the fan.

In the videos of the surgical equipment, no difference was noted between baseline and all equipment turned on.

In the videos of nursing equipment only the FAWB with a 48 CFM or 23L/sec airflow rate affected the air over the patient table. However, fog was still able to travel over the patient table: just a smaller amount than that seen at baseline.

In the videos of anesthesia equipment only, the fog was removed from the area faster than at baseline; however, not one single equipment could be identified as the reason for the faster airflow.

In the videos of perfusion equipment only, fog passed over the patient table; however, some of the fog was seen being pulled into the HCU area.

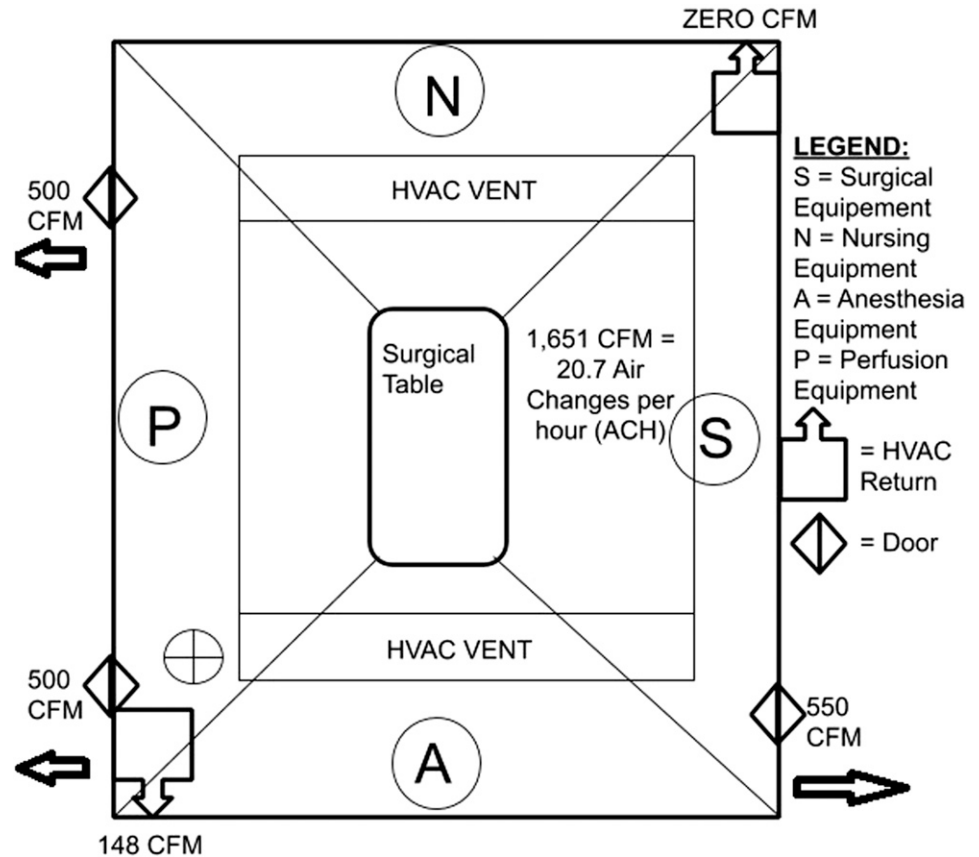
In the videos where all the equipment is turned on, fog is perceived to be removed from the room at a faster rate. The FAWB seemed to disperse the fog and allow for the HCU to pull the fog into the perfusion section and return vent easier.

In the videos where the fogger was in the surgical section, as the fog is seen traveling toward the patient table, it swirls above the table and most of the fog seems to cross over the table. The fog that crosses over is pushed up toward the ceiling: some is pulled down to the HCU, whereas most is held up on the ceiling and not removed from the room.

In the videos where the fogger was in the perfusion section, as the fog is seen traveling toward the patient table, it swirls above the table, and only a small portion crosses over. Most of the fog is pulled over to the anesthesia side of the room, and more fog is seen recirculating above the patient table.

In the videos where the HCU is moved to have four intake vents facing the patient table, it seems that more fog is pulled into the HCU area. The fog is then removed from

Figure 3. Airflow rate for the OR, return vents, and base of the doors. The OR had an exchange rate of 20.7 ACH. The base of the doors showed the strength of the negative pressure being applied outside of the OR, depicted by the arrows. The return vents show the airflow taken in by the air handling system of the operating department.



the OR in the same manner as in the video, with all the OR equipment on.

DISCUSSION

The CDC recommends that a hospital ventilation system should “maintain ≥ 15 ACH (air changes per hour), of which ≥ 3 ACH should be fresh air(4), and ANSI/ASHRAE/ASHE recommend ACH ≥ 20 , of which ≥ 4 ACH should be fresh air (5). The HVAC system in our institution was measured to have 20.7 ACH (Figure 2), well above the recommended level for an OR, and the fresh air exchange, later calculated, for the hospital was ≥ 4 ACH. The fog machine, at a preset factory rate of 12,000 CFM, was able to overcome the HVAC system and completely pass through both fields being created by the discharge vents. In the baseline video with no equipment on, fog passed over the surgical table and was pulled into the return vent located between the anesthesia and perfusion section. We can hypothesize from this video that the exhaust vents do not help remove the air in the surgical area as much as the return vent. In fact, in the video where we moved the fogger to the surgical side, we showed stagnant areas in the OR where air can linger for longer periods of time. We are

able to show that the return vent is as important as the location and direction of the exhaust vents. The stagnant areas may increase the opportunity for contamination of sterile fields or where the fog was seen being held up at the ceiling may increase the chance of surgical site infection.

Using all equipment with an internal fan to help direct and remove air is important to reduce the chances of contaminating sterile fields. However, healthcare providers should take extra care in cleaning equipment with an internal fan. HCUs’ exhaust should be kept at an acceptable distance to prevent exhaust airflow from coming in contact with a provider’s face or eyes and the surgical table. We should make sure to clean visible and hidden exhaust ports on all devices with internal fans. For instance, our perfusion monitor has an intake vent on the back panel and an exhaust port on the bottom panel.

When we compare Figures 2 and 3, we see that having all of the OR equipment on changes the airflow around the OR. Pockets in the OR where there was 0 CFM increased and distributed more airflow around the room. In the Perfusion section, perfusion equipment helped to increase CFM and reduce the risk of stagnant air. In the Surgical section, the 0 CFM increased, which may be due to the change in room dynamic, and should be a concern when setting up and trying to maintain a sterile area. However, in

Air Flow formulas

CFM = Duct area sq ft x Velocity
(Mercury)

Standard Air= 70F @ 29.92" HG

1 cubic foot of standard air = 0.075 pounds **13.3 cubic feet of standard air** = 1 pound

FAN LAWS:

Remember RPM is interchangeable for CFM
Note: new is the same as 1 and old is the same as 2

Fan Law #1

$$\left(\frac{CFM_{new}}{CFM_{old}}\right) = \left(\frac{RPM_{new}}{RPM_{old}}\right)$$

Formulas for problem solving

$$CFM_{new} = CFM_{old} \times \left(\frac{RPM_{new}}{RPM_{old}}\right) \quad RPM_{new} = RPM_{old} \times \left(\frac{CFM_{new}}{CFM_{old}}\right)$$

Fan Law #2

$$\left(\frac{CFM_{new}}{CFM_{old}}\right)^2 = \frac{SP_{new}}{SP_{old}} \quad \text{Or} \quad \left(\frac{CFM_{new}}{CFM_{old}}\right) = \sqrt{\frac{SP_{new}}{SP_{old}}}$$

Formulas for problem solving

$$CFM_{new} = CFM_{old} \times \sqrt{\frac{SP_{new}}{SP_{old}}} \quad SP_{new} = \left(\frac{CFM_{new}}{CFM_{old}}\right)^2$$

Fan Law #3

$$\left(\frac{CFM_{new}}{CFM_{old}}\right)^3 = \frac{BHP_{new}}{BHP_{old}} \quad \text{Or} \quad \frac{CFM_{new}}{CFM_{old}} = \sqrt[3]{\frac{BHP_{new}}{BHP_{old}}}$$

Formulas for problem solving

$$CFM_{new} = CFM_{old} \times \sqrt[3]{\frac{BHP_{new}}{BHP_{old}}} \quad BHP_{new} = BHP_{old} \times \left(\frac{CFM_{new}}{CFM_{old}}\right)^3$$

Volume calculations:

$$\text{Air Changes Per Hour} = \frac{CFM \times 60}{\text{Cubicfeet}}$$

$$CFM = \text{Room Volume} \times \frac{\text{AirChangesperhour}}{60}$$

the Anesthesia section, CFM decreased in certain areas as the anesthesia equipment competed against the negative force from under the door. Understanding the airflow dynamics of the OR will help with planning how to best set up a room to minimize competition of devices, increase return vent exchange, and help prevent any pathogen from lingering in the air of the OR for longer.

Another reason for understanding airflow can be seen in all videos where the fog was sent perpendicular to the exhaust vents over the patient table. The fog was able to pass from one side of the room to the other and was only prevented from reaching the ceiling because of the exhaust vents. Comparatively, when the fog was sent parallel to the exhaust vents, from the surgical and perfusion side, the

FAWB was able to push the fog up to the ceiling where the fog was able to stay longer due to limited airflow. In other words, the direction in which a pathogen is expelled from a device may increase or decrease the risk of contamination.

When comparing the difference in airflow based on positioning of the fogger, we saw that fog traveling from the perfusion side was stopped at the patient table and directed toward anesthesia; however, fog traveling from the surgical side was lifted above the patient table and either stayed near the ceiling or was pulled down toward the HCU. The FAWB had the greatest effect on airflow over the surgical table by directing upward, dispersing, or recirculating the fog. The recirculation part is crucial when the FAWB is positioned above the sterile field because this may increase

Figure 4. Airflow formulas provided by Testing, Adjusting, and Balancing Bureau.

the risk of surgical site infection. The HCU can be seen directing fog toward the intake sides of the machine, although the effect was not as great as a FAWB. The HCU has four intake vents on the north side and two intake vents on the south side, with discharge vents on the east and west sides. The intake vents are automatically adjusted and can change the strength of the air rate at certain time periods. However, the HCU and FAWB effects on airflow were shown to be compounded when both devices were on.

One unexpected find for us was that the ultrasound equipment and Haemonetics cell saver have three internal fans that are automatically adjusted at different speeds. Based on the videos, the exhaust vents could be positioned toward the OR return vent to help facilitate air removal and help maximize the exchange of all air in the room. At the same time, because of the uncertainty when all three fans will be on, we are unable to predict when the cell saver or ultrasound would have the least or greatest effect and should be positioned more for air removal. This was a preliminary study and will need further research to validate findings.

Our next study would entail a mock sterile surgical field with a mock patient on the surgical table prepped and draped. All surgical equipment and sterile fields would be moved to their corresponding locations to the table as if a procedure is going on. The fogger would be placed one foot above the surgical table at each wall of the room to see the effect each section has on the airflow. Then, the fogger would be placed at the same spot at each wall, except on the ground to see the effect devices have on airflow at the ground level. We recommend that at minimum, the FAWB be placed under the patient and secured under the sterile drapes to prevent air from reaching the sterile field. We also recommend that all exhaust vents be pointed toward a return vent in the OR, or, at minimum, have all intake vents pointing toward a sterile field to help direct air away from those areas.

Limitations

The OR where the study was conducted is an older positive pressure version and does not have a new HVAC system setup. The OR only had one working return vent. We did not have an opportunity to test a negative pressure OR. Most part of the study was only completed with the fogger on a single side. We were not able to collect evidence of the airflow below the patient table. We used personal devices to record the study, and not all of the videos are equal in quality or size. We did not collect the air rate of all devices with internal fans. We had a limited budget, location, and time frame to conduct the research. We were not able to collect data on the amount of air particles being passed through each equipment within the OR. We were not able to collect biological samples from each equipment to see if they contained possible contaminants.

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REFERENCES

1. Albrecht M, Gauthier RL, Belani K, et al. Forced-air warming blowers: An evaluation of filtration adequacy and airborne contamination emissions in the operating room. *Am J Infect Contr.* 2011;39:321–8.
2. Aliabadi AA, Rogak SN, Bartlett KH, et al. Preventing airborne disease transmission: Review of methods for ventilation design in health care facilities. *Adv Prev Med.* 2011;2011:124064.
3. Andersson AE, Bergh I, Karlsson J, et al. Traffic flow in the operating room: An explorative and descriptive study on air quality during orthopedic trauma implant surgery. *Am J Infect Contr.* 2012;40:750–5.
4. ASHRAE. Ventilation of health care facilities. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. ANSI/ASHRAE/ASHE Standard 170-2017: 1–42.
5. CDC. Guidelines for Environmental Infection Control in Health-Care Facilities. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. 2003:132–9.
6. Eames I, Shoaib D, Klettner CA, et al. Movement of airborne contaminants in a hospital isolation room. *J R Soc Interf.* 2009;6(Suppl 6):S757–66.
7. FDA. Nontuberculous *Mycobacterium* Infections Associated with Heater-Cooler Devices: FDA Safety Communication. 2015.
8. Griffiths WD, Bennett A, Speight S, et al. Determining the performance of a commercial air purification system for reducing airborne contamination using model micro-organisms: A new test methodology. *J Hosp Infect.* 2005;61:242–7.
9. Kakwani RG, Yohannan D, Wahab KH. The effect of laminar air-flow on the results of Austin-Moore hemiarthroplasty. *Injury.* 2007;38:820–3.
10. Kuehl R, Banderet F, Egli A, et al. Different types of heater-cooler units and their risk of transmission of *Mycobacterium chimaera* during open-heart surgery: Clues from device design. *Infect Control Hosp Epidemiol.* 2018;39:834–40.
11. Ogunremi T, Taylor G, Johnston L, et al. *Mycobacterium chimaera* infections in post-operative patients exposed to heater-cooler devices: An overview. *Can Comm Dis Rep.* 2017;43:107–13.
12. van Doremalen N, Morris DH, Holbrook MG, et al. Aerosol and surface stability of HCoV-19 (SARS-CoV-2) compared to SARS-CoV-1. *N Engl J Med.* 2020;382:1564–1567.
13. Reed M, Kimberger O, McGovern PD, et al. Forced-air warming design: Evaluation of intake filtration, internal microbial buildup, and airborne-contamination emissions. *Am Assoc Nurse Anesth.* 2013;81:275–80.
14. Rezapoor M, Alvand A, Jacek E, et al. Operating room traffic increases aerosolized particles and compromises the air quality: A simulated study. *J Arthroplasty.* 2018;33:851–5.
15. Rosemurgy A, Whitaker J, Luberic K, et al. Cost-benefit analysis of reducing surgical site infections. *Am Surg.* 2018;84:254–61.
16. Singh S, Reddy S, Shrivastava R. Does laminar air flow make a difference to the infection rates for lower limb arthroplasty: A study using the national joint registry and local surgical site infection data for two hospitals with and without laminar air flow. *Eur J Orthop Surg Traumatol.* 2017;27:261–5.
17. Stauning MT, Bediako-Bowan A, Andersen LP et al. Traffic flow and microbial air contamination in operating rooms at a major teaching hospital in Ghana. *J Hosp Infect.* 2018;99:263–70.
18. Klingenberg S. Smoke studies: Clearing the mystery of air flow visualization. *J Validation Technol.* 2010:11–7.
19. Wing's Testing & Balancing Company, Inc. 94 North Branford Road, Suite 1. Branford, CT.