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Major Article

Operating room air delivery design to protect patient and surgical site results in particles released at surgical table having greater concentration along walls of the room than at the instrument tray

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Background: During the coronavirus disease 2019 (COVID-19) pandemic, recommendations have included that personnel not involved in procedures releasing airborne contaminants reduce their exposure by moving >2 m away. We tested whether air particle concentrations in operating rooms (ORs) are greater in the periphery, downstream from the supply airflow.
Methods: We analyzed data from 15 mock surgical procedures performed in 3 ORs. Two ORs were modern, one with a single large diffuser system above the surgical table, and the other using a multiple diffuser array design. An air particle counting unit was located on the instrument table, another adjacent to an air return grille.
Results: Concentrations of air particles were greater at return grille than instrument table for the single large diffuser at 26 air exchanges per hour, and the multiple diffuser array at both 26 and 20 air exchanges per hour (all $P \leq .0044$), including during electrocautery (all $P \leq .0072$). The ratios of concentrations, return grille versus instrument table, were *greater* during electrocautery for 0.5 to 1.0-micron particles and 1.0 to 5.0-micron particles (both $P < .0001$).
Conclusions: Modern OR airflow systems are so effective at protecting the surgical field and team from airborne particles emitted during surgery that concentrations of particles released at the OR table are greater at the OR walls than near the center of the room.

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INTRODUCTION

During the coronavirus disease 2019 (COVID-19) pandemic, there have been recommendations of safe distances from other people (eg, 2 m), including within operating rooms (ORs).[1] Distancing is a theme of public conversation,[2] including during tracheal intubation and/or extubation, and other aerosol generating procedures, when personnel cannot safely or practically leave the room.[3-7] (See Google search at https://FDshort.com/WagnerAirParticles). Inside ORs, is exposure to pathologic airborne particles (eg, potentially SARS-CoV-2) less when people stand or sit farther from the patient?[3-7] When an anesthesiologist intubates or extubates the patient, or surgical smoke is produced,[8] would others in the room be safer by moving away (eg, complete their charting at a computer along a wall)?

OR air handling systems are designed to move particles away from the surgical field. These are particles that were generated (eg, surgical smoke) or exhaled or shed by patients, surgeons, anesthesiologists, etc.[9] Some ORs have a single large diffuser system in the ceiling above the surgical field.[10] Particle tracing studies show that single large diffusers help to prevent particles from settling into the wound by sweeping them downward and away toward the periphery of the OR.[10] (See Supplementary Fig 1 at https://FDshort.com/WagnerAirParticles.) Thus, moving physically in the OR away from the surgical table toward the walls may *increase* personnel exposure to higher concentrations of airborne contaminants. That would be a consequence of how contemporary ORs are designed to prevent surgical site infection.[9]

We are unaware of studies testing this relationship for airborne particles; the hypothesis, that moving to a corner of the OR furthest away from the patient would result in greater exposure to airborne contaminates, is based on airflow.[11-13] However, the authors recognized that experimental data from 2018 could be reanalyzed to estimate relative concentrations of airborne particles between the surgical field and periphery of the operating room at air registers.[14] We hypothesized greater concentrations in the periphery than at their source at the OR table.

METHODS

In January 2018, mock surgical procedures were performed in 3 fully functional ORs regularly used.[14] Two of the ORs were constructed at the same time in 2017. One OR had a single large diffuser[10] system in the ceiling above the surgical table. The other new OR used a multiple diffuser array design[10] above the OR table. The 55 m^2 ORs were the same except for the configuration of air delivery.[14] Both rooms had positive pressure, 26 air changes per hour, and high-efficiency particulate air filtration using 4 low-wall return grilles.[14] The single large diffuser was constructed with 9 diffusers coincident to one another, 2.35 m by 2.95 m total dimension.[14] The multiple diffuser array design had 6 diffusers each 1.17 m by 0.575 m, separated by hard ceiling surfaces and ceiling-mounted equipment.[14]

The original study was conducted to compare performance of different airflow designs at protecting the surgical field.[14] The 2 new ORs were compared to a third, older, room constructed in 1992, with a 4-way throw diffuser system.[14] Each of the four diffusers was 0.109 m^2.[14] The room was 44.3 m^2 in dimension.[14] There were 2 low wall return grilles. There was no air distribution directly over the surgical table and sterile field as required by current ASHRAE 170 Guidelines.[10].

The mock surgical procedure was designed for analyzing multiple environmental quality indicators within ORs.[15] An air particle counting unit was located at the instrument table along the foot of the surgical table.[15] That unit was 2.5 m from the midpoint of the head of the bed, 7.9 m from the return grille in the 2 new ORs, and 7.1 m from the return grille in the older OR. The Aerotrak particle counter model 9500 (TSI Incorporated) sampled at 100 L of air per minute. A second stationary particle counter was located on a pedestal in front of one of the return air grilles.[14] The script and timeline were displayed on monitors showing responsibilities in 4-minute increments for each person in the OR during a 1-hour mock procedure.[15] The script included gowning, gloving, draping, passing instruments, personnel entering and leaving the room, and the use of electrocautery on an uncooked steak to generate particulate surgical smoke.[15] The steaks were positioned 1.6 m from the air particle counting units on the instrument tables, 6.4 m from the units at the return grilles in the 2 modern ORs, and 6.1 m from the units at the return grille of the older OR. For diagrams of the ORs, see Supplementary Figs 2-4 at https://FDshort.com/WagnerAirParticles.

Study personnel wore standard hospital-issued scrub attire, head covers, surgical masks, shoe covers, and scrubbed for the procedure per protocol.[15] There were 10 people in the ORs including surgeon, 4 surgical nurses, script timekeeper, microbiologist, industrial hygienist, and 2 indoor environmental engineers.[14] The script included the multiple measurements to be made including airflow, humidity, temperature, pressure, air velocity, particle, and bacterial counts, all reported in the original paper.[14] Electrocautery, patient warming device, all computers and monitors, lights, and insufflator all were "on" throughout the mock procedures to result in realistic airflows. In addition, besides the circulating nurse and the "runner" exchanging petri dishes for bacterial sampling, other personnel remained in stationary positions while performing the simulated procedure, including passing of instruments, movement of light booms, etc.

The 2 stationary particle counters recorded particle counts over each 2-minute increment. Particle sizes recorded were ≥0.5 microns, ≥1.0, ≥5.0, and ≥10.0 micron-sized particles per cubic meter. There were 28 consecutive measurements at 2-minute increments starting at the second minute of the mock surgical case.

The OR with the single large diffuser had 2 mock surgical cases per day for 3 consecutive days, one case with 26 air exchanges per hour and the other case with 20 air exchanges per hour. The same 6 cases were done in the room with the multiple diffuser arrays. Finally, the older OR with 4-way throw diffuser system had 3 cases on 3 consecutive days, all with 26 air exchanges per hour. Each day, there was a random sequence of the 5 combinations of ORs and air changes.

Statistical methods

This analysis was unplanned when the study was conducted. The sample size was finite, experiments already completed.[14,15] Therefore, we treated $P < .01$ as the criterion for statistically significant differences, used nonparametric analyses, and interpreted the results conservatively in the Discussion and Conclusions, limiting statements to "greater." The principal issue for managerial decision-making is different, specifically whether concentrations of airborne particles are comparable at the periphery of the operating room.

Longitudinal analyses of airborne particulate concentrations generally are studied using 2-parameter log-normal distributions.[16] Rumburg et al compared fits of 7 probability distributions to airborne particulate concentrations.[17] From their Table 4, none of the other 5 probability distributions consistently performed better.[17] We calculated ratios of pairwise measurements of particle concentrations, adjacent to return grille/instrument table. As expected for log-normal distributions, we too found that probability distributions of ratios were more symmetric than differences, and thus analyzed ratios. However, the logarithms of ratios were not normally distributed due to substantive kurtosis (Shapiro-Wilk $P < .0001$). Therefore, in Tables 1 and 2, we used Wilcoxon signed-rank tests for pairwise comparisons (ie, ratios differing than 1.0). We report medians and interquartile ranges, with the percentiles calculated using the STATA *summarize* function (STATA 16.1, College Station, TX). In the Results,

Table 1
Ratios of air particles' concentrations between return grille and instrument table: median (25th percentile, 75th percentile) and results of Wilcoxon signed-rank test

Room type	≥0.5 microns, <1 micron	≥1.0 micron, <5 microns	≥5.0 microns, <10.0 microns	≥10.0 microns
Multiple diffuser array, 26 air exchanges per hour, N = 84, 2-minute periods	1.42 (0.93, 4.52), $P < .0001$	1.44 (1.00, 3.20), $P < .0001$	1.67 (1.29, 2.05), $P < .0001$	1.62 (1.31, 1.93), $P < .0001$
Single large diffuser, 26 air exchanges per hour, N = 84, 2-minute periods	1.16 (0.84, 1.54), $P = .0044$	1.18 (0.90, 1.49), $P < .0001$	1.55 (1.31, 1.78), $P < .0001$	1.70 (1.40, 2.05), $P < .0001$
Multiple diffuser array, 20 air exchanges per hour, N = 84, 2-minute periods	1.13 (0.90, 2.07), $P < .0001$	1.16 (0.95, 1.77), $P < .0001$	1.42 (1.15, 1.58), $P < .0001$	1.43 (1.22, 1.68), $P < .0001$
Single large diffuser, 20 air exchanges per hour, N = 84, 2-minute periods	1.05 (0.87, 1.25), $P = .022$	1.03 (0.92, 1.17), $P = .068$	1.18 (1.05, 1.44), $P < .0001$	1.36 (1.16, 1.61), $P < .0001$
Older, 26 air exchange per hour, N = 84, 2-minute periods	0.89 (0.76, 1.10), $P = .0016$ *	0.91 (0.77, 1.05), $P = .0021$ *	1.15 (0.94, 1.33), $P < .0001$	1.20 (1.03, 1.40), $P < .0001$

*Two-sided *P* value shows result for the opposite of the hypothesized relationship that there would be greater concentration at air return grilles than at the instrument table (ie, at the surgical table).

Table 2
Ratios of air particles' concentrations between return grille and instrument table, limited to periods with use of electrocautery, with same format as Table 1

Room type	≥0.5 microns, <1 micron	≥1.0 micron, <5 microns	≥5.0 microns, <10.0 microns	≥10.0 microns
Multiple diffuser array, 26 air exchanges per hour, N = 24, 2-minute periods	4.46 (2.01, 6.47), $P < .0001$	2.86 (1.79, 4.03), $P < .0001$	1.95 (1.52, 2.16), $P < .0001$	1.55 (1.32, 1.92), $P < .0001$
Single large diffuser, 26 air exchanges per hour, N = 24, 2-minute periods	1.30 (0.89, 1.78), $P = .0072$	1.25 (0.88, 1.68), $P = 0.0087$	1.50 (1.35, 1.69), $P < .0001$	1.72 (1.40, 2.00), $P < .0001$
Multiple diffuser array, 20 air exchanges per hour, N = 24, 2-minute periods	2.89 (1.75, 5.12), $P < .0001$	2.21 (1.61, 3.10), $P < .0001$	1.59 (1.47, 1.93), $P < .0001$	1.43 (1.23, 1.68), $P < .0001$
Single large diffuser, 20 air exchanges per hour, N = 20, 2-minute periods	1.25 (1.06, 1.76), $P = .0020$	1.13 (0.94, 1.25), $P = .070$	1.18 (1.01, 1.39), $P = .0083$	1.46 (1.11, 1.65), $P = .0001$
Older, 26 air exchange per hour, N = 16, 2-minute periods	0.92 (0.65, 1.14), $P = .23$ *	0.89 (0.71, 1.01), $P = .058$ *	1.09 (1.00, 1.29), $P = .034$	1.19 (1.00, 1.38), $P = .0042$

*Two-sided *P* value is for opposite of hypothesized relationship that there would be greater concentration at air return grilles than at the instrument table (ie, at the surgical table).

we also use the Wilcoxon-Mann-Whitney test to compare ratios during versus not during electrocautery. All *P* values were 2-sided and exact.

There could be a time lag between particle measurements between instrument table and return air grille. For both <1.0-micron and ≥10-micron particles, the observed Kendall's τ_b and Pearson r correlations were greater for no lag versus lag 1 (ie, 2 minutes) or lag 2 (ie, 4 minutes). Therefore, the ratios of particle concentrations at the 2 fixed room locations were calculated using the same 2-minute periods, as above using 28 observations per case.

RESULTS

The concentration of air particles was greater at the return grille than instrument table for the single large diffuser at 26 air exchanges per hour, and the multiple diffuser arrays at both 26 and 20 air exchanges per hour (Table 1, all $P \leq .0044$). The single large diffuser at 20 air exchanges per hour and the older room's 4-way throw diffuser systems had greater concentrations at the return grille for larger particles (≥5.0 microns).

Electrocautery was important to understand the study results because the location of emission was known to be the OR table, unlike for larger particles, shed from people throughout the ORs. The ratios of concentrations, return grille versus instrument table, were *greater* during electrocautery for the 0.5 to 1.0-micron particles (N = 108 during electrocautery median [25th percentile, 75th percentile] of 1.61 [1.03, 3.80] vs N = 312 without 1.03 [0.82-1.24], $P < .0001$) and 1.0 to 5.0-micron particles (during 1.32 [0.99, 2.35] vs 1.05 [0.88, 1.28], $P < .0001$). There were greater concentrations of air particles during electrocautery at the return grille than instrument table for the single large diffuser at 26 air exchanges per hour and the multiple diffuser arrays at both 26 and 20 air exchanges per hour (Table 2, all $P \leq .0072$).

DISCUSSION

Increasing air exchanges per hour reduces time for clearance of air particles (eg, SARS-CoV-2 or cautery).[18] Our results show that benefit is achieved with a consequent greater relative concentration at the periphery versus at the OR table, because the airflow is from above the OR table down and then out toward the return air grilles along the walls. Our results for the periods with electrocautery highlight how effective modern OR airflow designs can be at reducing the risk of surgical site infection and exposure of the surgical team. Specifically, even though the "surgery" on the uncooked steak was done at the OR table, the increase in particle concentration was greater at the particle counter along the walls of the ORs. Thus, by design, particles have been carried away from the patient.[9]

Comparisons with previous studies

Previous studies have shown the bacterial colony forming units in air samples of (actual) surgical cases being greater when there were more people in ORs (ie, people are the source, with a Spearman rank correlation coefficient of 0.45).[19] Previous studies have also shown airborne concentrations of bacteria being greater outside versus inside the sterile field.[9,14,20] Our results for multiple particle sizes indicate strong chance that infectious aerosols, including viruses generated by patients, would pose as much a risk to health care workers at the periphery of the room than adjacent to the patient.

We are aware of 1 previous study with data analogous to ours permitting some comparison.[21] Alsved et al used computational fluid dynamics to model airflow velocities.[21] Laminar airflow had relatively high velocity straight down from the ceiling above the OR table, then out along the floor to the walls, where the flow extended upward with turbulent flow.[21] Temperature-controlled airflow had lower velocity over the table and less turbulent flow up the walls.[21] The designs of the simulated rooms would be expected to have greater concentration of air particles at the lower walls, as we observed. They measured colony-forming units of viable airborne bacteria (≥5 microns).[21] The bacteria were not released deliberately and personnel were not preferentially at the OR table (ie, the authors appropriately did not examine associations between OR locations appropriately, and one area of the OR may not have caused observation at another area).[21] Nevertheless, for both of the modern designed systems, laminar flow and temperature-controlled airflow, median concentrations at the periphery of the room were greater than at the wound or instrument tray.[21] However, for the older design with substantial resulting turbulent flow, that relationship was disrupted.[21] These findings qualitatively match our results.

Limitations

A limitation of our study is that particle concentrations were measured above air return grilles, not at the height of a circulating nurse sitting in a chair at a computer. However, based on airflow, we doubt that our results would differ. First, air does not all exit the air register grilles; some travels up walls.[21] This is shown by particle-tracing studies of single large diffusers and computational fluid dynamic simulations of laminar or temperature-controlled airflows.[10,21] Second, nonuniformity and greater rates of airflow near the return grilles and corresponding air particle counting units would not affect results because particle counting was analyzed as a density, particles per volume, thus normalizing the values for flow.

Another limitation is that the particle sizes were appropriate for pathogenic bacteria (eg, 10 microns for *Staphylococcus aureus* clusters or skin cells carrying bacteria) but larger than some viruses (eg, the minimum studied size of 0.5 microns exceeds the diameter of SARS-CoV-2).[22] However, aerosolized particles in ORs apply to all types of particles (eg, surgical smoke[8]) and our findings qualitatively applied to all sizes studied (Tables 1 and 2).

Applications

Our paper applies generally to airborne transmission of a pathogen in the OR, whether SARS-CoV-2[3-5] released by surgical or airway manipulation, or to other airborne contaminants such as electrocautery smoke and tuberculosis. However, maintaining distances from released airborne particles has permeated colloquial considerations since the onset of the COVID-19 pandemic (See Google search at https://FDshort.com/WagnerAirParticles).[2] We recommend personnel awareness that in an OR it may be a counter-productive strategy to move away from the patient toward a wall (ie, where air return grilles are located). During robotic surgery, considerations for placement of the surgical console traditionally have included being outside the sterile field and at a location that facilitates line of site to the operative field and easy communication with the assistant surgeon and scrub nurse.[23] With COVID-19, there is the additional consideration of exposure of the surgeon at the console to the patient.[6]

CONCLUSIONS

Our results show the value of education that the seated surgeon should expect to be exposed to a higher concentration of particles than the anesthesia team, assistant surgeon, or scrub nurse. Modern OR airflow systems are so effective at protecting the surgical field and team from airborne particles emitted during surgery that concentrations of particles released at the OR table are greater at the OR walls than near the center of the room.

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