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Major Article

Cost-benefit analysis of different air change rates in an operating room environment

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Background: Hospitals face growing pressure to meet the dual but often competing goals of providing a safe environment while controlling operating costs. Evidence-based data are needed to provide insight for facility management practices to support these goals.

Methods: The quality of the air in 3 operating rooms was measured at different ventilation rates. The energy cost to provide the heating, ventilation, and air conditioning to the rooms was estimated to provide a cost-benefit comparison of the effectiveness of different ventilation rates currently used in the health care industry.

Results: Simply increasing air change rates in the operating rooms tested did not necessarily provide an overall cleaner environment, but did substantially increase energy consumption and costs. Additionally, and unexpectedly, significant differences in microbial load and air velocity were detected between the sterile fields and back instrument tables.

Conclusions: Increasing the ventilation rates in operating rooms in an effort to improve clinical outcomes and potentially reduce surgical site infections does not necessarily provide cleaner air, but does typically increase operating costs. Efficient distribution or management of the air can improve quality indicators and potentially reduce the number of air changes required. Measurable environmental quality indicators could be used in lieu of or in addition to air change rate requirements to optimize cost and quality for an operating room and other critical environments.

BACKGROUND

Lean measures are implemented within the health care industry to control costs while maintaining high quality. Evidence-based information is paramount to guide professionals to achieve the optimum balance for best hospital practices. This applies to hospital ventilation systems, which are important to ensure clean air within sterile environments, but at the same time, they also require significant amounts of energy to operate. The required ventilation rates for operating rooms (ORs) have increased over the years with minimal data to suggest that more ventilation provides cleaner conditions or reduces surgical site infections (SSIs). Energy costs have continued to increase from both a financial and an environmental perspective.

Energy consumption for buildings is high in the United States and accounts for 40% of the total national energy usage. Heating, ventilation, and air conditioning (HVAC) is the largest component of that at 17%. Hospital buildings in particular have one of the highest energy demands because of their stringent heating and air conditioning requirements, the significant amount of diagnostic and therapeutic equipment available, and the need for 24-hour availability. Within the hospital, the OR suites are the most expensive to heat, cool, and ventilate.[1] This cost is associated with the stringent

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need for climate control and vigorous rates of air exchanges to help maintain a healthy indoor environment.

ORs have specific requirements for the design, construction, and operation of the space and the systems serving the area. These are necessary to protect the patients and staff with one of the primary goals being to provide sterile conditions to help minimize the risk of SSIs. Proper ventilation of the physical space and filtration of the air are 2 primary practices within ORs to reduce the airborne transmission of contaminants. Ventilation is accomplished by systematically changing the air in the OR on a regular schedule. The new air is typically a mixture of fresh air (approximately 20%) from the outside environment and air recycled from the OR space that has been filtered to remove particles and contaminants (approximately 80%). The introduction of large quantities of conditioned and filtered air helps to dilute the number of contaminants within the room, while the proper placement of supply and return air devices directs the contaminants away from the sterile field.

It is estimated that $9.8 billion is spent annually on hospital-acquired infections, with SSIs contributing the most to the overall cost at 33.7%.[2] OR air quality is only part of a complex list of factors that can contribute to SSIs; therefore, direct connections between air quality and surgical infections are difficult to prove.[3] However, intuitively, the more pathogens present in the air, the greater the chance for contamination of the surgical site, surgical instrumentation, and surrounding environmental surfaces. Furthermore, there is ample evidence to support the potential for airborne transmission of harmful pathogens.[4,5]

The requirements for air changes in hospital ORs have changed frequently over the years. In 1967, the requirement was 12 air changes per hour (ACH), it increased to 25 ACH in 1974, and then back to 15 ACH in 1987. Today, the requirements are primarily defined in The Guidelines for Design and Construction of Hospital and Outpatient Facilities[6] and ASHRAE 170.[7] In the 2010 edition of the guidelines, the 2 standards were combined resulting in an increase from 15 to 20 ACH required in new ORs built in many states in the United States. Additionally, the requirement for the number of these air changes to be fresh, outside air, as opposed to recirculated, increased from 3 to 4 ACH. Although these are the minimum requirements, in practice, most hospitals use 20-30 ACH for their ORs with known anecdotal outliers using 40 ACH, despite minimal evidence to suggest that a greater number of air changes will provide cleaner air. On the other extreme, the State of California code currently allows for the use of 12 ACH in OR systems that provide 100% outside air; however, this approach is not used frequently.[8]

Requirements for air change rates vary in other countries and some even use other standards, such as ISO classifications from the International Organization for Standardization.[9] These numerical quantifications and ISO classifications for particles and microbial colony forming units (CFU) are standard practice for pharmaceutic and semiconductor cleanrooms. Despite the variations in OR ventilation rates, SSI rates remain surprisingly similar among modern countries. Surgical infection rates averaged 1.9% in the United States, 2.2% in Europe, 1.6% in Germany, 1.4% in England, 1.6% in France, and 2.0% in Portugal.[10]

Given the variation in required air change rates in hospital ORs with similar SSI rates and the high energy costs of providing more ACH, research in this field could help clarify the appropriate balance between the costs and benefits of different ventilation rates. This practical, evidence-based data could help guide policy to define the codes and the practical applications for the estimated 30,633 ORs in the United States.[11]

We therefore hypothesized that (1) higher air change rates in an OR would not necessarily provide cleaner air, and (2) higher air change rates would be associated with increased theoretical costs.

MATERIALS AND METHODS

Environmental quality indicator testing

Three different ORs in 3 different hospitals in 2 different states were chosen for experimentation. The ORs in 2 hospitals (OR A and OR B) were associated with academic medical schools. Both had high efficiency particulate arresting (HEPA)/minimum efficiency reporting values (MERV) 17 filters in the supply grilles supplying the rooms and were 59.3 and 51.5 m^2, respectively. The third OR (OR C) was located in a private community hospital, had MERV 14 filters in the air handling unit, and was 505 ft^2. The layout of all 3 ORs was generally the same, but the actual number and location of the supply air diffusers varied along with the location of overhead lights and equipment booms. Studies took place from the summer of 2015 to the spring of 2016.

Assessment of environmental quality indicators (EQIs) was performed as previously described.[11] A 1-hour scripted and simulated medical procedure was enacted to mimic the dynamic conditions of actual surgeries in an OR. Air velocity was measured using TSI Model 9565-P Thermoanemometers (TSI Incorporated, Shoreview, MN) at key locations in the ORs to provide insight into the direction and speed of the air being used for ventilation to provide clean conditions for surgery. The velocities were measured at the face of the supply grilles and the return grilles, and at 2 additional critical locations, the OR table (sterile field) and the back instrument table (back table).

Bioscience viable surface air samplers (SAS180) were placed at both the surgical operating field and at the back instrument table to detect microbial contaminants. Petri plates with tryptic soy agar media were used in the samplers and were changed in regular cycles to collect microbial data during the entire mock procedure. The viable microbial samples were sent under chain of custody to a third-party microbiology laboratory for qualitative and quantitative analysis of bacteria. Bacterial genus were identified and quantified as CFU per cubic meter.

Particle contamination was measured using a Climet Model CJ-750T 75 LPM particle counter. ISO 14644 standards were used, which required measuring the number of particles at 9 points based on the size of the space. The particle sizes recorded were 0.3, 0.5, 1.0, and 5.0 μm in particles per cubic meter.

Testing was performed at 15, 20, and 25 ACH during the mock surgical procedure. The air change rates were measured using a standard HVAC test and balance hoods (ADM860C; Shortridge). In addition, the building automation systems were used to set and monitor the ventilation rates, relative humidity, pressure relationships, and temperatures in the ORs. The measurements were taken at each supply and return grille in cubic feet per minute (CFM), and the air change rates, in ACH, were calculated based on the actual size of each individual OR. Although the layout of supply grilles varied slightly in each OR, all 3 ORs had 2 low wall return grilles.

Cost analysis

The higher ventilation rates require a substantial amount of additional air to be conditioned, filtered, and supplied to the OR. The ventilation rate is calculated by using the following formula: volume of the room in cubic feet multiplied by the ventilation rate in ACH gives the cubic feet per hour, which is converted into CFM, which provides the amount of air that must be provided through the ceiling grilles. It is typically around 2,000-2,500 CFM for an OR which is supplied at 25-35 ft/min as measured at the face of the grille. The number of supply grilles may vary depending on the engineer's design.

The operating costs at each facility varied by hospital as a result of the differences in the cost of energy and the type of systems in

the different locations. Research personnel worked with the facility managers at the 3 sites to estimate the cost for 1 air change per OR per year based on the cost per kilowatt hour and the cost per therm. The 3 primary elements included in the pricing were the fan power (supply and return), cooling (chillers, pumps, and cooling tower fans), and preheat-reheat-humidity control.

The calculated energy savings were established by each site's surgery ventilation system's cooling, heating, humidification-dehumidification, and economizer functionalities. The individual site's costs for utilities included the following factors: (1) surgery space required a dehumidification cycle to maintain 64°F and <60% relative humidity environment during a portion of the cooling season; (2) utility costs were operational which included line losses, equipment efficiencies, fouling, water treatment, auxiliary equipment, blow down, and other maintenance costs; and (3) based on 24 hours of operation, 365 d/y.

Statistical analysis

Skewness and kurtosis statistical analysis were run on continuous distributions to test for the assumption of normality. All distributions in the study were assumed to be nonnormal with skewness and kurtosis statistics above an absolute value of 2.0. Because of this violation of normality, only nonparametric statistics were used to answer research questions in this study. Kruskal-Wallis tests were used to assess main effects when comparing ≥3 groups. In the event of a significant main effect, Mann-Whitney *U* tests were used in a post hoc fashion to explain pairwise differences. When comparing 2 groups on outcomes, Mann-Whitney *U* tests were used. Medians and interquartile ranges (IQRs) were reported to give context to all inferential findings. When assumptions of normality and homogeneity of variances were met, means and SDs were used. All analyses were conducted using SPSS Version 21 (IBM, Armonk, NY).

RESULTS

EQIs

Particles

Total particles per cubic meter (mean with IQR) were not significantly different between 15 and 20, or 20 and 25 ACH at any of the 3 sites. This observation was likely because of a high variability in the particle samples created by the electrocautery during the mock procedure. However, when the median and IQR were calculated for each particle size separately, a few significant differences were revealed. In OR B, there were significantly fewer 0.3-μm particles seen at 20 ACH compared with 15 ACH ($P = .03$). Additionally, we noted significantly fewer 5.0-μm particles at 25 ACH compared with 20 ACH, and at 20 ACH compared with 15 ACH ($P = .02$ and $P = .01$, respectively) (Table 1). In OR C, there were significantly fewer particles at all sizes (0.3, 0.5, 1.0, and 5.0) at 20 ACH compared with 15 ACH ($P < .001$, $P < .001$, $P < .004$, and $P < .001$, respectively). Surprisingly, OR C actually maintained significantly higher 0.3- and 0.5-μm particles at 25 ACH compared with 20 ACH ($P < .001$) (Table 1). Increasing air change rates did not impact ISO classifications at 0.5 μm, with all measurements falling in either ISO 7 or ISO 8 (not to exceed 3.52×10^5 and 35.2×10^5, respectively) (Table 2).

Microbial contaminants

The median and IQR for total microbial CFU per cubic meter were significantly different at both the back table and in the sterile field between 15 and 20 ACH at all 3 sites (Table 3). In OR A, 20 ACH had

Table 1
Particle data for tested operating rooms compared by ACH

Operating room site	Particle size/volume	15 ACH Median (IQR)	20 ACH Median (IQR)	*P* value	20 ACH Median (IQR)	25 ACH Median (IQR)	*P* value
OR A	0.3-μm particles/m³*	5.99 (39.2)	1.59 (18.5)	.06	1.59 (18.5)	1.02 (16.83)	.60
	0.5-μm particles/m³*	2.21 (10.25)	0.85 (6.57)	.07	0.85 (6.57)	0.57 (6.04)	.58
	1.0-μm particles/m³*	0.90 (3.17)	0.45 (2.24)	.08	0.45 (2.24)	0.30 (2.10)	.59
	5.0-μm particles/m³*	0.037 (0.027)	0.026 (0.025)	.17	0.026 (0.025)	0.023 (0.024)	.27
OR B	0.3-μm particles/m³*	2.38 (5.64)	1.34 (4.03)	.03†	1.34 (4.03)	0.87 (2.28)	.11
	0.5-μm particles/m³*	1.05 (1.71)	8.53 (1.00)	.11	8.53 (1.00)	0.49 (0.95)	.08
	1.0-μm particles/m³*	0.45 (0.55)	0.45 (0.47)	.26	0.45 (0.47)	0.27 (0.41)	.07
	5.0-μm particles/m³*	0.022 (0.015)	0.018 (0.011)	.02†	0.018 (0.011)	0.013 (0.010)	.01†
OR C	0.3-μm particles/m³*	118.1 (10.55)	111.5 (7.29)	<.001†	111.5 (7.29)	136.1 (7.36)	<.001†
	0.5-μm particles/m³*	10.85 (2.93)	9.12 (2.17)	<.001†	9.12 (2.17)	14.20 (2.71)	<.001†
	1.0-μm particles/m³*	1.08 (0.86)	0.61 (0.66)	.004†	0.61 (0.66)	0.66 (0.93)	.72
	5.0-μm particles/m³*	0.030 (0.021)	0.022 (0.016)	<.001†	0.022 (0.016)	0.021 (0.02)	.97

ACH, air changes per hour; *IQR*, interquartile range; *OR*, operating room.
*95% upper confidence level, particles per cubic meter × 10^5.
†Significant at $P < 0.05$.

Table 2
Maximum particle count and example ISO classification

Operating room site	Particle size/volume	15 ACH 9-point cycle 1	15 ACH 9-point cycle 2	15 ACH 9-point cycle 3	20 ACH 9-point cycle 1	20 ACH 9-point cycle 2	20 ACH 9-point cycle 3	25 ACH 9-point cycle 1	25 ACH 9-point cycle 2	25 ACH 9-point cycle 3
OR A	Particles/m³*	5.03	21.06	10.57	2.72	25.8	2.62	3.1	21.54	4.14
	ISO	8	8	8	7	8	7	7	8	8
OR B	Particles/m³*	2.997	5.02	1.92	4.56	2.64	1.42	3.91	2.76	0.57
	ISO	7	8	7	8	7	7	8	7	7
OR C	Particles/m³*	9.91	11.90	12.83	8.35	11.52	10.1	12.87	15.32	17.23
	ISO	8	8	8	8	8	8	8	8	8

ACH, air changes per hour; *OR*, operating room.
*95% upper confidence level, 0.5-μm particles per cubic meter × 10^5. ISO classification according to standard 14644-1. ISO 7 cannot exceed 3.52×10^5. ISO 8 cannot exceed 35.2×10^5.

Table 3
Microbial contaminants and velocities assessed at various air changes at the sterile field and back table

Operating room site	Room location being BT or SF	Microbial levels measured in CFU or *P* value by comparison	15 ACH, median (IQR)	20 ACH, median (IQR)	*P* value, 15 vs 20	20 ACH, median (IQR)	25 ACH, median (IQR)	*P* value, 20 vs 25
OR A	BT	Microbial (CFU/m^3)	39.00 (13)	27.00 (11)	.004†	27.00 (11)	22.00 (15)	.04†
	SF	Microbial (CFU/m^3)	7.50 (6)	3.00 (3)	.006†	3.00 (3)	3.00 (3)	.84
		P value, BT vs SF	<.001†	<.001†			<.001†	
	BT	Velocity (ft/min)	12.00 (7)	13.00 (8)	.14	13.00 (8)	14.56±8.336*	.36
	SF	Velocity (ft/min)	28.00 (28)	32.00 (10)	.36	32.00 (10)	40.59±13.580*	.001†
		P value, BT vs SF	<.001†	<.001†			<.001†	
OR B	BT	Microbial (CFU/m^3)	34.5 (19)	16.00 (6)	<.001†	16.00 (6)	16.00 (7)	.86
	SF	Microbial (CFU/m^3)	51.00 (24)	22.00 (12)	<.001†	22.00 (12)	16.00 (8)	<.001†
		P value, BT vs SF	.004†	.002†			.33	
	BT	Velocity (ft/min)	18.41±6.755*	13.00 (12)	.008†	13.00 (12)	16.41±11.050*	.12
	SF	Velocity (ft/min)	27.52±6.351*	31.00 (6)	.02†	31.00 (6)	39.67±12.746*	.001†
		P value BT vs SF	<.001†	<.001†			<.001†	
OR C	BT	Microbial (CFU/m^3)	7.00 (5)	5.00 (4)	.001†	5.00 (4)	5.00 (5)	.84
	SF	Microbial (CFU/m^3)	8.00 (6)	6.00 (4)	.03†	6.00 (4)	5.50 (5)	.93
		P value, BT vs SF	.94	.16			.41	
	BT	Velocity (ft/min)	8.00 (7)	9.52 (5.345)	.25	9.52±5.345*	16.56±9.982*	.001†
	SF	Velocity (ft/min)	9.00 (12)	13.63±7.318*	.23	13.63±7.318*	16.85±10.014*	.09
		P value, BT vs SF	.19	.02†			.91	

ACH, air changes per hour; *BT*, back table; *CFU*, colony forming units; *IQR*, interquartile range; *OR*, operating room; *SF*, sterile field.
*Means and SDs were used to calculate significance because the assumptions of normality and homogeneity of variance are met.
†Significant at <0.05.

Table 4
Microbial range and example USP 797 classification

Operating room site	ISO standard 14644 class	15 ACH		20 ACH		25 ACH	
		Sterile field	Back table	Sterile field	Back table	Sterile field	Back table
OR A	Range	1-18	24-98	1-10	16-51	1-8	10-31
	ISO	8	8	8	8	7	8
OR B	Range	28-104	16-164	14-41	10-24	7-27	7-199
	ISO	>8	>8	8	8	8	8
OR C	Range	2-15	5-18	0-13	2-15	3-15	0-20
	ISO	8	8	8	8	8	8

ACH, air changes per hour; *CFU*, colony forming units; *OR*, operating room.

significantly fewer CFU per cubic meter than 15 ACH in the sterile field (3 vs 7.5 CFU/m^3) and at the back table (27 vs 39 CFU/m^3) ($P = .006$ and $P = .004$, respectively). In OR B, 20 ACH had significantly fewer CFU per cubic meter than 15 ACH in the sterile field (22 vs 51 CFU/m^3) and at the back table (16 vs 34.5 CFU/m^3) (both $P < .001$). In OR C, 20 ACH had significantly fewer CFU per cubic meter that 15 ACH in the sterile field (6 vs 8 CFU/m^3) and at the back table (5 vs 7 CFU/m^3) ($P = .001$ and $P = .03$, respectively).

Significant differences in total CFU per cubic meter (median and IQR) between 20 and 25 ACH were identified in only 2 instances, the back table in OR A and the sterile field in OR B. In OR A, at the back table, the median CFU per cubic meter was significantly less at 25 ACH than at 20 ACH (22 vs 27 CFU/m^3; $P = .04$). At the sterile field in OR B, the median CFU per cubic meter was significantly less at 25 ACH than at 20 ACH (16 vs 22 CFU/m^3; $P < .001$) (Table 3).

When comparing the median CFU per cubic meter at the back table versus in the sterile field at any given air exchange rate, significant differences were revealed in OR A at all 3 ACH ($P < .001$) and in OR B at 15 and 20 ACH ($P = .004$ and $P = .002$, respectively). In OR A, at all 3 ACH, the sterile field had significantly fewer CFU per cubic meter than the back table. Conversely, in OR B at 15 and 20 ACH, the back table actually had fewer CFU per cubic meter than the sterile field. No significant differences between median CFU per cubic meter at the back table versus the sterile field were detected in OR C (Table 3). Increasing air exchange rates did not readily impact United States Pharmacopeia (USP) Standard 797 classification scores, again placing all ORs in class 7 or 8 (not to exceed 10 or 100 CFU/m^3, respectively) (Table 4).

The microbial sampling confirmed the presence of >15 different airborne bacterial genera. The independent laboratory identified human-derived *Micrococcus* spp, coagulase-negative and coagulase-positive *staphylococci*, and environmentally derived *Bacillus* spp, *Corynebacterium* spp, *Acinetobacter* spp, *Pseudomonas* spp, among others. Although species of these genera, and others, are either common human flora or are ubiquitous in the environment, they are opportunistic pathogens that pose a health risk to

immunocompromised patients. In all 3 ORs at all 3 ACH, coagulase-negative *staphylococci* (CoNS) was the most abundant. In OR A, in the sterile field, the median CFU per cubic meter for CoNS at 15, 20, and 25 ACH were 4, 2, and 2, respectively and at the back table, 25.5, 19, and 15, respectively. In OR B, in the sterile field, the median CFU per cubic meter for CoNS at 15, 20, and 25 ACH were 17, 10, and 8, respectively, and at the back table, 13, 8, and 7, respectively. In OR C, in the sterile field, the median CFU per cubic meter for CoNS at 15, 20, and 25 ACH were 3, 2, and 2, respectively, and at the back table, 2, 1.5, and 1.5, respectively.

In all 3 ORs at all 3 ACH, *Micrococcus* spp was the second most abundant microorganism. In OR A, in the sterile field, the median CFU per cubic meter for *Micrococcus* spp at 15, 20, and 25 ACH were 1.5, 1, and 1, respectively, and at the back table, 8, 6, and 3.5, respectively. In OR B, in the sterile field, the median CFU per cubic meter for *Micrococcus* spp at 15, 20, and 25 ACH were 21.5, 9, and 5, respectively, and at the back table, 10.5, 6, and 5, respectively. In OR C, in the sterile field, the median CFU per cubic meter for *Micrococcus* spp at 15, 20, and 25 ACH were 3, 2, and 3, respectively, and at the back table, 5, 2, and 3, respectively.

Velocity

Our testing in all cases showed there was significant variability in air velocity between the ceiling diffuser, the sterile field, and the back table. The velocity of the air ranged from high of 76 ft/min at the diffuser at 25 ACH to a low of 2 ft/min at the back table at 15 ACH. The mean velocities were more consistent, but still varied from 64 to 12.5 ft/min at the 3 different ventilation rates—15, 20, and 25 ACH.

Our testing also indicated that the air flow is very low at the back table where the surgical instruments are opened and accessible during surgery. At the academic medical centers, the velocities at the back table were significantly lower ($P < .001$) than at the sterile field. The velocities at the community hospital were consistently lower at both the back table and sterile field than at the academic medical centers. With the mean velocities at the back table ranging from 8.0-18.41 ft/min, there would be very little flow of conditioned and filtered air over the open sterile instruments. (Table 3, air velocities at sterile field and back table).

Cost

The costs to provide ventilation to the 3 ORs varied based on location, local utility rates, and the type of HVAC system. Based on analysis of these factors, the estimated costs for one air change per OR per year were developed for each of the 3 sites. These estimates included energy costs for the fan, pumping, cooling, heating, and steam. These are as follows, with additional detail in Table 5:

Table 5
Cost analysis for air changes at each OR

	Per 5 ACH reduction per year per OR			
	System components			Total yearly savings per OR*
Operating room site	Fans and pumping power	Cooling system	Steam heating and humidification system	
OR A	$3,452	$5,035	$1,581	$10,068
OR B	$4,373	$1,979	$2,125	$8,477
OR C	$3,836	$1,736	$896	$6,468

ACH, air changes per hour; *OR*, operating room.

- Site A: $ 2,013/ACH/OR/y
- Site B: $ 1,695/ACH/OR/y
- Site C: $ 1,293/ACH/OR/y

This results in an average of $1,466 for 1 air change per OR per year. Therefore, a decision to use 25 ACH to be safer, in lieu of the typical code requirement of 20 ACH, could cost the hospital an additional $7,330 per year per OR.

DISCUSSION

Evidence-based practices are used routinely in the clinical care of patients. There have regularly been changes in hospital building codes that mandate increasing the number of ACH to limit theoretical infection. In practice, most hospitals provide more air changes than required. Increasing the ACH places added costs on hospital systems with little evidence to support a benefit. Herein, we used a previously established method for measuring EQIs in a dynamic OR environment[12] to formulate a performance-based metric that can be used to design, construct, and operate patient spaces in a health care facility.

ISO classifications are typically used to describe the level of cleanliness in the semiconductor and pharmaceutic industries. Class 1 describes the cleanest of clean rooms, whereas class 9 describes the dirtiest clean room. However, in this study, based on microbial load, in only 1 of 18 comparisons did 25 ACH actually improve the numerical, hypothetical ISO rank above that seen at 20 ACH. Furthermore, in only 2 of 18 comparisons did 20 ACH improve the ISO numerical rank compared with 15 ACH. This may, in part, be because of the logarithmic nature of ISO classifications which allows for substantial variation in numerical value within each class. Hence, increasing from 15 to 20 ACH did significantly reduce the CFU per cubic meter at the back table and in the sterile field in all 3 ORs. Additionally, increasing the ACH from 20 to 25 ACH only significantly reduced the CFU per cubic meter in 2 of the 6 comparisons (the back table in OR A and the sterile field in OR B). Based on particle counts, the hypothetical ISO numerical classifications were not improved at all by increasing the ACH from 15 to 20 or from 20 to 25. Therefore, simply altering the air changes in an OR may not be the most effective way to improve the cleanliness of the clean space. Additionally, although a numerical benchmark may be necessary, placing ORs into logarithmic ISO classes may not be the most appropriate way to measure the cleanliness of the space.

Surprisingly, we also discovered that although all 3 ORs met the code requirements for minimum air velocity of 25-35 ft/min, the actual velocity at the sterile field and back table fluctuated greatly throughout the EQI testing, with lows reaching 2 ft/min. The best practice design with the HVAC supplying air from ceiling-mounted diffusers, and directing the flow over the OR table to low return grilles mounted in opposing corners of the room may, in practice, not successfully provide a consistent flow of clean air to the surgical site. Along these lines, we discovered significant differences in both air velocity and microbial load between the back table and sterile field. In OR A, the velocity of air was significantly less at the back table than the sterile field, and the microbial load was significantly greater at the back table at all 3 air change rates. Similarly, in OR B, the velocity at the back table was significantly lower than in the sterile filed. However, despite the higher velocity at the sterile field, the microbial load was actually greater in the sterile field than at the back table. Furthermore, in OR C, where HEPA filters were not used, running the OR at 25 ACH significantly increased the number of 0.3- and 0.5-μm particles in the space.

Although all 3 ORs were designed to meet industry best practice, the EQI method revealed they are not all operating the same. Therefore, determining the appropriate performance-based metric

for an OR is essential to optimize the functionality of any given operational space. This research indicates that optimizing function based on a performance metric may improve environmental stewardship, and reduce operational cost and energy consumption, without jeopardizing, and even possibly improving, clinical outcomes.

In addition to the clinical reasons for providing proper ventilation in ORs, there is also the practical need to manage operating costs of the clean space. For example, in a typical 600-ft^2 OR with a 10-ft ceiling, 25 ACH requires 60,000 more total cubic feet of air per hour than 15 ACH. This increases the capital or construction costs as a result of incrementally larger fans, duct work, and heating-cooling capacity that are required. It also significantly increases the operating or energy cost as a result of conditioning, filtering, and moving the additional air. We determined that increasing the air exchange rate by 5 ACH increased operational costs for the hospital on average of >$7,000 per OR per year.

However, the business of health care mandates a delicate balance between cost and safety. It appears that providing more ACH is the safest approach because the national standards have consistently increased, and many hospitals provide ≥25 ACH in certain ORs. To date, there is no scientific evidence to support that increasing the ventilation rates to higher levels actually reduces SSIs. In fact, one study using a computational fluid dynamics model concluded fewer particles landed on the test site at the lower ACH of 20 than did at the high ACH of 150. This same study suggested that the design of the ventilation system was potentially a more important factor in proper ventilation than the number of air changes.[13]

Although ventilation rates as measured in ACH have been the standard for many years, the amount of air circulated through the room may not tell the whole story. Through better or different approaches for air management in the ORs, cleaner air could be delivered at key points, such as the back table and sterile field, at no more or maybe even less cost. By using EQIs, as opposed to simply reporting ACH or ISO classifications, the cleanliness of the air and proper air flows could be monitored and maintained at the minimum air change rates required to provide an adequately clean space as opposed to at a set standard.

LIMITATIONS

Although this study is unique in its design and offers some scientific merit to support future building codes, it does suffer limitations. Unfortunately, it is impossible to correlate the findings in this study with SSIs. Although many would argue that dirtier air promotes infection, there are multiple other variables that come into play. These include variations in OR personnel and patient characteristics and disease processes. Performing EQI testing with live patients in the room would be very costly to repeat to generate the statistical numbers needed, and would be disruptive to the surgical team and patients.

Another limitation is seen with measurement of the particle counts. Although we observed decreased total number of particles at the higher air exchange rates, these measurements were not statistically different. This is likely because of the extreme sensitivity of the machines and the wide variation seen in the counts. Variation could be attributed to movements within the room at specific times of the test or more likely to the high particle counts generated by the electrocautery device as part of the mock procedure.

A final limitation surrounds the use of filters in the ORs. OR A and OR B used HEPA filters, whereas OR C used MERV 14 filters. It was not practical in the scope of this research to rework the HVAC system to change the MERV 14 filters to HEPA.

CONCLUSIONS

The use of EQIs for the OR environment may be a better approach or even a supplemental standard for current air change rates. These indicators, such as level of microbial contaminants, number of particles, and velocity of the air at key points, could provide more accurate measurements of the actual quality of the air and the potential to minimize the risk of SSIs.

The cost of higher air change rates in an OR can be a significant expense to the health care system when factored over the number of total ORs. We demonstrated that although some microbial and particulate parameters were improved by increasing air changes, not all were universally beneficial. Additionally, air velocity in the OR at key locations varies significantly, which could make certain areas of the room more susceptible to microbial contamination. As hospital systems and building engineers continue to face the dual challenge of improving quality while reducing costs, the use of measurable air quality indicators may provide the tools to define the optimum ventilation parameters within today's modern OR environments.

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