WHITE PAPER

LIMITS OF LAMINAR AIRFLOW IN AN OPERATING ROOM AND HOW TO BREAK THROUGH THEM

Surgical facilities have trusted laminar flow diffusers to protect their patients for decades. However, empirical data shows that laminar flow diffusers at typical supply air parameters do not provide the expected air behavior or patient protection, even when they exceed minimum requirements. An alternative method of controlling operating room airflow is proposed and shown to produce superior results.

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AUTHORS:

Ted Folstad, Member ASHRAE
Casey Zimmerman
Derek Weinschenk

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Precision Air

BACKGROUND

The importance of clean air, especially when performing surgical procedures, is a critical part of patient protection and infection control. In medical practice, patient protection is the number one priority. There are many ways in which patient protection may be compromised, but poor control over the behavior of air and the contaminants it carries continues to be a prominent and elusive root cause. It has long been stated in medical journals that "to reduce prolonged morbidity and healthcare costs associated with these infections, airborne bacteria and other sources of contamination must be reduced to the minimum."[1] A current strategy for reducing these infections caused by bioaerosol contamination is to control its cleanliness and behavior with carefully engineered ventilation systems using laminar flow. It should not be assumed that all systems utilizing laminar airflow are providing ultraclean air, but rather, there is a significant reduction in potential air contaminants when these systems are designed carefully and precisely.[2]

When designing airflow systems to deliver clean air over patients in an operating room (OR), the term "laminar airflow" is often used. In many engineering disciplines, particularly fluid dynamics, the traditional use for the word "laminar" is to describe the flow behavior of a fluid based on the calculated figure called the Reynolds number. However, there currently is no measurement of how laminar the air delivered through a laminar flow diffuser (LFD) is in an OR. In this setting "laminar" simply refers to air delivered within the OR with the intention to be unidirectional and at constant velocity.

A few studies published in the surgical literature suggest that operating room laminar airflow (LAF) ventilation is associated with a significant reduction in bioaerosol microbial contamination versus conventional turbulent ventilation.[3,4] However, in 2020 the beneficial impact of LAF in total joint replacement surgery is currently viewed as controversial.[5] A recent original investigation published in JAMA Network Open/Orthopedic looked at a total of 6,972 consecutive patients undergoing primary total knee arthroplasty or total hip arthroplasty at 2 tertiary care orthopedic hospitals with a minimum of 1-year follow-up. Patients were divided between conventional turbulent airflow (3,027) and LAF (3,945) and the findings suggested that use of LAF in the operating room was not associated with a reduced incidence of periprosthetic joint infections (PJI) after primary total joint arthroplasty.[6]

ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) has authored the standard which is widely used for the basis of airflow system design. According to ASHRAE 170-2017, 7.4.1 "The airflow shall be unidirectional, downwards, and the average velocity of the diffusers shall be 25 to 35 cfm/ft^2".[7] This is to say that when there are multiple LFDs, the average velocity per square foot shall fall within that range. The majority of ASHRAE's design parameters come from *Comparison of Operating Room Ventilation Systems in the Protection of the Surgical Site* .[8] This study advocates the use of LFDs within spaces intended for surgery. Many of the standard's specifications and ranges can be noted to originate from this study, which utilized CFD modeling for different ventilation cases. In addition to the flowrate range mentioned previously, the diffusers are also required to be non-aspirating. It is important to note that ASHRAE 170 represents an engineering design standard, but is not validated as a microbiological aerosol standard, which would have a greater impact on clinical outcome. Preventing contaminants from entering an air stream and reaching the patient can only be accomplished by eliminating or minimizing the entrainment of the surrounding air. Though this is not the only source of contamination, it should be considered a large factor for potentially compromising patient protection.

How air behaves in a system is based on a multitude of factors. Important physical properties to note for designing these ventilation systems are pressure, volume, and temperature. Gas laws define the relationship between these gaseous properties and can assist with understanding varying states of air in an OR.

The overall pressure differential between the air inside a certain type of room within a hospital and its adjacent spaces is stipulated by the intended procedures to be performed within that room. For example, a typical OR where surgeries may be done should be positively pressurized. This is done to keep air that is not directly controlled within the space from entering and possibly bringing harmful particulates to the patient undergoing surgery. While it is a facility's responsibility to maintain this pressure, it has a negligible effect on the local performance of an airflow system in the OR. However, when thinking in terms of general air behavior, it is very important to be aware that all these properties directly correspond.

Concerning the volume of air delivered to an OR, a designer will typically focus on the heat and humidity requirements of the space as well as the minimum 20 air changes per hour (ACH) required by the ASHRAE 170 standard. A higher volume of air delivered to the space with proper filtration will dilute the number of contaminants present, but energy consumption and space availability often results in only the minimum amount being delivered. It is well-known within the industry that it is not possible to keep a space completely sterile, or free from harmful particulates, while accommodating necessary personnel (surgeons, nurses, etc.) within that same space. The focus of laminar flow ventilation systems is to create an area specifically around the patient that is as clean and controlled as possible by focusing most of the delivered air around the patient. However, due to the lack of agreed upon configurations and environmental control among these systems, there is no evidence that they accomplish the patient protection they set out to achieve.

The last physical property is the temperature of the air. For obvious reasons, the comfort in the room needs to remain favorable and the temperature of a patient under anesthesia needs to be properly maintained. It is vital that the surgeon(s) perform to the best of their ability while also ensuring patients not reach dangerous temperatures that may put them at risk. ASHRAE 170 does indicate typical room temperature ranges for the various hospital spaces, but they may be overridden by the surgeons or surgical procedures taking place. It is commonly observed that the ASHRAE temperature specifications are indeed overridden by surgical personnel.

The relationship between these properties can be described by this simplified version of an energy balance:

$$\dot{Q} = \dot{V}\rho C \Delta T$$

EQUATION 1

From the equation, $\dot{Q}$ is the heat load in terms of rate, $\dot{V}$ is the volumetric flowrate of air, ρ is the density of the air, C is specific heat capacity of air, and ΔT is the temperature difference between delivered air jet and the air leaving the room.

For an operating room, the temperature of the air leaving the room can be assumed to be equal to the temperature of the air in the room or surrounding the delivered air. From this equation, the temperature difference between the delivered and surrounding air is dependent on the heat load and volume of air delivered to the room. A standard OR design, compliant with ASHRAE 170, will typically see a temperature difference (ΔT) of roughly 8-12°F between the LFD-delivered air and the surrounding air.

Coinciding with temperature differences is Archimedes' principle, which describes how differences in density can create a buoyant force that counteracts the force of gravity. In this discussion, the least dense air will rise, while the densest air will fall. Because air temperature directly impacts air density, the differences in air temperature throughout the OR can affect its behavior and performance.

It is crucial to consider all of air's properties simultaneously when attempting the design of a fully functional laminar airflow system inside an OR. When examining gas laws and balancing pressure, volume, and temperature, it becomes clear that the impact of one variable directly affects the output of the others. These properties must be strictly controlled to manipulate the desired effects of an airflow system's performance. Furthermore, the more locally these properties can be controlled, the more efficient the performance. In an extremely critical environment such as surgery, rapid response time from all the supporting systems, including airflow control, is pivotal to the outcome of the procedure.

REALITY OF TRADITIONAL LAMINAR AIRFLOW

It is impractical to try to anticipate the exact behavior of air at boundaries such as the perimeter of an LFD or an LFD array. However, it can be predicted how the air will behave over the operative field within the perimeter of a single large diffuser (SLD) which is accomplished by organizing multiple LFDs into a large, contiguous array. Stand-alone diffuser configurations inherently have many more boundary locations and are much more unpredictable than contiguous arrays. This makes them undesirable when trying to achieve patient protection and air control. The performance limits of an SLD are the focus of this paper. Compliance with ASHRAE 170 in a typical OR yields surprising results when it comes to performance of the air at the surgical table. Meeting ASHRAE's minimum of 20 ACH and neglecting the effects of air temperature differences can greatly increase the velocity of the delivered air to the patient. This is a result of Archimedes' principle, which expresses that when there is an increase in the temperature difference between the delivered air and the surrounding air, the resulting acceleration of the centerline velocity is also increased.[9] The diffused air, being denser than the surrounding air, experiences acceleration downwards. For this acceleration to be consistent with flow continuity principles, the cross-sectional area of the jet will adversely be reduced as well.

Considering the general effects of this acceleration and contraction, it follows that increasing the temperature differential will result in greater entrainment of surrounding air into the delivered air stream. As compared to a steady, uniform air stream that acts as a theoretical barrier, greater temperature differences can break that boundary and allow for any contaminants suspended in the surrounding air to be swept into the delivered air jet and reach the patient. Although this can be extremely cumbersome to model, the empirical repercussions are quite apparent by the measurement of particles within the delivered air stream.

PHYSICAL TEST RESULTS / DISCUSSION

To visualize the impact of an 8-12°F ΔT on the velocity of LFD-delivered air in a typical OR, physical data points for velocity in a mock OR were collected with a TSI VelociCalc 9555-P. This OR consisted of (8) 2' x 4' contiguous LFDs and the results were obtained at a range of 1 ft. to 6 ft. below the array to document from ceiling to table height. The LFDs were HEPA-filtered and non-aspirating to comply with the ASHRAE 170 standard. Additionally, for evidence of entrainment, particle counts were collected in the same fashion. These data were collected using a TSI AeroTrak 9310-02 portable particle counter to monitor the presence of particles with a diameter of 0.3 µm. To achieve a ΔT of 2-4°F within the same OR, the air volume to the room was approximately tripled.

Whatever method is chosen to understand this dynamic situation of air being delivered to a typical OR, there is certainty that an increased temperature differential between the delivered and surrounding air yields a logarithmic acceleration of air centered within a contiguous array of LFDs. To be clear, this is for a case where the delivered air is the source for cooling, as in nearly every OR. The difference in velocity from 1 ft. to 6 ft. can be seen from **FIGS. 1 & 2** to be more than three times in magnitude,

VELOCITY OF AIR / FPM

TYPICAL ΔT 8-12°F

STANDARD FACE VELOCITY

25 fpm ↓

1 FT. BELOW ARRAY

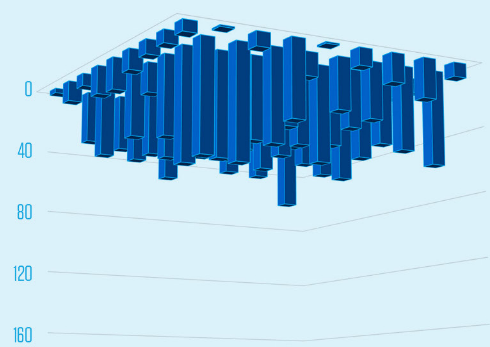


FIG. 1

6 FT. BELOW ARRAY

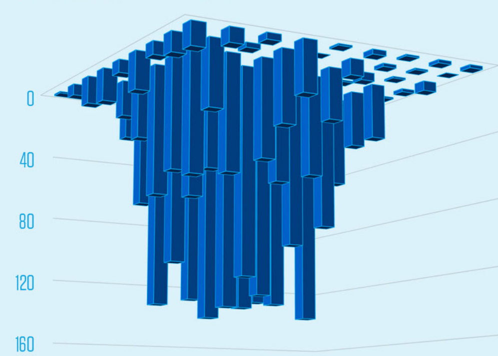


FIG. 2

VELOCITY OF AIR / FPM

REDUCED ΔT 2-4°F

INCREASED FACE VELOCITY

75 fpm ↓

1 FT. BELOW ARRAY

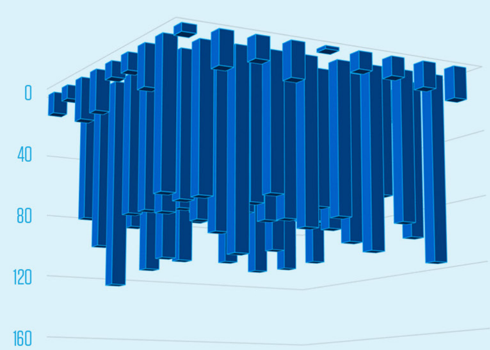


FIG. 3

6 FT. BELOW ARRAY

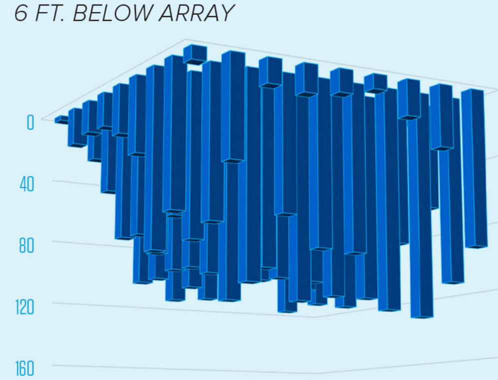


FIG. 4

FIGS. 1 - 4: Velocity profiles at stated distances below an 8' x 8' contiguous array of LFDs focused around the centerline region, when there is a significant ΔT present. These graphs depict a scenario that is common for an ASHRAE 170-compliant OR design. On the contrary, **FIGS. 3 & 4** show a much more stable and uniform velocity profile when the temperature differential is reduced by increased delivered air volumes. In this case, the face velocity has been increased by three times and the velocity profile has negligible acceleration. It is evident the acceleration of LFD-delivered air will be increased as the ΔT between the delivered and surrounding air is increased.

From **EQUATION 1**, it is known that an increase in delivered air volume will reduce the ΔT, so long as the heat load remains the same. With the same surrounding influences and only an increased flowrate, the acceleration seen between **FIGS. 1 & 2** does not appear to be present for **FIGS. 3 & 4**. Even with only a third of the average face velocity at the diffuser, the velocity at the patient table height with a high temperature difference in **FIG. 2** is still greater than that with a small temperature difference in **FIG. 4**.

It was previously mentioned that the acceleration of the delivered air when there is a ΔT present most closely corresponds to a logarithmic trend. To help support this statement, **FIG. 5** shows the development of velocity as the cross-sectional flow area is narrowed from the perimeter of the LFD array. Velocity averages were determined starting with an area of 7' x 7' and

VELOCITY VS. DISTANCE BELOW ARRAY

TYPICAL ΔT: 8-12°F

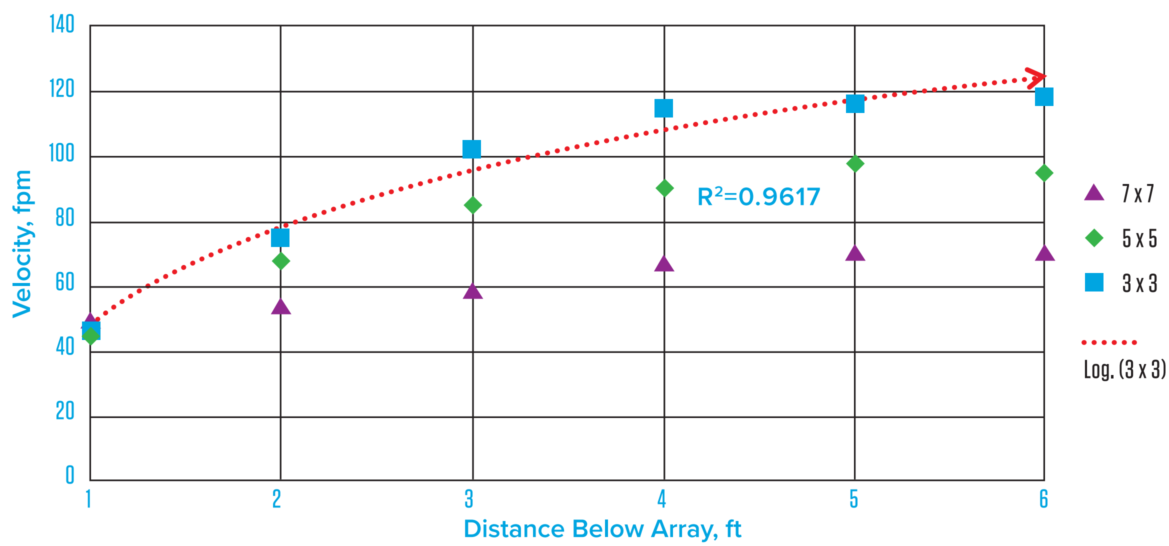


FIGURE 5

REDUCED ΔT: 2-4°F

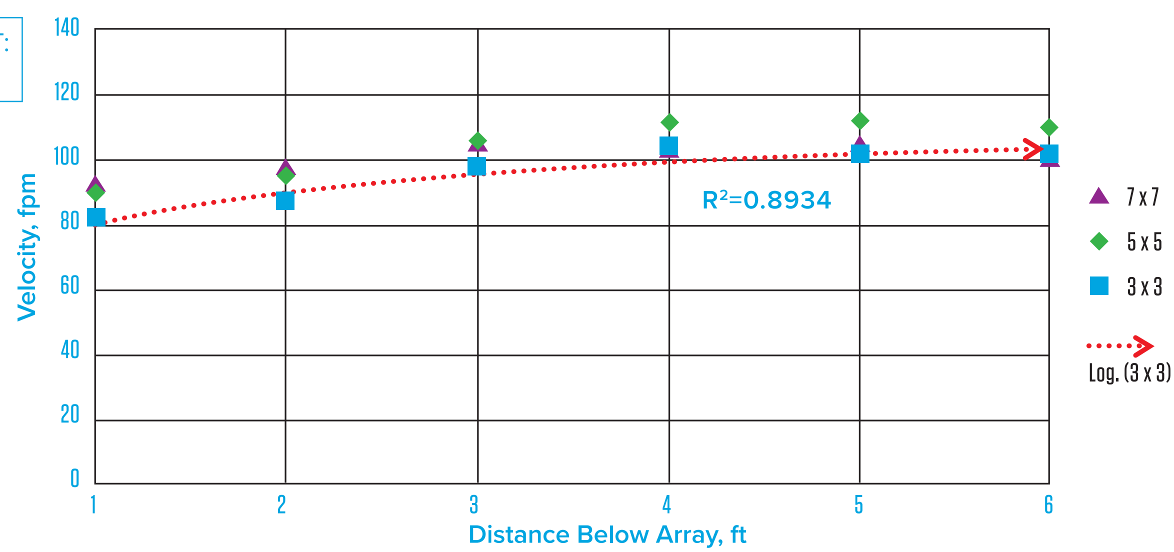


FIGURE 6

FIGS. 5 and 6: Display of increasing velocity averages taken at decreasing cross-sectional flow areas and a range of displayed distances below the 8' x 8' contiguous array of LFDs. Fig. 5 shows Typical ΔT while Fig. 6 shows reduced ΔT between the delivered air and the surrounding air.

working inward to 3' x 3', centered within the array. In all cases, there is some increase in the average as readings were taken farther downward from the array. However, the most notable increase in velocity is at the 3' x 3' center region.

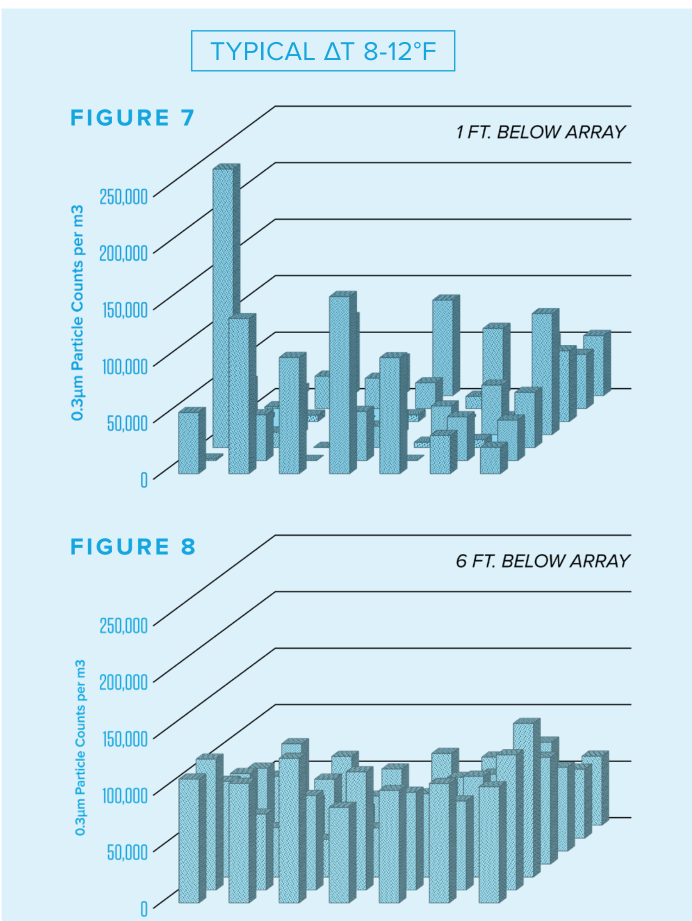
To contrast, **FIG. 6** shows the average velocities across the same array at a reduced ΔT, which were achieved by increased ACH and face velocity. This leads to a much more stable and uniform velocity profile across the entire array as opposed to the variability of the high ΔT.

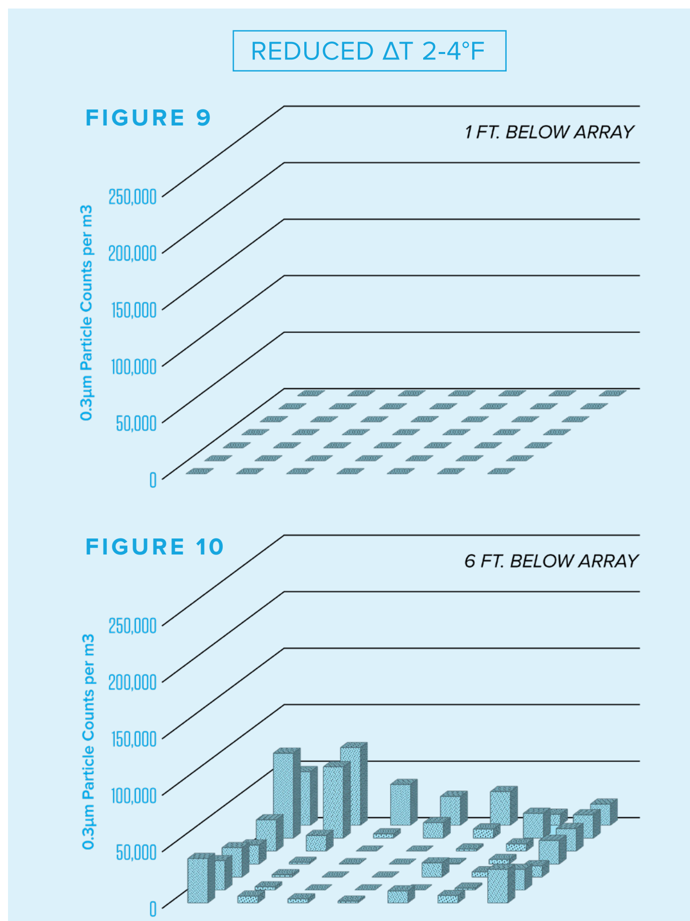
This acceleration can lead to entrainment and particle contamination at the patient level. Because there is not an actual physical boundary, but instead relatively stagnant air surrounding the flow, increasing velocities begin to form voids that act as vacuums pulling in particle laden air. Again, this is a repercussion of surrounding air entrainment that must be eliminated to keep the patient as safe as possible. **FIGS. 7 & 8** show the particle counts collected at stated distances below the LFD array with an 8-12°F ΔT. These graphs capture a cross-sectional flow area of 7' x 7' to illustrate the effects of entrainment, specifically within the array. In an ideal situation for surgery and patient protection, these particle counts should be zero.

FIGS. 9 & 10 show the drastic reduction of particle counts when the ΔT is decreased. Instances of higher particle concentration can be seen near the perimeter of the collection region, but the center region over the patient table is immensely improved and favorable for patient protection. Comparing **FIGS. 7 & 9** shows the entrainment of particles almost immediately below the array when there is a higher ΔT present. It is evident that the correlation between increased ΔT and the subsequent increased acceleration directly affects the increased magnitude of particle entrainment that reaches the patient table.

Finally, comparing **FIGS. 5 & 6**, there is evidence of the

PARTICLE COUNTS





FIGURES 7 AND 8:
Particle counts collected at a size of 0.3 µm/m³ and a cross-sectional flow area of 7' x 7' at stated distances below the 8' x 8' contiguous array of LFDs. **Typical ΔT** between the delivered air and the surrounding air.

FIGURES 9 AND 10:
Particle counts collected at a size of 0.3 µm/m³ and a cross-sectional flow area of 7' x 7' at stated distances below the 8' x 8' contiguous array of LFDs. **Reduced ΔT** between the delivered air and the surrounding air.

considerable difference that a decreased ΔT has on the performance of air in an OR. Again, the key takeaway is that increasing ACH reduces the temperature difference between the delivered and surrounding air, ultimately leading to cleaner air for the patient.

FIG. 11 is an overlay of the innermost cross-sections for both cases and their coinciding trendlines. The ΔT of 8-12°F reached a max average velocity of 118 fpm at patient level, while the ΔT of 2-4°F only reached 102 fpm.

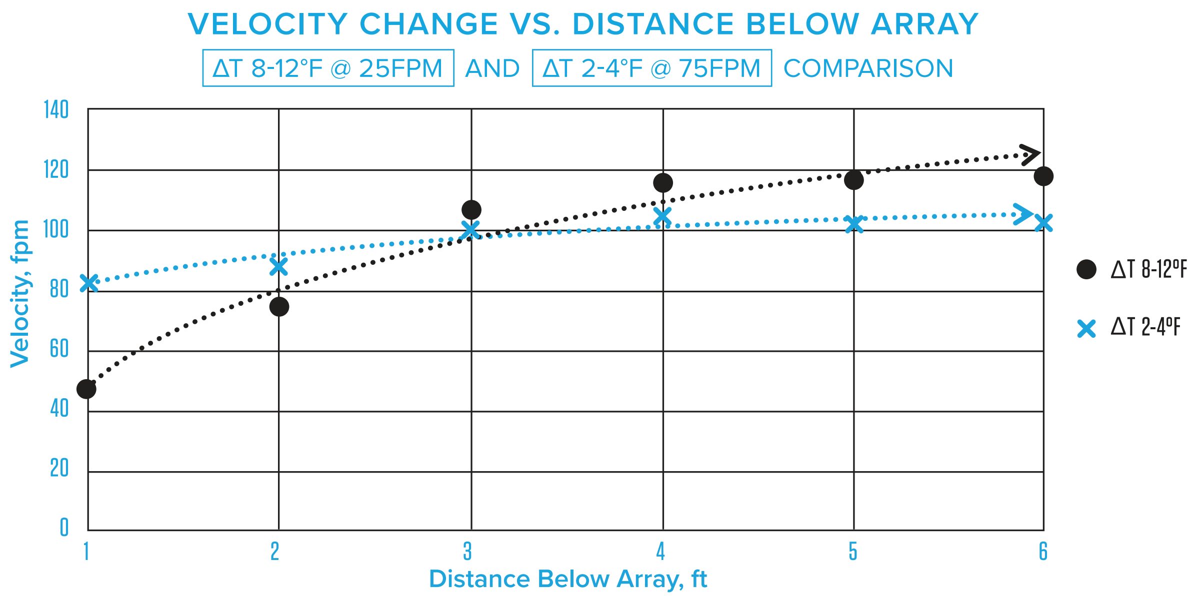


FIGURE 11: Display of each velocity average taken at 3' x 3' cross-sectional flow areas and a range of displayed distances below the 8' x 8' contiguous array of LFDs.

THE PRECISION AIR SOLUTION

To address some of the problems introduced, the SurgicAir Zero System closely maintains all the discussed air characteristics, including the ΔT that is often ignored between the LFD-delivered air and surrounding air. A standard OR design, compliant with ASHRAE 170, will characteristically see a ΔT of roughly 8-12°F. Such a large difference will easily cause one or all of the negative effects from acceleration and entrainment. The smaller the ΔT, the greater the reduction in contraction, acceleration, and entrainment. With SurgicAir Zero, the ΔT is maintained at approximately 2-4°F and, thereby, particle entrainment and compromised patient protection can be minimized or completely eliminated.

The air behavior is determined by a collection of physical air properties that if regulated separately and without regard to one another will mean the disruption of system control and patient protection. Exceeding ASHRAE 170's intended face velocity range of 25 to 35 cfm/ft^2 should be permissible so long as the velocity at the table remains acceptable. Exceeding this range under the conditions of a large ΔT might indeed supercool the patient due to increased air velocities at the center of the array. Contrarily, the situation at a greatly reduced ΔT produces velocities at the table that are much more stable. Increasing the air volume to the room and, in effect, the face velocity of a diffuser array makes maintaining a small ΔT between the delivered air and the surrounding room air possible without causing additional design complications.

More control and stability in air delivery is significant when discussing the issue of entrainment as well. By maintaining as many of the physical air characteristics as possible, the unwanted particle entrainment can be completely eliminated at the patient table. The reduction of ΔT between the delivered and surrounding air effectively prevents the formation of voids in the delivered air stream that act as vacuums pulling in surrounding air and the particles it carries. If particle contamination at the patient table can be averted, steps to do so should be implemented immediately. Entrainment of surrounding air is an avoidable threat still present in the OR today and the SurgicAir Zero System is the leading solution to eliminate this threat.

REFERENCES

1 Dharan, S., & Pittet, D. (2002). "Environmental controls in operating theatres," *Journal of Hospital Infection*, 51(2), 79-84.

2 Second International Consensus Meeting (ICM) on Periprosthetic Joint Infection (PJI). (2018). Philadelphia, PA. *www.icmphilly.com*

3 Birgand G, Toupet G, Rukly S, et al. "Air contamination for predicting wound contamination in clean surgery: a large multicenter study," *American Journal of Infection Control*. 2015;43(5):516-521.

4 Erichsen Andersson A, Petzold M, Bergh I, Karlsson J, Eriksson BI, Nilsson K. "Comparison between mixed and laminar airflow systems in operating rooms and the influence of human factors: experiences from a Swedish orthopedic center," *American Journal of Infection Control*. 2014;42(6):665-669.

5 Bischoff P, Kubilay NZ, Allegranzi B, Egger M, Gastmeier P. "Effect of laminar airflow ventilation on surgical site infections: a systematic review and meta-analysis," *The Lancet Infectious Diseases*. 2017;17(5):553-561.

6 Wang Q, Xu C, Goswami K, Tan TL, Parvizi J. "Association of laminar airflow during primary total joint arthroplasty with periprosthetic joint infection." *JAMA Netw Open*. 2020;3(10):e2021194. doi:10.1001/ jamanetworkopen.2020.21194

7 ASHRAE. (2017). ANSI/ASHRAE/ASHE Standard 170-2017. "Ventilation of Health Care Facilities."

8 Memarzadeh, Farhad & Manning, Andrew P. (2002). "Comparison of Operating Room Ventilation Systems in the Protection of the Surgical Site," *ASHRAE Transactions*, Volume 108, part 2

9 Khankari, Kishor. (2017) "Analysis of airflow distribution and contaminant flow path in the hospital operating room," *ASHRAE Transactions*, Volume 123, no. 1

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