Air Motion Control

In the Hospital Operating Room

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A source of contamination bypasses HEPA installations with every surgical procedure performed in the operating room (OR). That source of contamination is the surgical staff themselves, and the previously settled particles stirred up by their movement. Since a HEPA filter cannot control this source, and bioaerosols given off by the surgical staff are exuded continually during the procedure, we must turn to air motion control to maximize air asepsis.

The operating room environment is unique in that the procedures performed within its walls literally carry the effects of that environment into the patient's body. Since air touches every surface in the space, failure to maintain air asepsis risks exposing the patient to post-operative infection. Proper air motion control helps ensure that contaminated particles are not carried to objects that, in turn, contact the patient, or are not carried directly into the wound. Although air motion control is only one factor involved in controlling infection rates in the OR, controlling air motion is well within our grasp and should be considered in every design.

In hospital ORs, using HEPA-filtered air and downward, unidirectional, low-induction airflow (vertical laminar flow) are nearly *de facto* standards. However, many HVAC designers are unaware that these two methods alone may not ad-

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equately solve the problem of maintaining optimal air asepsis during surgical procedures.

While laminar flow diffusers, what the *ASHRAE Handbook* refers to as Type E air outlets,[1] appear to always solve the problem of air motion control, they may not adequately do so in all cases. In general, they do provide downward flow over the surgical staff and patient. However, stepping back from the diffusers themselves and looking at overall room air motion reveals another picture: one in which the behavior of the laminar diffusers is actually contributing to decreased air asepsis.

Laminar Diffusers Obey Laws of Physics

The normal environment for a laminar diffuser is a cleanroom, which typically uses a combination of high air change rates (Class 1000 cleanrooms, ISO Classification 6, can range from 70 – 160 ach); ceilings devoted to air distribution; floor exhausts; and controlled room pressure. In this scenario, laminar flow diffusers behave quite predictably, producing characteristic laminar flow. This is because the high air change rates help maintain conditions close to isothermal air supply. Ceilings devoted to air distribution reduce initial diffuser face velocities. Floor exhausts and controlled room pressure minimize areas of recirculation and help enforce the concept of "one pass, then out." Airborne particles are moved directly through the space with little chance to recirculate. The OR environment, however, is quite different.

OR environments typically require fewer than 25 ach. Additionally, it is common to have a supply air ΔT that is about 12°F (7°C) cooling. The rooms are normally positively pressurized at around 1 in. w.g., but this is done without the use of airlocks. And floor exhausts are never used, with the preference being low, symmetrical, sidewall returns. Also, a laminar array clustered in the center of the room in an island arrangement is given preference over devoting the entire ceiling to air distribution.

These differences may mean that the laminar diffusers will not be as unidirectional as intended. But more importantly, it means that overall room airflow may not behave as expected. This is because cold air is denser, and cold supply air will have a tendency to project itself downward from a diffuser much more rapidly than isothermal supply air.

When dealing with typical office ceiling diffusers, designers and engineers easily accept this premise. However, when dealing with laminar diffusers, there is a common misconception that they will produce unidirectional, low-induction, low-speed airflow regardless of the application. The laws of physics prevent this from being the case.

The reality is that cold vertical laminar flow will tend to accelerate as it moves from the ceiling to the floor. Exactly how much it will accelerate is a function of mass and potential energy. The more supply air there is, and the colder it is relative to ambient air, the more rapidly it will accelerate into the space.[2] *Figure 1* shows that a 32 ft^2 (3 m^2) laminar array with a supply ΔT of 15°F (9°C) cooling will result in a threefold increase in velocity just 6 ft (1.8 m) below the laminar panels.

As shown, an initial velocity of 30 fpm (0.15 m/s) would mean that the air could accelerate to more than 90 fpm (0.46 m/s) by the time it reaches the level of the surgical table.

That flows of this velocity in the OR are counter-productive has long been realized. In their CFD study of OR air distribution,[3] Memarzadeh and Manning note: "The systems in these cases [2,3,4,5,6,7, and 9] avoided the higher velocities typically associated with them, namely, 90 fpm (0.45 m/s) to determine if the laminar flow concept could be made to work practically." Their introduction lists studies by Salvati et al. (1982), and Lewis (1993), implicating laminar flow systems in higher infection rates and impingement on the wound site and note that "this seems to be based on the use of high laminar flow velocities...."

This is logical for several reasons. First, for the flow to reach these levels of acceleration from lower initial velocities, it must coalesce. This means that, even if the flow were unidirectional and low induction at that point, it would no longer protect the area defined by the laminar array boundaries, but a much smaller zone instead.

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Next, at 90 fpm (0.46 m/s), the flow is no longer low induction. Diffuser designers understand that velocities above 50 fpm (0.25 m/s) are capable of inducing room air into the flow. Ninety fpm (0.46 m/s) from a laminar diffuser is no different than similar velocities from conventional ceiling diffusers. The flow will induce slower, or stationary, room air.

Finally, the general room air motion set up by the physics of the space nearly guarantees the induction of pathogenic particles into the flow. This is because of recirculating air resulting from the need for room pressurization, which requires roughly 10% less air leaving the space than being supplied to it. Functionally, if less air is leaving the space than entering it, some air in the space must recirculate. By definition, recirculating air is aging air and, therefore, is gathering particles. These particles, being immediately adjacent to the accelerated airflow, can be induced into it. And, because of the coalescence, this particle induction could take place within the sterile zone we thought we were protecting.

Aside from the potential of inducing pathogenic particles into the space, there are additional problems caused by the high

Table 1: Effects of laminar area and supply temperature on velocity.[2]

	IP Data						
	Flow Rate	Ps	Velocity at 6 ft Below Panel				NC
			5°F ΔT	10°F ΔT	15°F ΔT	20°F ΔT	
	cfm/ft²	in. w.g.	fpm	fpm	fpm	fpm	
Single Panel	10	0.008	20	25	30	35	<20
	20	0.032	35	40	45	55	<20
	30	0.072	50	60	70	80	21
	40	0.128	65	80	95	105	25
15–30 ft² (1.5–3.0 m²)	10	0.008	20	30	30	35	<20
	20	0.032	35	45	50	60	22
	30	0.072	50	65	80	90	26
	40	0.128	70	90	105	–	30
Over 30 ft² (<3 m²)	10	0.008	25	30	35	40	21
	20	0.032	40	50	60	65	25
	30	0.072	60	75	90	100	29
	40	0.128	80	100	–	–	33

velocities. One is the possible erosion of squames from the exposed skin of the surgical staff. High velocities can contribute to this erosion, and might also result in directly depositing those particles into the surgical wound. Additionally, some post-operative infections are related to hypothermic conditions in the patient.[2] High velocities of cold supply air is one situation that could cause a hypothermic condition.

So, the laminar flow diffuser, which works well in the cleanroom, may be less than stellar when used in normal operating room conditions.

We are discussing only 32 ft² (3 m²) of laminar panels, only enough to protect the area directly around the surgical table. Larger arrays are necessary. ANSI/ASHRAE/ASHE Standard 170-2008, *Ventilation of Health Care Facilities*, suggests laminar panels have a face velocity of approximately 30 fpm (0.15 m/s), which is a supply volume of 30 cfm (14 L/s) per square foot (0.09 m²). In our example array this results in 960 cfm (460 L/s). At its recommended 20 ach, this gives us a 2,280 ft³ (64 m³) operating room. This is a bit small by modern standards. It is more common for an OR to be in excess of 4,800 ft³ (135 m³). This requires larger laminar arrays. Larger arrays mean increased cold air mass, more potential energy, and more of the flow to accelerate after leaving the diffuser.

As we move into larger operating rooms, such as those used for orthopedic surgery, cardio-surgery and the like, having a way to make laminar flow behave better becomes more important.

How Clean is Clean?

Aside from the problems with airflow, we really cannot be certain what level of asepsis any of the above conditions result in. This runs counter to the fact that most design guides and standards for hospital ORs implicate the HVAC system as a means for helping to control infections.

For example, Standard 170-2008 lists achieving asepsis as one of the purposes of the standard. And, the *HVAC Design Manual for Hospitals and Clinics*[4] notes that "a well-designed HVAC system ... minimizes the airborne transmission of viruses, bacteria, fungal spores, and other bioaerosols." It has a subsection devoted to the HVAC system's role in infection and hazard control. The *VA Design Guide Surgical Services*[5] states it directly: "The air supply system must be designed to minimize airborne bacteria from entering the sterile field, in addition to keeping the remaining operating room as clean as possible."

However, these same guides and standards never directly address the means of determining if a certain airflow method achieved a particular level of asepsis. Often, designers must look elsewhere for such information. In the case of the hospital operating room, this was addressed more than 30 years ago.

As early as 1975 the American College of Surgeons Committee on Operating Room Environment, or CORE, began studying air cleanliness in the operating room environment. CORE was a multidisciplinarian group consisting of doctors, engineers, scientists, infection control experts. One member was Willis Whitfield, the Sandia National Laboratory scientist credited with being inventor of the cleanroom. Another was Harold Laufman, M.D., Ph.D., a vascular surgeon and expert on operating room environments. At the conclusion of the study, CORE wrote the "Definition for Surgical Microbiologic Clean Air."[6]

The definition is important for two reasons. The first, as explained by Laufman,[7] is "The difficulty in directly applying the (cleanroom) particle count concept to the OR environment is that little or no relationship exists between total particle counts/ft³ and bioparticle counts/ft³." Next, the definition included the means for catching and counting microbes to determine air cleanliness and provided the language for stat-

ing that 'x' microbiologic air cleanliness was achieved under 'y' conditions. At its cleanest, it lists <1 viable particle per cubic foot of air (35 viable particles per cubic meter) as the cleanest level.

This definition picks up where most standards leave off. Most standards describe the means of achieving a particular type of environmental condition but do not directly address the results or a means of measuring them. The Definition of Surgical Microbiologic Clean Air takes the opposite approach: defining a means for measuring the results, and the language for stating the results.

Unfortunately, the definition is less than helpful in designing OR air-distribution systems. One of the requirements of the definition is that microbe counts be "taken during periods of normal work activity," or more simply stated, during surgery. This is logical since the conditions present during surgery are the conditions under which we need to measure air cleanliness. But, that leaves us with the need to design the system, install it and measure it over the course of several surgical procedures before we can know how well it works. As system designers, this puts us in an untenable position.

However, we need to understand we are not stuck with uncontrolled airflow in the OR, or that we cannot have a means of knowing the level of asepsis a system might provide before applying it to an OR.

Enter the Air Curtain

The essence of a cleanroom is the supply and exhaust working in harmony. Neither alone can achieve the "one pass, then out" type of particle control needed. By reexamining the supply and exhaust relationship in the OR, it is possible to correct some of the problems described above and obtain much improved airflow. We cannot devote most of the ceiling to air distribution as we might in a cleanroom. And, we cannot have any exhausts in the floor. These would be impractical to clean, and, therefore, unsanitary. The island arrangement of clustering laminar diffusers over the patient with low sidewall returns has much validity when it comes to achieving the general airflow we want in a cost-effective method. Systems that are too obtrusive, complex, or expensive are not good solutions for ORs.

Because of these factors, designers began looking at other means of making laminar flow more predictable, more like airflow in a cleanroom, but in less expensive, less obtrusive ways.

One means that has achieved a relative degree of success is the use of air curtains. The goal of an air curtain is to achieve a known, predictable, repeatable velocity differential between the laminar flow and a specialized perimeter flow. The perimeter flow is typically in the form of a narrow "sheath" of higher velocity air. While called a curtain, and generally thought of as a protective barrier that prevents reentraining contaminated air into the laminar flow, the air curtain is multifunctional.[2] Its main function is acting as a continual exhaust. And, it is this that causes it to make laminar behave better.

Visualizing the OR as being negatively pressurized by means of exhausts covering all four walls would make it easier to picture just how an air curtain works. In such a scenario, the supply air coming from the laminar island in the middle of the room would not only move downward, it would be forced to expand outward as well. This reduces any zones of recirculation, pockets of aging air that are gathering pathogenic particles (*dilution control*). It would prevent the coalescing of the laminar flow, preventing its acceleration, and ensuring that low velocity, downward flow encompasses the entire sterile area (*suppression*). It would aid the drawing away of bioaerosols from the surgical team (*extraction*). And, it would prevent the migration of contamination from outer portions of the room into the sterile zone (*isolation*). Dilution, suppression, extraction, and isolation are the four principles of cleanroom airflow.

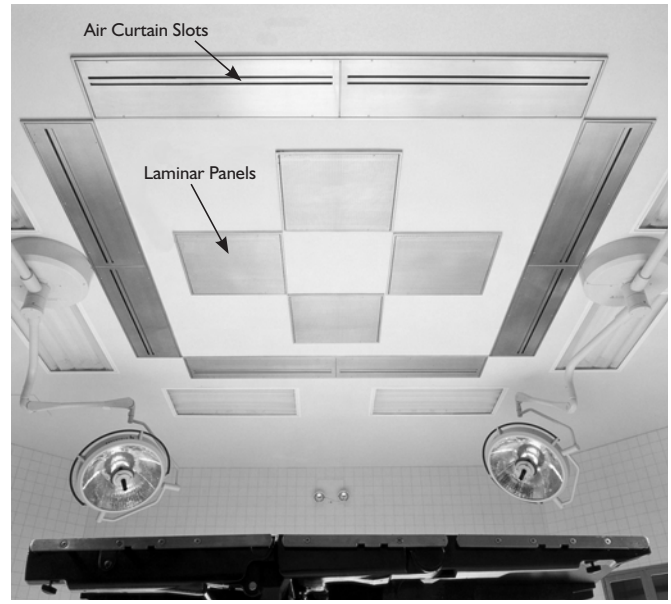

Figure 2: Layout of a typical air curtain system.

Figure 2 shows a typical air curtain system, centered in the room, with laminar panels inside the perimeter air curtain slots.

How such an arrangement helps prevent laminar flow from coalescing is important. With vertical laminar flow, we encountered the effects of cold air mass—the flow wants to accelerate upon leaving the diffuser face. The acceleration is compounded by the tendency of the air to coalesce as it accelerates. However, by placing a continual exhaust at the periphery of the laminar, we create a different effect. The exhaust forces the flow to expand, filling the zone inside the curtain. This prevents coalescence, and helps maintain the desired laminar velocity. *Figure 3* shows a computational fluid dynamics (CFD) model of the cross-section of an air curtain. Note that the laminar flow moves downward and outward, with the arrows representing its velocity being even. Also note that the general recirculation outside the air curtain (represented by the longer arrows) is prevented from entraining in the laminar flow.

Figure 4 shows the actual measured velocity of a properly designed air curtain. This data helps visualize the relation-

ship between the laminar flow and the air curtain, and validates the CFD model. Note that the center laminar flow is not accelerating.

A properly designed air curtain eliminates the impracticality of trying to install a full, four wall exhaust system in the space. Instead, the walls can contain the same general room exhaust normally used in an OR. The air curtain handles the zone immediately surrounding the surgical staff, controlling dilution, suppression, extraction, isolation, and providing velocity control. However, since it is not at the walls of the room, it must also add its most well known function: preventing the reentrainment of contaminated particles into the primary airflow.

Once we design our air curtain system, we are right back where we were with a conventional vertical laminar design: how clean is it? Or, what level of asepsis have we achieved under what conditions?

These are good questions to ask since it is just as possible to design bad air curtain systems as it is bad vertical laminar systems. One bad design would be having an air curtain that has a higher velocity than required. This would extract the laminar flow too quickly. Such a system might pull all the laminar flow outward before it reaches table level. The resulting absence of controlled downward flow (suppression) would risk pulling contaminating particles upward from the floor. Using a standard off-the-shelf slot diffuser may result in such a design. Of course, the opposite is true. An air curtain that is not exerting enough influence on the laminar flow may not control it properly. It may even be pulled into the laminar flow and revert the room back to the same conditions that would be encountered using vertical laminar alone. Using additional laminar flow diffusers as the air curtain might result in such a design.

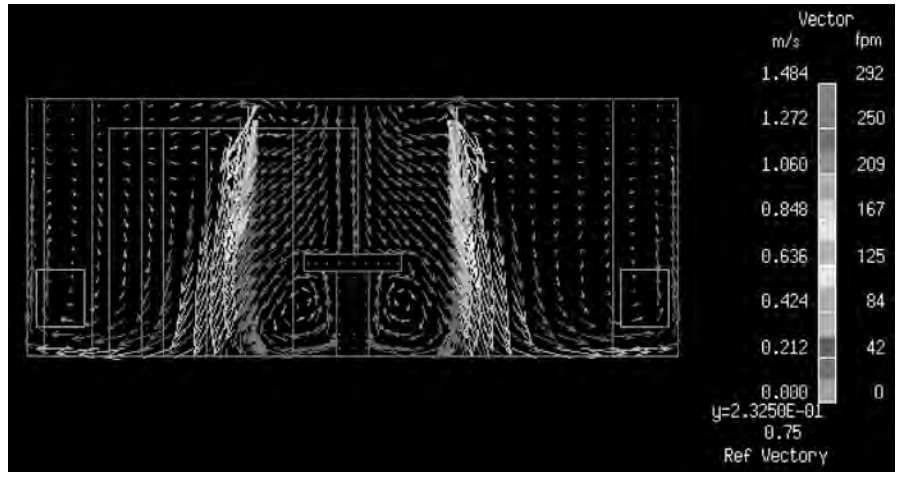

Figure 3: CFD analysis of a typical air curtain.

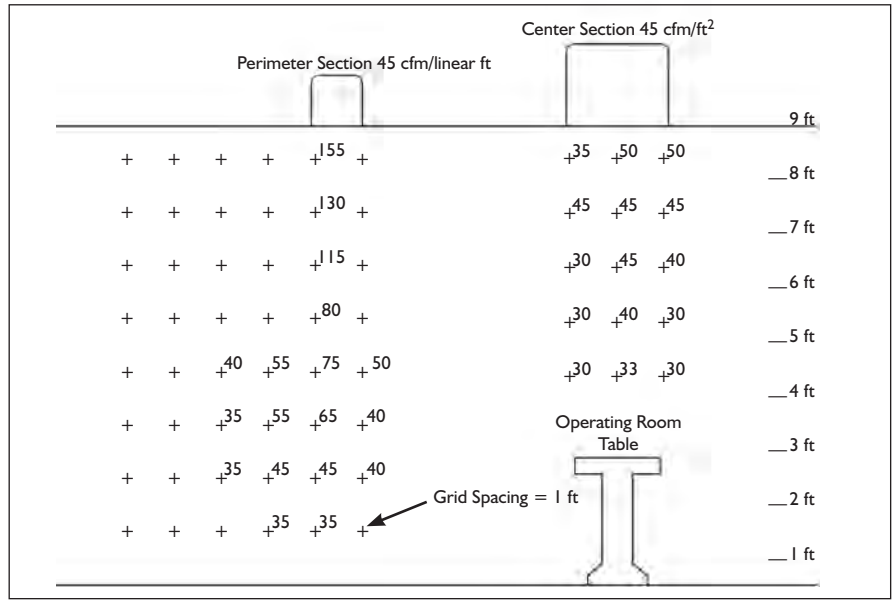

Figure 4: Measure velocity profile of a typical air curtain.

However, just the opposite is true. Once a proper range of velocities are established, it becomes an easy matter to ensure that any given system fits within the range profile. If a reliable means of controlling the air curtain velocity and the laminar velocity is established, then it is possible to create a scalar system: the design can simply be scaled up or down to meet any particular room's airflow requirements.

This has a direct impact on predicting its aseptic qualities. Once a scalable design is achieved, that design can be tested in accordance with the Definition for Surgical Microbiologic Clean Air. Since the proven design is scalar, there is no need to test every individual size variation.

Essentially, then, such a design makes it possible to have a pre-engineered, scalar, particulate control system in the OR with predictable aseptic qualities.

Fortunately for engineers today, there is no need to go down the road of designing and qualifying your own system. Many HVAC manufacturers make air curtain systems that have been qualified to CORE's Definition of Surgical Microbiologic Clean Air.

Despite the many advantages of air curtain systems, it would not be wise to apply them blindly. The ultraclean airflow that many air curtains are able to maintain during surgery are not considered necessary in all cases. One easy method of determining the level of air asepsis required is to simply ask the surgeons. (They may not know that they had a choice.) Standard 170-2008 states: "Surgeons may require alternate air distribution

systems for some specialized surgeries. Such systems shall be considered acceptable if they meet or exceed the requirements of this standard."

However, the intended use of the operating room may suggest that air curtains are a preferred solution. Laufman wrote[7] "Airborne organisms assume a proportionately more important role as a cause of wound infection when ... (2) a large foreign body is surgically implanted, as in complete joint replacement; (3) the patient's immune mechanism is suppressed; or (4) the quantity and/or virulence of the invading microorganisms is overwhelming."

For surgeries that are protracted; particularly invasive; affect sensitive areas of the body (such as the chest or cranial cavities); and for patients with compromised immune systems, airborne infections take on a proportionately larger role. For these types of surgeries and patients, the extra protection afforded by proven air curtain systems should be considered.

Summary

Vertical laminar flow may not behave predictably when laminar diffusers are used outside of the cleanroom environment for which they were primarily designed. This may result in general room flow that does not result in optimal asepsis. Air curtain systems help optimize vertical laminar flow, bringing it closer to the "one pass, then out" ideal of the cleanroom. The Committee on Operating Room Environment has written a Definition of Surgical Microbiologic Clean Air that establishes a means of determining the level of air asepsis in the OR. Air curtain systems can be designed to be scalar, preengineered systems that facilitate their being tested to this definition.

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