# Effect of Operation Room Geometry and Ventilation System Parameter Variations on the Protection of the Surgical Site

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## ABSTRACT

*In this study, airflow modeling and particle tracking methodologies were used to consider the effect of geometry changes—in particular, ceiling height variations—in an operating room (OR). The ceiling height of the OR was varied from 9 ft (2.74 m) to 12 ft (3.66 m) in 1 ft (0.30 m) increments, and a range of different air change rates were considered at each height—between 20 and 30 air changes per hour (ACH). The contamination of the surgical site was monitored to determine the primary effect of the geometrical and flow rate variations. The results of the study indicate that the ACH becomes an important parameter as the ceiling height is reduced. In order to explain this phenomenon, a mathematical study of the main driving forces in the room was made. In particular, a consideration was made of the Archimedes number (Ar) equation (ratio of Grashof to Reynolds numbers) in a simplified representation of the OR. The result of this consideration is that the contamination of the surgical site becomes sensitive to the value of Ar as the ceiling height is progressively reduced. A consideration of Ar is therefore recommended in the design of the ventilation system of an OR.*

## INTRODUCTION

The issue of using numerical analysis techniques to optimize operating room (OR) ventilation system design was addressed in Memzaradeh and Manning (2002). In this paper, use was made of both airflow modeling, in the form of computational fluid dynamics (CFD), and particle tracking techniques to assess the risk of contaminant deposition on the OR surgical site and back table for different ventilation system designs. The primary conclusions from this study were:

- Cases that have the same air changes per hour (ACH) show marked differences in terms of the percentage of particles removed via ventilation.
- The practice of increasing ACH to high levels results in excellent removal of particles via ventilation, but it does not necessarily mean that the percentage of particles that strike surfaces of concern will continue to decrease.
- The percentages of particles that hit the surgical site from the "main" or "nurse" sites are low—in particular, less than 1%. This is because of the relative dominance of the thermal plume caused by the surgical site. Only when the particles are released close to the site—in particular, the "surgery" source—does the percentage become significant.
- ACH is not as significant in the "surgery" source/"surgical" site analysis as design of the ventilation system. In particular, a lower percentage of particles hit the site in a case that has an ACH of 20 than one that has an ACH of 150.
- In a system that provides a laminar flow regime, a mixture of exhaust location levels works better than either low or high level locations only. However, the difference is not significant enough that the low or high level location systems are not viable options.
- Systems that provide laminar flow regimes represent the best option for an operating room in terms of contamination control, as they result in the smallest percentage of particles impacting the surgical site. The reason for this is that such a system provides a controlled, consistent column of air to the surgical site area, which is effective in sweeping the contaminant from the surgical site area and does not naturally create recirculation

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regions where contaminants can become trapped around the site. However, care needs to be taken in the sizing of the laminar flow array. A face velocity of around 30 to 35 fpm (0.15 to 0.18 m/s) is sufficient from the laminar diffuser array, provided that the array size itself is set correctly.

What was not addressed in that paper, however, was the effect that any changes in the geometry of the OR would have on the results. In particular, the change of geometry of most concern would be a reduction in the ceiling height of the OR. The reason for considering this parameter is that the original study suggested that there was a balance between plume generated by the heat-dissipated objects in the center of the OR and the flow generated by the diffuser array. Therefore, in this study, the issue of ceiling height was considered between sensible limits, namely, from 9 ft (2.74 m) to 12 ft (3.66 m) in 1 ft (0.30 m) increments, using airflow modeling and particle-tracking methodologies. Further, in order to better define the flow provided by the ventilation system, a range of different air change rates was considered at each height—between 20 and 30 ACH. This paper represents an extension to Memarzadeh and Manning (2002), intended to answer this issue.

## CASES CONSIDERED

### Numerical Models

The airflow modeling and particle tracking methodologies used in Memarzadeh and Manning (2002) are not repeated in detail here for the sake of brevity. In brief, the CFD package used was a finite volume based package (FLOVENT 1995), while the particle tracking methodology used was a Lagrangian-based algorithm based on Alani et. al (1998). In terms of validation of the airflow modeling section of the study, the 1998 publication titled *Ventilation Design Handbook on Animal Research Facilities Using Static Microisolators*, by National Institutes of Health, provided the most extensive empirical validation to date. The methodology and the results generated in the 1998 publication were peer reviewed by numerous universities and research organizations.

In this study, in order to analyze the ventilation performance of different settings, numerical methods based on computational fluid dynamics were used to create computer simulations of numerous room configurations. The performance of this approach was successfully verified by comparison with an extensive set of experimental measurements. A total of 12.9 million experimental (empirical) data values were collected to confirm the methodology. The average error between the experimental and computational values was 14.36% for temperature and velocities, while the equivalent value for concentrations was 14.50%. Also, the results of Memarzadeh and Manning (2002) were tested independently in an experimental operating room scenario and were found to be in good agreement (generally 15% to 20%).

The geometry of the baseline model used in this study is shown here for reference. The model represents a typical operating room layout in terms of number of surgical staff, lights, machinery, tables, and patient. The geometry and contents were suggested by a panel of physicians and engineers during the initial stages of the Memarzadeh and Manning (2002) study. Note that the ventilation system used in the baseline model represents the "best" ventilation system design, as calculated in Memarzadeh and Manning (2002). The general features of the baseline room are given in Figures 1 and 2 and Table 1 and are listed below.

#### *Description in brief*

*Room*

- 20 × 20 × 12 ft (6.1 × 6.1 × 3.66 m) high
- five surgical staff
- one patient

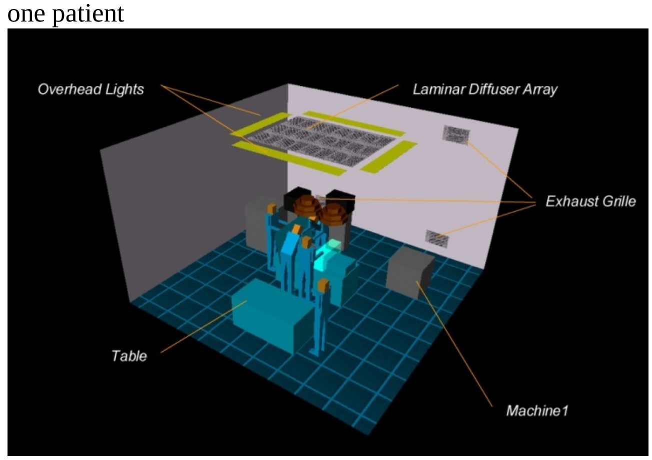


***Figure 1*** *Isometric view of ventilation system in baseline model.*

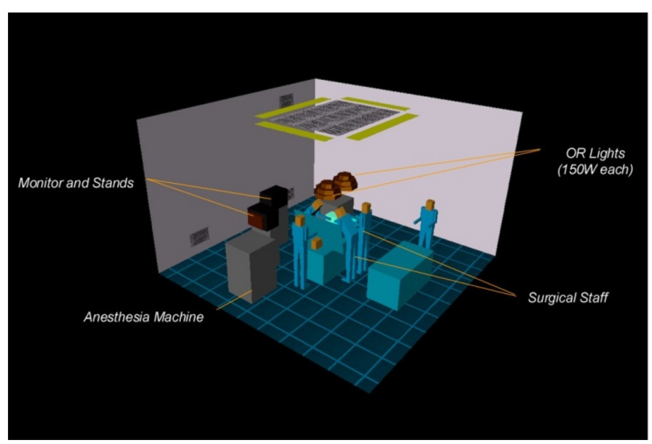


***Figure 2*** *Isometric view of geometry in baseline model.*

Table 1. Dimensions and Heat Dissipations of Major Items in Operating Room

| Item | Dimensions | Heat Dissipation |
|---|---|---|
| Operating Table | 30 in. wide × 30 in. high × 72 in. long | None—operating table only operates intermittently |
| Surgical Lights (×2) | 2 ft diameter × 1 ft hemisphere | 150 W |
| Surgical Staff | Height assumed as 5 ft 9 in. | 100 W Each |
| Anesthesia Machine | 30 × 30 × 48 in. high | 200 |
| Machine1 | 30 × 30 × 30 in. high | None—represents blockage only or intermittently oper- ating machinery |
| Mayo Stand | 10 × 30 in., located 8 in. above patient level | No |
| Back Table | 30 × 30 in. high × 60 in. long | No |
| Monitor and Stand (×2) | Stand: 12 × 24 × 40 in. high<br>Monitor: 16 × 18 × 10 in. high | Monitors dissipate 200 W each |
| Patient | With drape, patient covers most of table | Exposed head dissipates 46 W (70% of 65 W); Surgery site is 1 × 1 ft area with surface temperature = |
| Overhead lights (×4) | 6 × 1 | 180 W |

Table 2. Cases Considered in Study

| Case | Volume Flow Rate, cfm | AC | Supply Temp. | Supply Velocity fpm | Ceiling Height ft (m) |
|---|---|---|---|---|---|
| 1 | 1600 (0.76) | 2 | 67.6 (19.8) | 33.3 (0.17) | 12 (3.66) |
| 2 | 1467 (0.69) | 2 | 67.3 (19.6) | 30.6 (0.16) | 11 (3.35) |
| 3 | 2200 (1.04) | 3 | 68.9 (20.5) | 45.8 (0.23) | 11 (3.35) |
| 4 | 1333 (0.63) | 2 | 66.8 (19.3) | 27.8 (0.14) | 10 (3.05) |
| 5 | 2000 (0.94) | 3 | 68.6 (20.3) | 41.7 (0.21) | 10 (3.05) |
| 6 | 1200 (0.57) | 2 | 67.6 (19.8) | 25 (0.13) | 9 |
| 7 | 1600 (0.76) | 26 | 68.5 (20.2) | 33.3 (0.17) | 9 |
| 8 | 1800 (0.85) | 3 | 68.2 (20.1) | 37.5 (0.19) | 9 |

- one back table
- one anesthesia machine
- two monitors (and stands)
- one inactive machine
- two surgical lights
- dimensions of internal blockages are given in Table 1

*Supply*

- Laminar flow supply diffusers arranged in 6 × 8 ft
- (1.83 × 2.44 m) array immediately above operating table
- Supply discharge temperature, 67.6°F (19.8°C), set such that the exhaust air temperature was 72.0°F (22.2°C)

*Exhaust*

- Three exhaust grilles, each extracting 533 cfm (0.25 $m^3/s$)—two at 1 ft (0.3 m) above floor level, the other 1 ft (0.3 m) below ceiling level. In the cases considered here, the exhausts are considered on one side only
- 24 × 14 in. (0.61 × 0.36 m) grilles

*Heat Sources*

- Heat sources were those that could be considered constant, not intermittent sources
- Total cooling load, 2166 W (see Table 1)

Table 2 outlines the cases considered in this study. The eight cases show variations on the ceiling height and supply ACH in the OR. Note that Case 1 was originally presented in Memarzadeh and Manning (2002).

The source of contaminants considered in this study was squames. Squames are cells that are released from exposed regions of the surgery staff, for example, neck, face, etc., and are the primary transport mechanism for bacteria in the OR. They are approximately 25 microns (μm) by 3 to 5 microns thick. Approximately $1.15 \times 10^6$ to $0.9 \times 10^8$ are generated

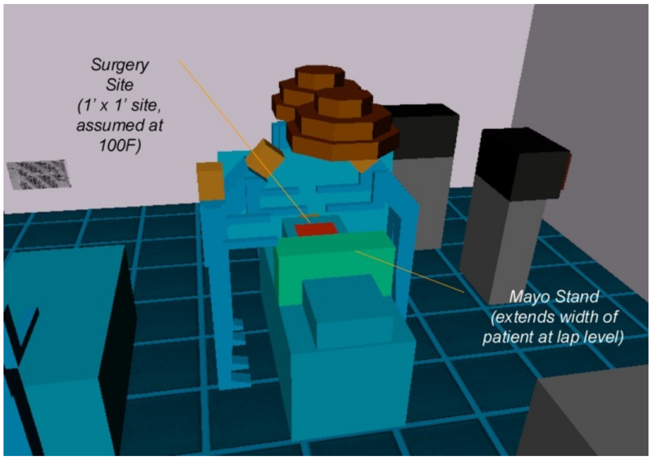


***Figure 3*** *Close-up view of surgical site and Mayo stand.*

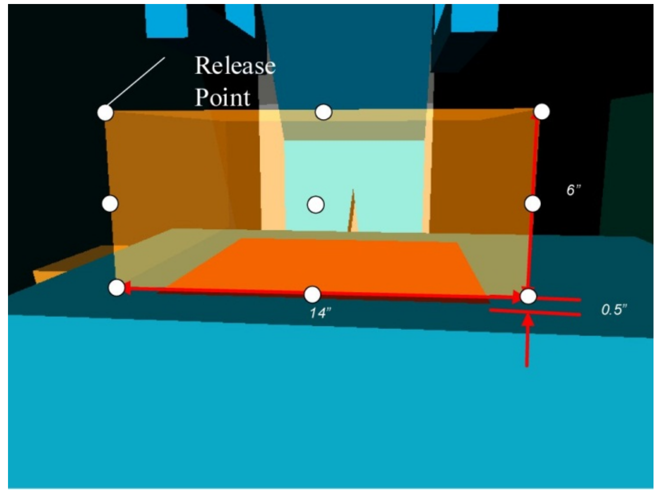


**Figure 4** *Detail of particle source over surgical site.*

during a typical (two to four hours) procedure (Synder 1996). For the purposes of this study, the surgical site was considered as a 1 × 1 ft (0.3 × 0.3 m) square, where the surface temperature was 100°F (37.78°C) and is shown in Figure 3. The Mayo stand, which is a device used to hold the surgical instruments during surgery, is also shown in Figure 3. The Mayo stand was included as it represents a blockage to airflow close to the surgical site and, as a result, could have an impact on the contamination rate of the surgical site.

In practice, it is not possible to consider as many particles as are actually generated during the operation due to computational run time constraints. Instead, a representative source of particles was considered, with the size of the particles set to approximate that of the squames. The particles representing the squames were considered to be released from a 3 × 3 × 3 pattern close to the surgical site. This source is shown in Figure 4, with the release points on the nearest face of the source displayed. The physical size of the source was 14 × 14 × 6 in. (0.36 × 0.36 × 0.15 m), with 500 particles released from each of the 27 points. This number was required to ensure that the results were consistent. The source was centered over the site and began 0.5 in. (1.27e-2m) above the surgery site.

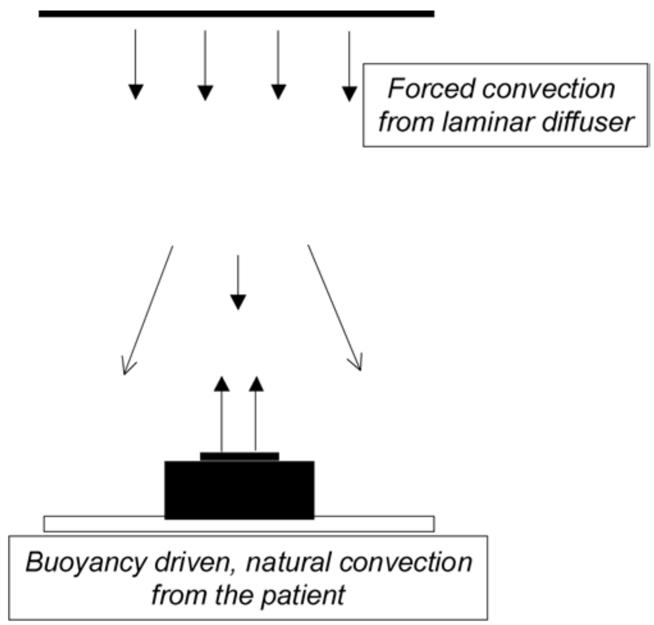


***Figure 5*** *Dominant driving forces in OR affecting surgical site.*

## Considerations of Airflow Conditions in Operating Room

It is useful to consider the issue of the different flow conditions in the room—in particular, those resulting from

- the major heat sources and
- the ventilation system.

In theory, the interaction of these two will become more significant as the supply is moved closer to the surgical site, i.e., when the ceiling height is reduced.

In a very simplified form, the flow pattern above the patient is determined by the two major driving forces: the forced convection from the diffuser and the buoyancy driven, natural convection due to the heat sources. This is demonstrated in Figure 5. The ratio of the strength of the two forces will determine if the forced air will take contaminants to the surgical area.

For the forced convection force, the characteristic time scale, $t_{forced}$, can be defined as

$$t_{forced} = \frac{L}{u} \tag{1}$$

**Table 3. Analysis of Contamination Rates for Different OR Ceiling Height/ACH Scenarios**

| Case | ACH | Supply Velocity fpm | Ceiling Height ft (m) | Ar | Percentage of Particles That Hit Surgical Site (from Close Source) |
|---|---|---|---|---|---|
| 1 | 2 | 33.3 (0.17) | 12 (3.66) | 8. | 1. |
| 2 | 2 | 30.6 (0.16) | 11 (3.35) | 9. | 2. |
| 3 | 3 | 45.8 (0.23) | 11 (3.35) | 2. | 2. |
| 4 | 2 | 27.8 (0.14) | 10 (3.05) | 11.03 | 1. |
| 5 | 3 | 41.7 (0.21) | 10 (3.05) | 3. | 2. |
| 6 | 2 | 25 (0.13) | 9 | 10 | 1. |
| 7 | 26 | 33.3 (0.17) | 9 | 4. | 3. |
| 8 | 3 | 37.5 (0.19) | 9 | 3. | 3. |

**where**

$L$ = characteristic length and

$u$ = velocity scale.

For the natural (or free) convection force, the characteristic time scale, $t_{free}$, can be defined as

$$t_{free} = \frac{L^2}{\nu}\frac{1}{\sqrt{Gr}} = \sqrt{\frac{L}{\beta g \Delta T}}, \qquad (2)$$

**where**

$\nu$ = kinematic viscosity,

$\beta$ = thermal expansion coefficient,

$\Delta T$ = temperature difference between maximum temperature and ambient temperature, and

$g$ = gravity.

The larger the time scale, the less important the corresponding driving force. Therefore, the ratio of forced convec- tion time scale over natural convection time scale can be considered as the relative importance of the two driving forces.

$$\frac{t_{forced}}{t_{free}} = \frac{\sqrt{L\beta g \Delta T}}{u} \qquad (3)$$

In natural convection, the Grashof number takes the place of Reynolds number, squared ($Re^2$), in forced convection; thus, the ratio of time scale can be related to

$$\frac{Gr}{Re^2} = \frac{L\beta\Delta T}{u^2} = \left(\frac{t_{forced}}{t_{free}}\right)^2 = Ar\,, \qquad (4) \quad 4)$$

**where**

Ar = Archimedes number.

Natural convection is generally considered dominant when Ar > 10. In this study, it is of interest to see whether the contamination level correlates to the value of Ar as calculated for the cases.

**RESULTS**

Table 3 shows the results from the eight cases in terms of the calculated Ar number and the percentage of particles that impinge on the surgical site from the contaminant source. The results show that the ventilation system used in these cases will generally provide good protection of the surgical site. This is

a legacy of the fact that the supply diffuser array is sized correctly, a point made in Memarzadeh and Manning (2002). As the ceiling height is reduced, however, there is a marked difference cal site based on the value of ACH. In particular, the difference

in the percentage between the 20 ACH and 30 ACH cases at each height progressively increases as the ceiling height is reduced. This dependence appears to correlate directly to the interaction between natural and forced convection forces, namely, the Archimedes numberin the number of particles that impinge on the surgi-

It is interesting to note that the percentage of particles that impinge on the surgical site generally reduces on decreasing ceiling height at 20 ACH. This highlights the value of the lami- nar flow diffuser array approach in the OR in that the flow pattern from the array is effective in sweeping the particles

from the area around the surgical site and out of the room. As this array is moved closer to the surgical site, its benefits are more evident. This benefit has to be tempered, though, with the knowledge that the ACH should be controlled to ensure lower

contaminant levels.

The difference between cases 7 and 8 is relatively small. The reason for this appears to be that although the ACH is increased, the difference in Ar is not substantial enough to

Dramatically increased the level of containment.

**CONCLUSIONS**

This study considered the effect of changing both the ceil-

ing height within sensible limits, namely, from 9 ft (2.74 m) to 12 ft (3.66 m) in 1 ft (0.30 m) increments, and the ACH, namely, between 20 and 30 ACH, on the level of contaminant present at the surgical site in an OR. This was done using airflow modeling and particle tracking methodologies. The results indicated that while the diffuser array generally gives reasonable contaminant protection for these parametric changes, there is a direct correlation between contaminant level and the Archimedes number, Ar, as the ceiling height is reduced.

An upper limit should therefore be imposed on the ACH used in the room. From the available results, the recommended range of ACH is 20 to 25. The main conclusion regarding array size, location, and face velocity drawn from Memarzadeh and Manning (2002) can therefore be readdressed as follows.

The recommended airflow rate in an operating room is 20-25 ACH (air changes per hour) for ceiling heights between 9 ft (2.74 m) and 12 ft (3.66 m). Systems that provide laminar (unidirectional) flow regimes with both high and low exhaust represent the best option for an operating room in terms of contamination control. A face velocity of around 25 to 35 fpm (0.13 to 0.18 m/s) is sufficient from the laminar diffuser array, provided that the array size itself is set correctly. The laminar diffuser array size should be set appropriately such that it covers at least the area footprint of the table plus a reasonable margin around it.

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