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REDUCING RISKS OF SURGERY



By Farhad Memarzadeh, Ph.D., P.E., and Andy Manning, Ph.D.

The risk of postoperative infection is present in all surgical procedures, but can be particularly serious in certain operations, for example, joint replacement. The National Institutes of Health (NIH), Office of Research Services, Division of Engineering Services, has conducted an extensive study on the issue of operating room ventilation systems and their effect on the protection of the surgical site.

Several factors can affect postoperative infection, including patient factors (e.g., susceptibility to infection), surgical field factors (e.g., the thermal plume from the site), room factors (e.g., cleanliness of the operating room), and HVAC factors (e.g., air change rate [ACH] and direction of airflow). *Figure 2* shows sources, routes and interactions of many of these factors.

The literature agrees that the primary source of bacteria that causes infection are squames, or skin scales or particles.¹ These particles are about 10 microns in diameter, and are shed from exposed regions of skin, both from the surgical staff and by the patient. In this study, only this source of contaminant is considered.

Suggested standards exist for air-conditioning systems for operating theatres in different countries. The standard for operating room design in Germany for example, is *DIN 1946/4*,² which had its latest revision in 1999. This standard contains some specific details for the design of the operating room, such as the supply air discharge, and defines a reference supply airflow rate. The actual amount to be supplied to the room, however, is defined using two factors, which require experimental measurement to be determined.

The *1999 ASHRAE Handbook—Applications*³ suggests that “the delivery of air from the ceiling, with a downward movement to several exhaust inlets lo-

cated on opposite walls, is probably the most effective air movement pattern for maintaining the concentration at an acceptable level.” The handbook suggests that the temperature range should be between 62°F (16.67°C) and 80°F (26.67°C), and that positive pressurization should be maintained.

It also suggests that the air should be supplied at the ceiling and exhausted or returned from at least two locations near the floor. It suggests that supply diffusers should be of the unidirectional type, and that high-induction ceiling or sidewall diffusers should be avoided. The suggested ACH is 15 for systems that use all outdoor air, and 25 ACH for recirculating air systems.

Some studies have considered the relative merits of different systems. However, studies such as Lidwell and Schmidt^{4,5} do not include specific system design data for these systems, so it is difficult to establish definitive recommendations for the actual design of the ventilation system. Further, conflicting data exists regarding the system that is generally recognized as the cleanest type of system. In particular, while laminar flow sys-

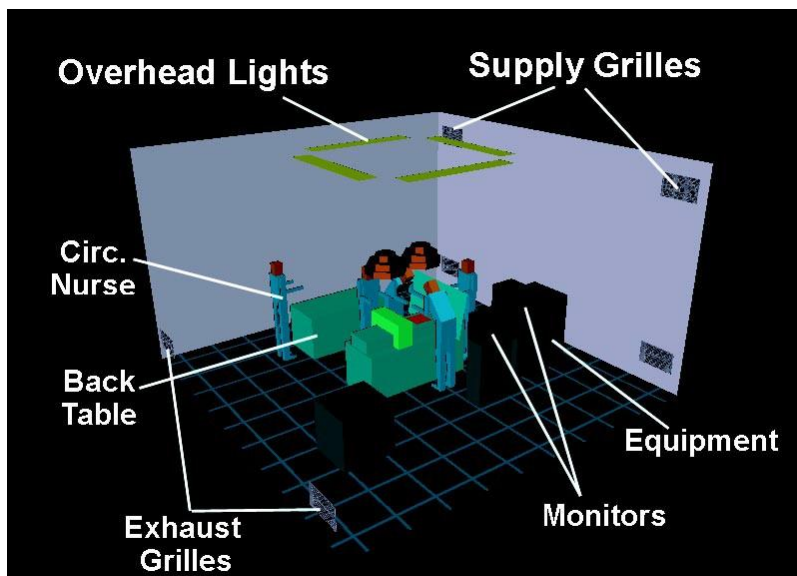


Figure 1: Layout of baseline operating room (Mayo stand view). This is a conventional system, with a volume flow rate of 1,500 cfm (0.71 m³/s) and an ACH of 18.75. The supply temperature is 67.5°F (19.7°C), supply velocity is 321.43 fpm (1.63 m/s), and conventional diffusers are used.

tems are recognized for providing lower general concentration levels in the room, they are sometimes blamed for higher infection rates than more conventional systems, for example, Salvati, et al.⁶ The theory put forward by Lewis⁷ is that laminar flow systems cause impingement on the wound site. However, this seems to be based on the use of high laminar flow velocities at supply. Schmidt⁵ defines a laminar system as having velocities of at least 90 fpm (0.45 m/s).

The previously mentioned studies were experiment based. However, an alternative technique, computational fluid dynamics, CFD, (sometimes known as airflow modeling) has proven to be powerful and efficient in research projects involving parametric study on room airflow and contaminant dispersion.^{8,9} Lo¹⁰ was the only CFD study identified in this literature search that addressed contamination control in an operating room.

However, this study made two assumptions that would make the conclusions less useful. In particular, the study only considered an isothermal operating room, and second, the contaminant was considered as a concentration. In the former case, therefore, the effect of significant thermal plumes in the room was ignored. In the latter case, the assumption that the particles in the room can be considered to follow Brownian motion of the airflow is strictly applicable to particles that are 1 micron or less in diameter.¹¹

While bacteria and viruses do conform to this criteria, as noted earlier, bacteria are usually transported in operating rooms by squames, which are considerably bigger (in the range of 10 microns), and so do not necessarily follow Brownian motion. For this reason, concentration sources were not used in this study. Another reason was that the use of concentration would make the question of impact of the particles on the

surgical site more difficult to determine.

In the study documented here, airflow modeling is used to consider the dispersion of squame-sized particles in various ventilation system design operating rooms. To establish the relative ranking of the different systems, two target areas of concern are considered: the surgical site and the top surface of the back table. The reason for the latter target is squames that strike this surface are likely to directly contaminate instruments.

The main purposes of the study are to:

- Use advanced numerical modeling and empirical data to evaluate the effects of some various room parameters on minimizing the risk of contamination of an operating room surgical site and a back table from specific particulate sources.
- Evaluate the same parameters to determine which ventilation systems evacuate the room of particles most effectively.
- Provide an architectural/engineering tool for good design practice that is generally applicable to conventional operating room use.

Methodology

The CFD code used in this study is a finite-volume code that has been validated against experimental data.¹² To analyze the ventilation performance of different settings, numerical methods based on computational fluid dynamics were used to create computer simulations of more than 160 different room configurations. The performance of this approach was successfully verified by comparison with an extensive set of ex-

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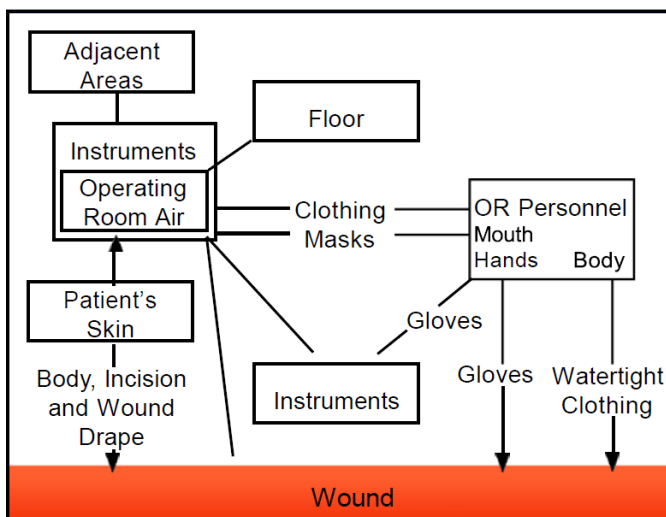


Figure 2: Source and routes of infection in operating room.⁷

perimental 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 14.5%.

In the case of the representation of squames, a Lagrangian particle-tracking algorithm was used to calculate their trajectories. Representative numbers of particles were released from appropriate locations in the room, as discussed later. As in the case of the CFD code, the particle-tracking algorithm was validated against appropriate experimental data¹³ while turbulence was incorporated into the Stochastic model via the k-ε turbulence model.¹⁴

The CFD and particle-tracking routine methodology are described in detail in Memarzadeh and Manning.¹⁵

Outline of Baseline Model

A typical operating room layout in terms of number of surgical staff, lights, machinery, tables and patient was considered for the baseline model for the CFD simulations. The room's dimensions are 20 × 20 × 12 ft (6.1 × 6.1 × 3.66 m). The general features of the baseline room (Case 1) are given in *Figure 1*.

A panel of physicians and engineers agreed upon the room layout during the initial stages of the study. Items such as gas columns were not included with the belief that they obstruct the free movement of large equipment in operating rooms, limit the placement and position of the operating table and are difficult to keep clean. Also, the panel thinks operating rooms should be moving toward connection of gas lines at the ceiling, since such lines would not provide significant blockage to airflow.

Other significant items of equipment, for example, a C-arm, were not included in this study, as the panel thought that they did not constitute "typical" equipment. It is recognized that such items may influence the airflow and temperature distribu-

Case	System	Volume Flow Rate, cfm (m ³ /s)	ACH	Supply Temp. to Maintain 72°F (22.2°C) F (C)	Supply Velocity, fpm (m/s)	Diffuser Types Used In Cases
1	Conventional	1,500 (0.71)	18.75	67.5 (19.7)	321.43 (1.63)	Conventional (Supply and Exhaust)
2	Laminar	12,000 (5.66)	150	71.5 (21.9)	30 (0.15)	Laminar (Supply) Conventional (Exhaust)
3	Laminar	1,200 (0.57)	15	66.2 (19.0)	37.5 (0.19)	Laminar (Supply) Conventional (Exhaust)
4	Laminar (Mixed Level Exhausts)	1,600 (0.76)	20	67.6 (19.8)	33.3 (0.17)	Laminar (Supply) Conventional (Exhaust)
5	Laminar (Low Level Exhausts)	1,600 (0.76)	20	67.6 (19.8)	33.3 (0.17)	Laminar (Supply) Conventional (Exhaust)
6	Laminar (High Level Exhausts)	1,600 (0.76)	20	67.6 (19.8)	33.3 (0.17)	Laminar (Supply) Conventional (Exhaust)
7	Unidirectional Flow with Curtains	3,000 (1.42)	37.25	69.7 (20.9)	25 (0.13)	Laminar (Supply) Conventional (Exhaust)
8	Upward Displacement	3,000 (1.42)	37.25	69.7 (20.9)	30 (0.15)	Upward Displacement (Supply) Conventional (Exhaust)
9	Non-Aspirating Diffusers	2,000 (0.94)	25	68.5 (20.3)	31.25 (0.16)	Non-Aspirating (Supply) Conventional (Exhaust)
10	Low Supply/High Exhaust	1,500 (0.71)	18.75	67.5 (19.7)	321.43 (1.63)	Conventional (Supply and Exhaust)
11	Goldman Concept ¹⁷	1,520 (0.72)	19	67.5 (19.7)	31.25 (0.16) & 320 (1.63)	Laminar (Supply) Conventional (Exhaust)

Table 1: Details of cases considered in study.

tion in the operating room, and that they should be considered in future studies. The total heat dissipated in the room was 2,166 W. Only constantly dissipating objects were included in the heat load.

Model Considerations

Several different ventilation systems were considered in this study (*Table 1*). The different systems considered are intended to replicate approximately those outlined in Schmidt.⁵ Figures representing eight of the cases are shown in *Figure 3*. Case 1 is represented in *Figure 1*. Case 3 is identical to Case 4,

Source	Physical Size	Particle Array	Position
Main	54 in. × 58 in. × 24 in.	3 × 3 × 3 (13,500 Particles)	<ul style="list-style-type: none"> Centered Over Bed Extends From Anesthesia Screen to End of Bed Begins at 4 ft (1.22m AFF)
Nurse	24 in. × 24 in. × 72 in.	2 × 2 × 2 (4,000 Particles)	<ul style="list-style-type: none"> Centered Over Circulating Nurse Begins at Floor Level
Surgery	14 in. × 14 in. × 6 in.	3 × 3 × 3 (13,500 Particles)	<ul style="list-style-type: none"> Centered Over Surgery Site Begins at 0.5 in. (1.27e–2m) Above Surgery Site

Table 2: Details of particle sources.

except that the laminar flow diffuser array is bigger. Case 5 is the same as Case 6, except that the exhausts are located at a high level in the latter case.

The various diffuser types considered in this project were modeled using a combination of several boundary conditions, which were validated prior to the room parametric study. Great care was taken with regards to the correct representation of the diffusers in the room, as well as the numerical grid used. The numerical diffuser models were validated against available manufacturers data to ensure that throw characteristics were matched accurately. This was performed for all the diffuser types (conventional grille, laminar flow, non-aspirating, displacement), and for an appropriate range of flow rates.

The number of grid cells used in these cases was on the order of 600,000 cells. Grid dependency tests were performed to ensure that the results were appropriate and would not vary on increasing the grid density.

Contamination Consideration

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 operating room. They are approximately 25 microns (mm) by 3 to 5 microns thick. Approximately 1.15×10^6 to 0.9 to 10^8 are generated during a typical (two to four hours) procedure.¹⁶ In this study, the particles would be tracked to see how many hit the back table, shown in *Figure 1*, or the surgical site. 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 4*.

Obviously, to keep track of so many particles in the study would not be feasible. Therefore, a representative number of particles were introduced from three arrays of sources. The locations and sizes of the sources, designated as Main, Nurse and Surgery (*Table 2*).

The Main source was intended to represent the general volume that the squames could be released from as the surgical staff passed around the table. The Nurse source was intended to represent the general volume that the squames could be

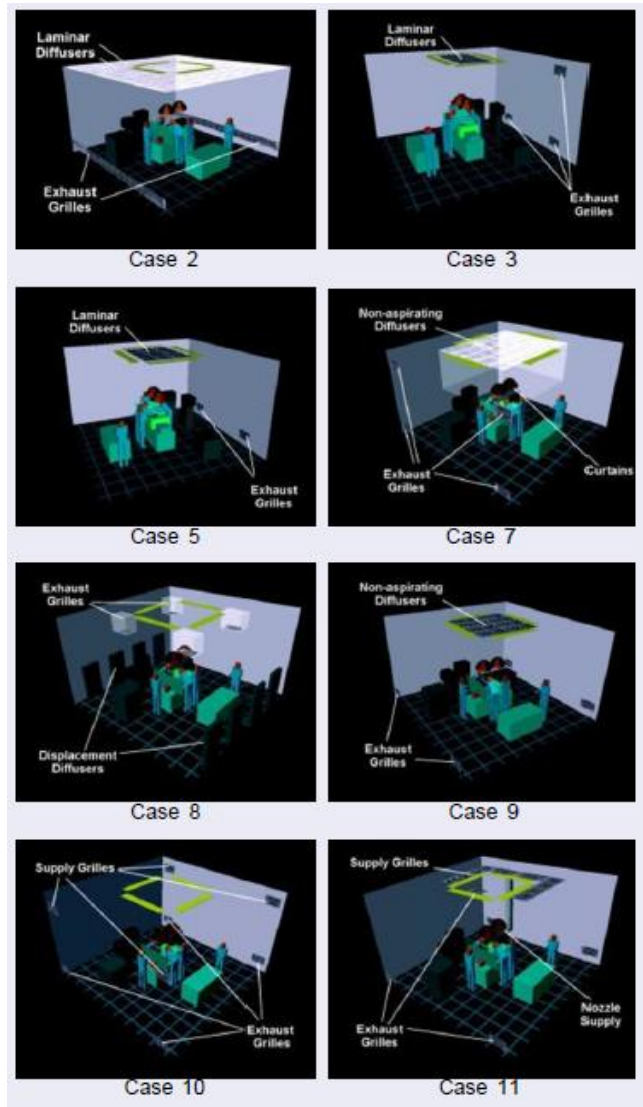


Figure 3: Eight cases with different ventilation systems.

released from the circulating nurse. Finally, the Surgery source was intended to represent the general volume that the squames could be released from the surgical staff as they leaned over the surgical site. Because the particles could readily pass to the instruments at this point, the Surgery source/top surface of back table target analysis was not performed in this study.

Tests were performed to determine how many particles were released from each point such that the analysis did not change. It was found necessary to release 500 particles from each of the source locations to ensure that the results were consistent.

Results

There are three potential particle outcomes:

- The particle vents from the room via exhaust grilles. In this case, the particle-tracking analysis is stopped.
- The particle strikes the surgical site or top surface of back table. In this case, the particle-tracking analysis is stopped.

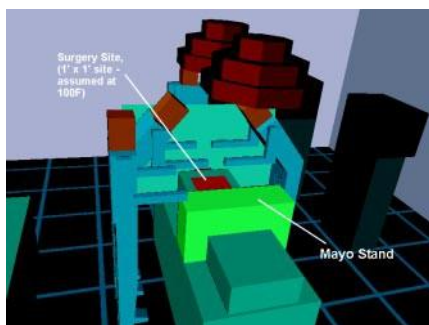


Figure 4: Surgical site and Mayo stand.

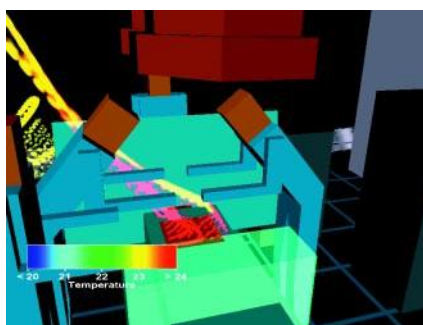


Figure 5: Thermal plume from surgical site in Case 2 (laminar design).

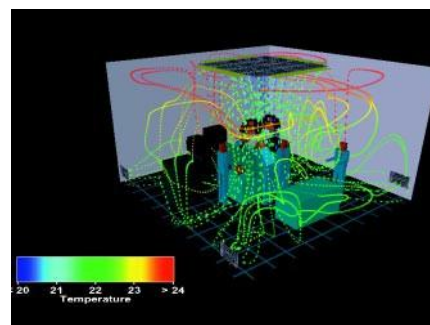


Figure 6: Flow field in Case 9.

- The particle remains in the room at the time when particle tracking is stopped.

The results are considered for two of the outcomes, namely the particle is vented via ventilation and the particle strikes a designated target, in terms of percentages of total particles released. The other outcome is a trivial calculation, namely:

Percentage of particles remaining in room at end of particle tracking analysis = $100 - [(\text{Percentage of particles vented from room at end of particle tracking analysis}) + (\text{Percentage of particles that strike surgical site or top surface of back table})]$.

In terms of the particles that remain in the room, the analysis shows that the particles either become trapped in recirculation regions (which they may exit after a long time), or fall by gravity to the floor in low velocity flow regions.

Percentage of Vented Particles

The percentages of particles vented from the room via ventilation at the end of the tracking period are given in *Table 3*.

The table shows a wide range in the level of effectiveness in removing the particles via ventilation. This is an expected result, but interesting points can be drawn from the results. First, cases that have the same ACH show marked differences in terms of the percentage of particles removed via ventilation. For example, Case 10 demonstrates a more effective removal of particles than Case 1. The reason in this example is that the ventilation system in Case 1 results in the formation of two large recirculations in the room where particles can become trapped. In Case 10 the ventilation system works with the thermal plume in the center of the room in driving the particles up to the high level exhausts.

Second, taking Cases 3, 4, 5, 6 and 9 as a group that adopts the same general approach to ventilation, the percentage vented becomes more uniform in terms of particle release location, though not necessarily in terms of magnitude, as the ACH is increased and the size of the supply array increases. The reason for this is that, for the smaller laminar arrays, the areas outside the direct influence of the supply have very low velocity flow fields. Here the particles tend to drop via gravity to the floor level, and remain in the room when the particle time limit is reached.

Percentage of Particles Striking Targets

Table 4 shows the percentage of particles that strike the surgical site or back table targets from the Main, Nurse and Surgery sources. As with the consideration of the vented out particles, several interesting points need to be made.

First, the percentages of particles that hit the surgical site from the Main or Nurse sites are low (less than 1%). This is because of the relative dominance of the thermal plume caused by the surgical site. For example, *Figure 5* shows such a plume for Case 2. It is only when the particles are released close to the site, in particular, the Surgery source that the percentage becomes significant.

Second, 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 Case 4, which has an ACH of 20, than Case 2, which has an ACH of 150.

Third, with the exception of Case 11, the percentage of particles that hit the back table from the Main or Nurse sites are relatively low. While there is no thermal plume preventing the particles from hitting the table, the particles only strike the target if they enter a region of low velocity flow, where the particles settle by gravity, or they are blown directly onto the table, which is the case in the high Nurse source value of 9.8%. The results for Cases 4, 5 and 6 indicate that a mixture of exhaust location levels is better than low or high only. Finally, the cases that can be placed together in a laminar flow type group, namely, Cases 2, 3, 4, 5, 6 and 9, do not show higher strike rates than the other systems. In fact, Cases 4 and 9 represent the lowest strike percentages of all the cases considered.

Conclusions and Discussion

From the previous results, the study showed:

- Cases that have the same 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 does not necessarily mean that the percentage of particles that strike surfaces of concern continue to decrease.
- The percentages of particles that hit the surgical site from the Main or Nurse sites are low (less than 1%). This is because

Case	ACH	Percentage of Particles Vented From Room After One Hour		
		Main	Nurse	Surgical
1	18.75	41.9	49.7	46.0
2	150	99.4	98.4	94.8
3	15	77.3	49.7	73.3
4	20	80.4	54.2	86.7
5	20	85.9	60.8	86.0
6	20	83.8	72.1	80.1
7	37.25	63.5	65.0	64.9
8	37.25	74.3	77.4	44.3
9	25	72.4	74.1	60.7
10	18.75	69.2	81.8	73.8
11	19	52.2	48.2	44.7

Table 3: Percentage of particles vented after one hour.

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. 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.

To expand on the issue of diffuser array size, it appears that the main factor in the design of the ventilation system is the control of the central region of the operating room. In particular, the operating lights and surgical staff represent a large heat density in the middle of the room. Particulates could become caught in buoyant plumes created by these heat-dissipating objects, at which point control of them is lost. However, if a laminar flow type system is employed, the particles are instead driven by the flow to be exhausted. Ideally then, the array size should be large enough to cover the main heat dissipating objects. This is illustrated in *Figure 6*, which shows the flow field for Case 9.

Further, another factor is the thermal plume created by the surgical site, shown for Case 2 in *Figure 5*. A laminar flow regime that provides air at 30 to 35 fpm (0.15 to 0.18 m/s) ensures that particles are not impinged on the surgical site, a danger highlighted by Lewis,⁷ as the thermal plume should be sufficient to protect the surgical site.

Case	ACH	Percentage of Particles That Hit Surgical Site			Percentage of Particles That Hit Back Table	
		Main	Nurse	Surgical	Main	Nurse
1	18.75	0.2	0.3	4.7	1.4	2.4
2	150	0.0	0.0	4.2	0.1	0.0
3	15	0.2	0.0	4.1	0.1	0.6
4	20	0.0	0.0	1.9	0.2	0.3
5	20	0.0	0.0	2.1	0.0	0.2
6	20	0.0	0.0	2.7	0.2	0.2
7	37.25	0.5	0.0	5.2	2.4	0.2
8	37.25	0.0	0.1	3.4	0.0	0.0
9	25	0.0	0.0	2.1	0.1	0.2
10	18.75	0.0	0.0	6.9	0.2	0.9
11	19	0.1	0.2	4.6	1.1	9.8

Table 4: Percentage of particles hitting surgical site or back table.

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