Particle Tracing: Analysis of Airborne Infection Risks in Operating Theatres

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Abstract: Patients undergoing surgery are very sensitive to infections. The operation staff may spread 10^4 particles per person per minute, of which ten percent are presumed bacteria-carrying. We visualize and analyse the influence of the personnel on the air and particle flows for the two most common ventilation systems in Swedish hospitals. *Comsol Multiphysics* is very suitable for the task with the new particle tracing module.The geometry was measured on two existing operating rooms in the hospital *Östra Sjukhuset* in Göteborg.

Our study shows that the Laminar Air flow-ventilation gives a much more controlled flow where fewer particles reach the patient than with conventional mixed ventilation where it is more likely that the staff unconsciously disrupt the flow. We also find that even for Laminar Air-flow ventilation it takes more than two minutes for the particles in motion to leave the room having implications for the time preceeding the operation when particles are assumed to settle.

Keywords: operation room, ventilation, post-operative infections, finite element simulations, particle tracing

1. Introduction

To judge which bacteria and particles have the potential of eventually leading to postoperative infections one has to know what particles are around, their size distribution and movements. In other words the source of the particles and their movement patterns is of particular value. The main particles of interest are human skin generated particles of size *5-6* μm with sedimentation velocities of the order of *0.3*m per minute, being the main carriers of bacteria such as *Staphylococcus epidermis* which land on instruments and the patient itself in the operation theater.

According to a study [1] the operation staff itself is the major factor for yielding the particles; typically of the order of 10^4 skin particles are released per person and minute. An estimate is that *10*% of these carry unwanted bacteria. The number of persons around, their clothing, physical activity, type of ventilation and door movements are therefore crucial for a good and clean environment [2]. Furthermore another study shows that there is a linear relationship between the number of airborne bacteria and the number of postoperative infections [3]. Measuring the number of colony forming units a good operation room should have less than *10* colony forming units per m^3 .

In order to fulfil stringent air quality conditions, hospitals have specific rules how personell should behave before, under and after an operation. One also classifies the operations themselves where some are more prone to yield infections than other like inserting a foreign object which facilitates the formation of an unwanted biofilm on its surface. Of major importance is of course how the ventilation system is constructed as well as its interaction with dead and live objects in the operation room. This is also the main factor studied in this paper.

Typicallly one considers three types of ventilation: Laminar Air-flow (Figure 1 top) where air flows down in a laminar manner over the patient from the roof and leaves the room at the floor and roof levels. Within the air flow only sterile personel are allowed. Figure 1 (bottom) shows another common ventilation type, turbulent or mixed ventilation, where air comes in from the side being mixed with the air already present. A third type of ventilation is deplaced ventilation where slightly cooler air is introduced at the floor level and being warmed up in the room raises and leaves the room at roof level. In this article, we consider only the first two ventilation types since they are most commonly found in Swedish hospitals [4]. We also notice that for a given configuration the air inlet velocity is a crucial factor for the over-all performance [5].

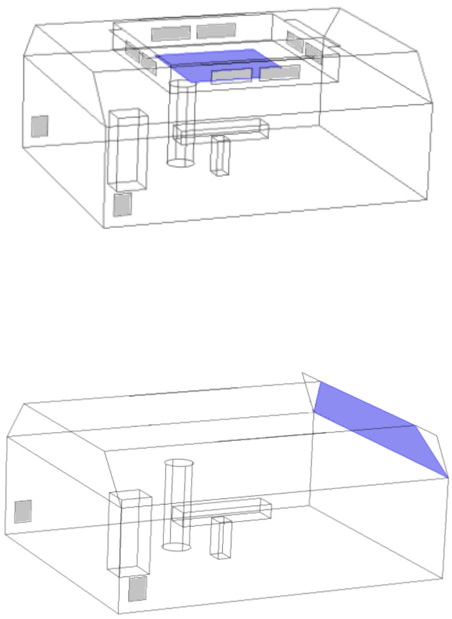

Figure 1. Operation room with Laminar Air-flow ventilation (top) and mixed ventilation (bottom). Air comes in through the blue areas and leave the room in the grey areas. Operation table, surgeon (cylinder) and equipment next to the operation table are also indicated.

In the following section we will introduce the parameters characterizing the real operation theater and describe how we imply COMSOL multiphysics to calculate ventilation patterns and particle trajectories. We present and discuss our results in the subsequent section and end the paper with our major conclusions and suggestions.

2. Modeling

In this chapter we present, implement and discuss simulations on the ventilation system in two operation rooms at a hospital (*Östra Sjukhuset*) in Göteborg, Sweden; laminar air-flow and mixed ventilation. The geometrical dimensions of the rooms were introduced into COMSOL Multiphysics 4.2a and are shown in Figure 1. All measures were parameterized in order to make it easier computationally to change the over-all scale of the rooms. The model as such was made as simple as possible still keeping in mind the most important objects in the room. Thus the model includes the operation table and a large piece of equipment just next to it for general aenesthesia. Staff present appears in the form of cylinders. This simple geometry is in fact sufficient to model the general behavior of the air and particle flows.

The position of lamps and their power was measured in order to include thermal effects on the air-flow. We measured the temperature in the room at the walls, roof, floor, air inlets and outlets using a warm thread thermometer *Velocicalc* model *9555 (+/- 0.3* C). Air velocities at air inlets and outlets were measured within +/- *1.5* cm/s.

In the COMSOL simulations we used an automatic generation of the mesh using a tetrahedral network with typical side length of *28* cm. A finer mesh was used in places where we have rapid air velocity and direction changes like at air inlets and outlets being *10* cm for the laminar air flow and *2* cm for the mixed ventilation. This mesh proved to be dense enough to yield sufficiently accurate results (which were confirmed by comparing results from simulations with several meshes of decreasing size), for a reasonably short simulation time (1-2 hours on a regular lap-top). Figure 2 below shows a represeentative picture of the mesh.

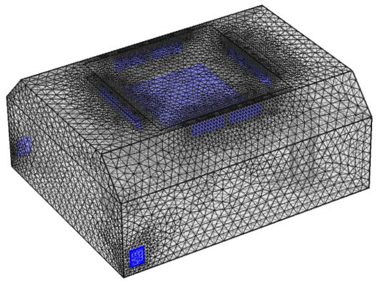

Figure 2. Calculational mesh for the operation room with Laminar air flow ventilation; blue areas indicate air inlets and outlets.

To simulate the effects of heat the module of COMSOL for *Heat transfer in fluids* was considered. However temperature differences were so small (*1* degree C or less) that no considerable effect can be observed, so in the final simulations no heat flow was considered. All temperatures were set to *20* C.

When simulating the air-flow we used modules for both turbulent and laminar flow (*Turbulent flow k-ε* and *Laminar flow* respectively). In short we used a finite element method to solve Navier Stokes equations for the air-flow. In all our simulations we used an ambient pressure of *1* atm and the air let into the room then created a slight over pressure as is also the case for the real operation room. Whereas the air-flow in the mixed ventilation is turbulent (air inlet velocity of *0.5* m/s) we found by comparing calculations that the flow in the laminar design is well described in the laminar model (air inlet velocity *0.3*m/s). The PARADISO method was used as numerical method in the laminar situation and a GMRES iterative solver in the turbulent situation.

An important feature of our work is to trace the particles which in the end could carry unwanted bacteria. The particle trajectories follow Newton's equations and in COMSOL we used the module *Particle Tracing for Fluid Flows* to encompass this. We used the humans as particle sources with particles sized *1* µm and a density set to that of water for simplicity. The calculated air flow was used as input for calculating the particle trajectories. Their initial velocity was set to *1* mm/s when leaving the source (surgeon, cylinder).

3. Results

In this chapter we give our main results from the simulations, to be further discussed below, starting with the laminar air-flow design and then turning to the mixed ventilation.

As mentioned above we did both a turbulent and a laminar calculation for the laminar air-flow design. Since the results were almost identical in the area where the patient is we conclude that the turbulence of the flow should not play any considerable role in this case, and present the result from the laminar flow simulations. Figure 3 shows our results. We notice in particular that

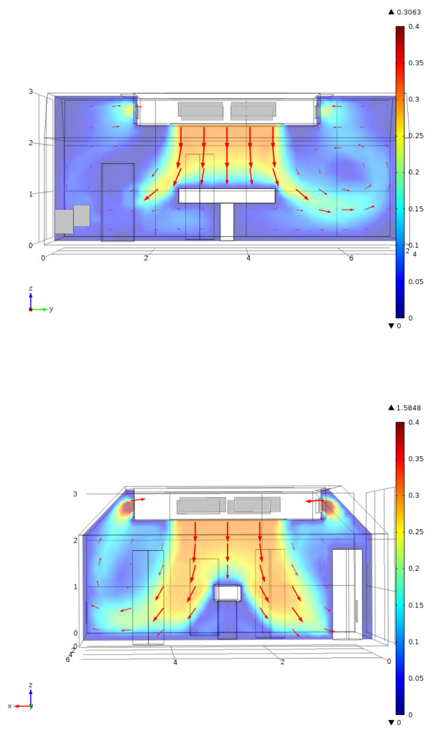

Figure 3. Two cross-secctions of the air-flow in the laminar air-flow design. Air (red arrows) move down from the overhead inlet and moves out through the (grey) outlets. Notice that the unsymmetrical position of these makes a vortice to the right. The color coding is in m/s.

the unsymmetrical placing of the outlets gives rise to a vortice in the part of the room not having an outlet at the floor level. The slanted roof features makes up for a smoother air-flow than straight corners would have made. We also notice that objects and people outside of the sterile zone do not significantly influence the air-flow over the patient.

Based on these observations we suggest a division into three zones (Figure 4) to convert our simulation results to a spatial representation of where sterility is a must. We suggest that the opening in the patient should be kept in the middle of zone 1 and special care should be taken by the personell in this zone to avoid crowding and making unnecessary motions that would disturb the air-flow. Any other activity than the operation, as well as additional equipment, should be restricted to zones 2 and 3.

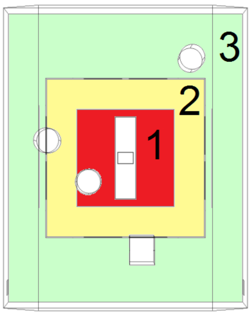

Figure 4. Suggested division of the operation room into three zones. The red zone is the most critical one corresponding to the size of the air inlet feature, while zone 2 and especially 3 has less influence on the air-flow around the patient. Zone 2 corresponds to the air outlets in the roof.

In Figure 5 (top) we show the particle trajectories in the laminar air-flow design for a person standing in the zone under the laminar air-flow. As can be seen most trajectories are such that they avoid the patient as well as do not touch the floor when being sucked out.

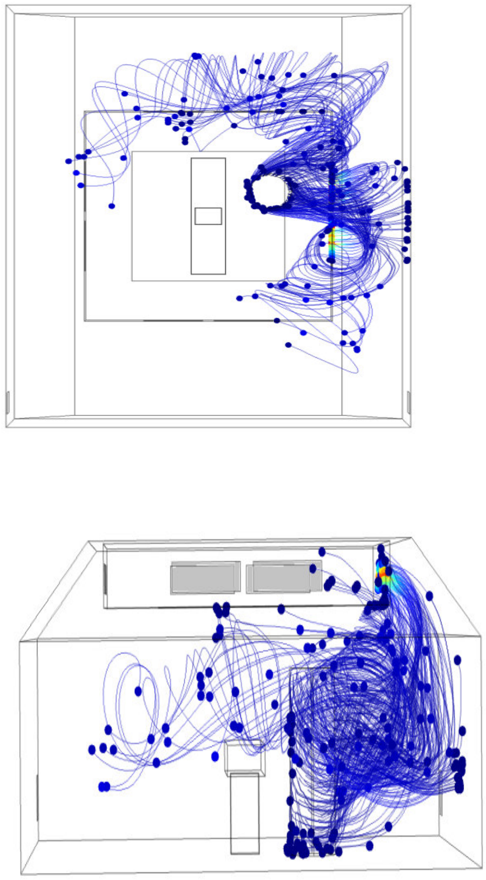

Figure 5. Particle trajectories in the laminar air-flow situation. Top shows particle positions (blue dots) after two minutes and their trajectories. Bottom the same from the side instead of from above.

We now consider the same situation for the mixed ventilation case as shown in Figure 6. Here air has to go a longer distance from inlet to outlet and is more sensitive to people being in the way. A situation easily occurs where a wake is created above the patient with almost no moving air at all which can have serious consequencies. Again doing a particle tracing calculation we see in Figure 7 how the air-flow should behave when the surgeon is in position. Almost no particles end up on the patient while if someone is standing in front of the air inlet there's a serious contamination risk. Vortices are created in front of and behind the person in questions and material is coming up from the floor contaminating the patient.

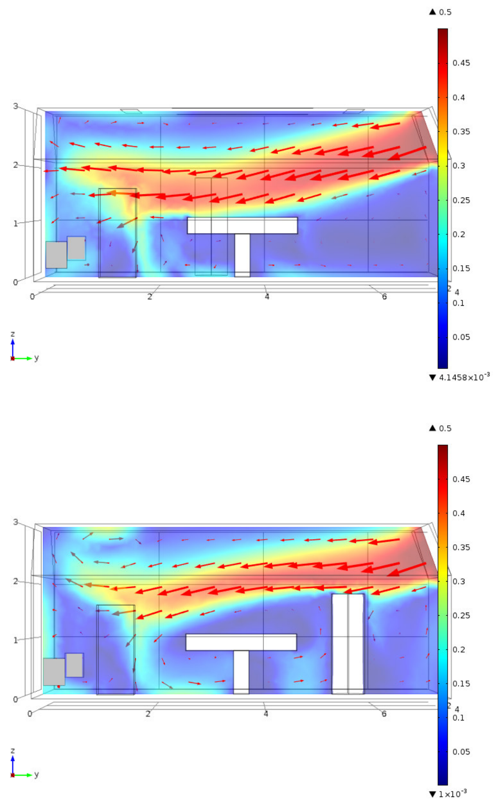

Figure 6. Two cross-secctions of the air-flow in the laminar air-flow design. Air (red arrows) move down from the inlet to the right and moves out through the (grey) outlets. The color coding is in m/s. The bottom figure shows the air-flow when a person is standing next to the operating table on the right hand side.

4. Discussion and suggestions for improvement

We have made a simulation of the air-flow in operation rooms with two different types of ventilation in a situation where the personell are static. In a real dynamic situation we would imagine that the disturbances and critical situations found here should be even larger.

In general we find that there is less air flow disturbances in terms of vortices when air outlets are at the floor level. The clean zone (zone 1 and 2 in figure 4) is marked in the operation room for the laminar air flow situation. We find from our simulations that it seems to be a reasonable area for static objects because of their negligible influence on the final impact on the patient. However, personell moving in and out of this area can possibly create disturbances as well as they act as new sources of particles.

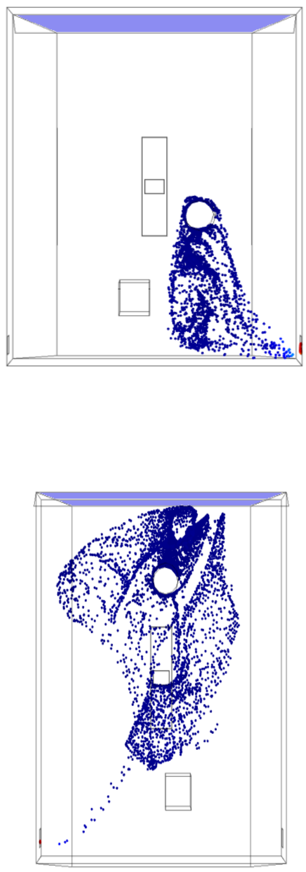

Figure 7. Particle positions after one minute after release for the mixed ventilation case. The top figure shows the wanted outcome when the surgeon is at the side of the operation table and the bottom figure the dramatic disturbance of the flow when a person is standing between the table and the inlet.

Of course of prime importance is that personell bending over the patient, being directly in the laminar air flow, have to be most careful, sterile and all measures being taken to eliminate their particle production. Notice also from our trajectory calculations that there is a large concentration of particles very close to the patient (figure 5) where only slight disturbances might bring them in over the patient. Since there are no air outlets on one side of the room at the floor level this increases the risk for unwanted contamination when the roof outlet naturally creates vortices in this part of the room. In other words one should avoid moving around to much in this part of the room. Finally we found for the laminar air-flow ventilation that it takes about two minutes for a particle to be transported out of the room. This indicates that one should wait at least this long before starting or continuing an operation if larger movements have taken place in the operation room.

When it comes to the mixed ventilation there is no well-defined sterile zone. It is also the most common type of ventilation around. We would suggest that one marks a zone between the air inlet and the operation table where no personell or equipment should be placed since it creates large disturbances in the airflow over the patient. In fact we find in our simulations that the air almost stalls over the patient meaning that particles have a long time at their disposal to settle onto the patient, instruments and alike.

Comparing to clean-room practice in industry one might think about introducing sticky mats on the floor where particles would be trapped. This is best when personell enters the room but our simulation shows that very few particles reach the floor during the operation and close to the operation table.

More and more robots are used for operations. They would not give off skin particles but could have other particles released from their mechanism which one should study carefully. Such a robot, and also for a "real" surgeon, one should study the possibility of introducing some kind of hood to pull down over the operation site controlling the local flow of air in a much better way than a general over-all installation as the ones we have studied. One should also in this context study if the over-all geometry of the operation room can be changed in an advantageous way.

We will continue our study by improving our simulations to take personell movement into account. We will also monitor one selected operation room with respect to important parameters needed as input for the simulations as well as checking the outcomes and reliability of the simulations. Having corroborated the findings in this initial analysis it should be possible to suggest the best position of particle-detectors in the room to alert the personell that a critical particle concentration is developing. We also envisage the need to develop a simple sensor to be placed near the patient which could give the surgeon an early warning that the bacterial or particle count is too high close to the patient.

We finally remark that our findings for the operation room can have implications for a number of other mileues where clean air is of importance such as different industries or in the transportation sector e.g. in airplanes. We should also point out that there is no single technical fix for the problem at hand. It has to be combined with the human factor; both when it comes to man-machine interaction as well as the way the staff behaves. The old saying "be few, keep quiet and stand still" is as important as before where one might think that a technical solution makes it possible to disregard such simple rules.

5. Conclusions

With a COMSOL modeling of the particle flow in an operation theatre we have found a way which gives hospital staff a powerful tool to understand the particle flows in the surgery rooms so they can take better precautions to reduce postoperative health care costs at the same time increasing patient comfort.

6. References

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