Visualizing bacteria-carrying particles in the operating room: exposing invisible risks

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ABSTRACT

Surgical site infections occur due to contamination of the wound area by bacteria-carrying particles during the surgery. There are many surgery preparation conditions that might block the path of clean air in the operating room, consequently increasing the contamination level at the surgical zone. The main goal of the current study is to translate this knowledge into a perceivable tool for the medical staff by applying state-of-the-art simulation and visualization techniques. In this work, the results of numerical simulations are used to inform visualization. These results predict the airflow fields in the operating rooms equipped with mixing, laminar airflow and temperature-controlled airflow ventilation systems. In this regard, the visualization uses a virtual reality interface to translate the computational fluid dynamics simulations into usable animations. The results of this study help the surgical and technical staff to update their procedures by using the provided virtual tools.

Keywords: Virtual reality, Ventilation systems, Bacteria-carrying particles, Surgical site infections

INTRODUCTION

The Swedish Board of Health and Welfare reported an annual death toll of 1500 patients due to surgical site infections (SSIs) in 2018, while the number of car accident deaths was about 500 persons in Sweden during the same period. These surgical site infections are caused due to presence of bacteria-carrying particles (BCPs) in the air. These particles are mainly released from the surgical team in the operating room (OR) and transported to critical regions via airflows (Hoffman et al. 2002). It has been reported that about 10% of the released particles from the surgical team carry bacteria (Noble 1975).

There is a demand for providing new tools to the surgical team to overcome this preventable health risk. In this regard, various ventilation strategies have been developed to reduce the contamination level at the OR's surgical zone. The three common ventilation systems are mixing, laminar airflow (LAF), and temperature-controlled (TcAF) ventilation systems. The mixing system reduces the BCPs level in the air through the dilution approach (Chen, Yu, and Lai 2006; Sadrizadeh et al. 2018)while the LAF ventilation systems supply a large volume of the clean air to the operating table (Chow and Yang 2005; Barbro 2012). TcAF ventilation is a recently developed system that performs based on the temperature difference between the central showers and ambient air temperature in the OR (Wang, Holmberg, and Sadrizadeh 2018; Alsved et al. 2017).

Several studies have shown that various factors, including the number of surgical staff(Sadrizadeh and Holmberg 2014; Cao et al. 2017; Birgand, Saliou, and Lucet 2015) and their behaviour, the frequency of door openings(Andersson et al. 2012; Lynch et al. 2009; Sadrizadeh et al. 2018; Perez et al. 2018), the type of medical devices affect the performance of the ventilation systems, consequently, increases the concentration of the particles which inevitably carry bacteria. The knowledge of airflow behaviour and particle distribution is not easily understandable since the airflow field and particles are invisible. Sadrizadeh et al. investigated the impact of the surgeon's posture on the BCPs level in the OR equipped with the mixing ventilation system. Their results showed that the surgeon's bending posture blocked the clean air path, consequently increasing the contamination level at the operating table.

The medical visualization techniques have been concentrated mainly on a single object, such as imaging from the patient body. This type of visualization improves the understanding of the current and past condition of the patient. However, there are no sufficient visualization tools to decrease the threshold for understanding the flow simulations' insights. This study aims to use a virtual reality interface to translate the computational fluid dynamics (CFD) simulations to an understandable animation. The long-term aim is to decrease hospital-acquired infections through better-informed decisions about medical and technical healthcare protocols.

METHODS

Physical Model

The simulated models' configuration is presented for the OR equipped with TcAF, LAF and mixing ventilation systems in Figure 1. The applied operating room model was replica of the New Karolinska Solna University Hospital in Sweden. The OR had size of 8.5 m (length) ×7.7 m (width) × 3.2 m (height).

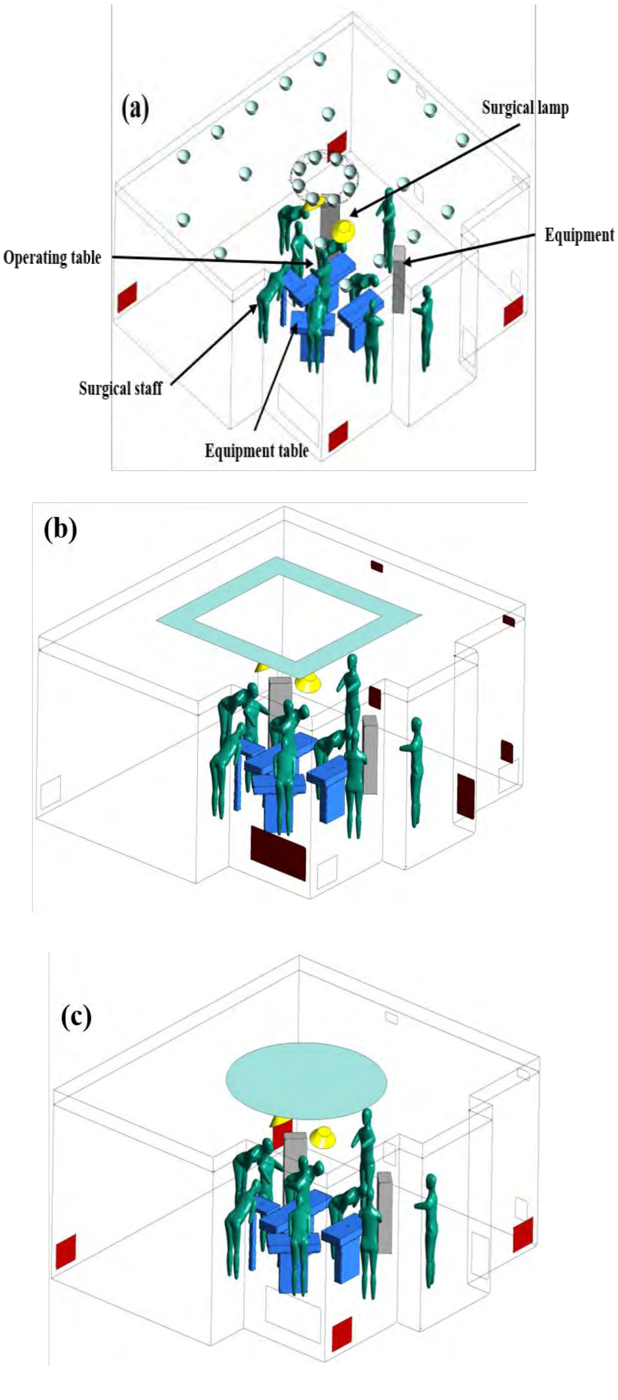

Figure 1. An isometric view of the OR with: a)TcAF , b)mixing and c) LAF ventilation systems

The air supplied to the OR equipped with the TcAF ventilation system with the airflow rate of 1.55 m^3/s. The central diffusers of the TcAF ventilation had the temperature of 18.5 ˚C while the surrounding diffusers had 1.5 ˚C temperature difference with the OR ambient temperature. All the supplied air diffusers had the surface area of 0.16 m2. In overall, there were four exhaust grills located at down part of two opposite walls in the OR using TcAF and LAF ventilation systems.

The mixing ventilation system had projected area of 8.64 m2 and supplied the clean air with flowrate of 2.0 m3/s and temperature of 20 ˚C. There were six exhaust grills located on two walls in the OR using the mixing ventilation system, as presented in Figure 1 (b).

The clean air supplied to OR equipped with LAF ventilation system with flowrate of 3.33 m3/s and constant temperature of 20 ˚C. The applied diffuser for supplying the clean air had the overall area of 10.17 m2, as shown in Figure 1 (c).

The operating table was located at the centre of the OR below the TcAF and LAF supply air showers with dimensions of a 2 m × 0.52 m × 0.9 m (length × width × height). Three equipment tables were around the operating table.

In order to model the surgical personnel in the OR, ten manikins were considered with constant heat flux of 50 W/m2. It was assumed that each manikin release the 5 CFU/s during the surgery. Two medical equipment were considered with constant heat flux of 255 W/ m^2 at the downside of the operating table. Moreover, two surgical lamps with constant heat flux of 250 W/ m^2 were used in the ORs.

Numerical Models

In order to predict the airflow field in the operating room the Reynolds-Averaged Navier-Stokes method was considered. Since the indoor airflow has a turbulent behaviour, the Realizable k- ε turbulence model was applied. The governing equations of mass, energy and momentum were considered to simulate the airflow.

To simulate the steady-state airflow field the CFD code ANSYS Fluent 19.2 was applied. The SIMPLE algorithm was used to couple the pressure and velocity. The no-slip boundary condition was assigned to all walls and it was assumed that all the OR walls had the adiabatic boundary condition.

In order to simulate the generated heat from the medical equipment and manikins, the constant heat flux condition was used.

The OR geometry was divided into 4.3 million grids through applying the ICEM CFD. The mesh independence study was accomplished to guarantee the independency of the results with grid resolutions.
The Lagrangian particle tracking approach with Discrete random walk method was used to predict particle distribution in the OR. The Saffman's lift force was considered while other forces were negligible in comparison with drag force. The bacteria carrying

particles had the diameter of 12 µm and were released from the head and leg of the manikins in the ORs.

Mapping simulation data to visual structures

In this section, we describe the steps to selecting and discretizing the most relevant data from the simulations to the interactive visual structures in a 3D space in virtual reality. Our goal was to have a practical and manageable data set that could be interactively analysed in real-time in a 3D VR environment.

As shown in Fig. 2, the first step of the process is to pre-compute the stable fluid dynamics of the environment given a fixed geometry. The second step is to create a stochastic real-time particle transport model. We want to know where particles will flow given an initial position and velocity in the stable airflow field. The third step is to compute, animate and visualize the flow of particles in the 3D model. Next, the fourth step, is to provide interactive control for the animations in a virtual reality visualization of the model. The fifth and final step is to, together with domain experts, analyse the risk of infections for a given model.

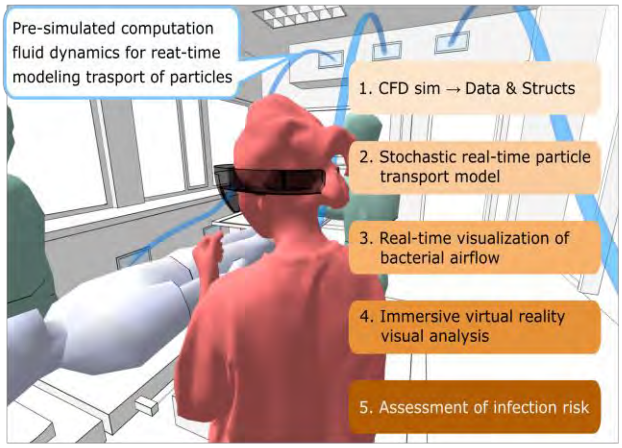

Figure 2. Mapping steps between CFD simulations and 3D immersive visualizations in VR.

A key point in the interface between simulation and visualization was determining the complexity of the data to visualize interactively in real time. The restrictions included the number of data points due to processing and visual limitations. Too many data points decrease the framerate of the rendering pipeline to the point that noticeable artefacts nullify the immersive experience. Furthermore, even with more powerful graphics hardware, there is a limit on what can be analysed in a 3-dimensional immersive space. Cluttered volumes of data are not practical for analysis as most of the overviews are self-occluding, forcing the user to spend significant time and effort filtering the views. We aimed at a compromise between completeness of data and practical interactive views.

For the handover of data, we defined a discrete number of points from which to release a practical amount of particles. We also selected a single slice of space to visualize the airflow as a vector field for each of the three ventilation conditions.

The release points include the nose and mouth of the main physician and the head and feet of all the people in the room. The points of capture were the room outgoing vents for the three layouts.

Visualization method

Our development and testing was KTH's Visualization Studio VIC[1], a state-of-the-art interactive computer graphics and visualization laboratory. We designed the visualizations using User-Centered Design (Abras 2004) and Participatory Design methods (Muller 1993). Our primary user in the first stage of the design were researchers in computational fluid dynamics, both co-authors of this paper and their colleagues. Our goal was for the team of researchers to understand the affordances and limitations of interacting with the data in a 3D immersive environment using heads-up displays (HUDs) and controllers. While the researchers understood the data and visual structures, the novel interaction environment needed to be tested.

We interacted on a number of low-fidelity prototypes and ran formative user studies until we arrived at the version we describe here. The studies included task-centric think-aloud protocols (Van Someren 1994), direct observations, interviews and focus groups (Gill 2008).

We created the 3D visualization environment using the Unity[2] game engine and we implemented the system on top of the HTC Vive Pro[3] virtual reality platform.

Unity is a cross-platform game engine developed by Unity Technologies, released in June 2005. Unity supports rapid graphics modelling, animation, interaction through a series of plugin extensions, including those necessary to run on mobile devices and VR headsets such as the HTC Vive. The engine has been adopted by both entertainment industries and academic research projects working on simulations and visualizations (Xu 2013).

The HTC Vive Pro is a virtual reality (VR) headset developed by Vive and Valve and introduced in 2015. The system includes a number of components aimed at providing room-scale immersion in 3D VR. Users can walk about their physical environment for up to a few meters at a time. The system includes the heads-up display (HUD) with earphones, controllers, infrared towers and driving software. The HUD and the controllers have patterns of infrared reflectors that are clearly detectable by the infrared projector - camera towers. The position and orientation of HUD and controllers are continuously tracked in real-time to

[1] https://www.kth.se/cs/cst/research/vicstudio
[2] https://unity.com/
[3] https://www.vive.com/eu/product/vive-pro/

provide a fluid and fully immersive user experience. Niehorster et al. (2017) provided a detailed analysis of the performance of the Vive applied to scientific research.

The most important questions when designing visualizations are: 1) who are the users? 2) What is the data? And 3) what are the tasks? In this research the target users are medical and technical staff in operating rooms. We aim at nurses and physicians to understand the impact of room layout and work practices on air flow and, ultimately, on the risk of infection. We aim to understand the impacts of human behaviour through visualizations of activity across space and time similar to the work presented in Gomez-Zamora et al. (2019), Romero et al. (2008), and Romero et al (2011). Furthermore, we aim at allowing engineers and scientists who design and maintain hospital ventilation systems to both understand and communicate the impact of their design choices.

In this research the data is the geometry of the room at key moments during operations and the CFD simulations of the airflow in those fixed geometries. This data framework includes greater details, such as velocity, temperature, vorticity and other details emergent from the simulations.

As mentioned earlier, the high-level tasks include understanding and communicating the impact of room layout, work practices, and ventilation design on the risk of infection by air-borne bacteria-carrying particles. The low-level tasks include filtering views to see different layers of the airflow, dropping particles into the flow field to track their movement across the room, playing, accelerating, decelerating, pausing and rewinding time, highlighting regions and particles of interest, displacing the views in space and time, zooming in and out of views, and re-scaling the models to provides both larger overviews and more nuanced detailed views. Users also need to be able to read data from the visual structures that include measures such as speed and temperature of particles and be able to quantify particles during a period of time over a region of space.

The other two main decision points in designing data visualizations are what visual structures to use, and what view transformations should be supported in those visual structures. These questions together with the three previous considerations frame the iterative design process. As one aspect of the visualization matures, others follow suit until the system matures. Card et al. (1999) provided a detailed account on designing visualizations, including the visualization pipeline.

Visual structures are graphical representations of data. For example, bar charts represent quantities by the length of the bar. In this research we chose three main visual structures. First, the geometry of the room is represented by abstract synthesized 3D models of the objects in the room. Figure 3 shows the simplified visual representation so of the solid objects in a real operation theatre. The model includes people, tables, lamps, ventilation equipment, walls, ceiling and floor plans. The objects can be hidden or viewed, yet the computed flow field remains, whether or not the object is visible. Users can also change the translucency of the solid objects to get a clearer view of the air flowing around them.

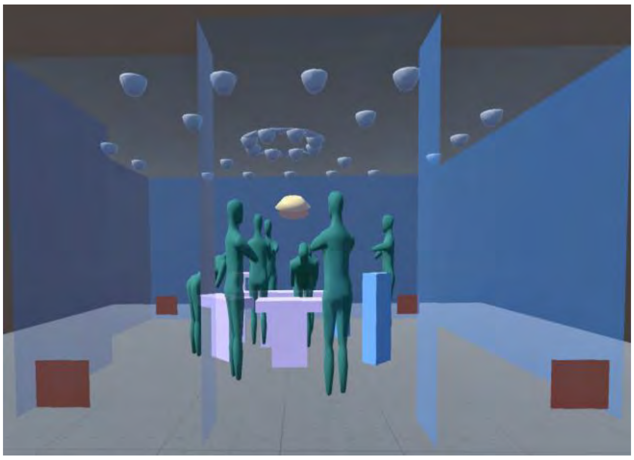

Figure 3. Fixed geometry of the room, objects and people.

For the second visual structure, we use a colorized vector field to represent the stable air flow in the centre of the room, the surface dividing the room in two directly above the operation table. The colour of the vectors is determined by the temperature of the air at that position. The colour scale uses the Jet colour map, from cool particles at 20 °C in blue to warm particles at 27 °C in red (Fig. 4). The length of the arrow (vector) is determined by the velocity of air in that location (the origin of the vector). Finally, we animate a white dot traveling the length of the vector, from base to tip, to provide the visual illusion of flow while using the VR (Fig. 4).

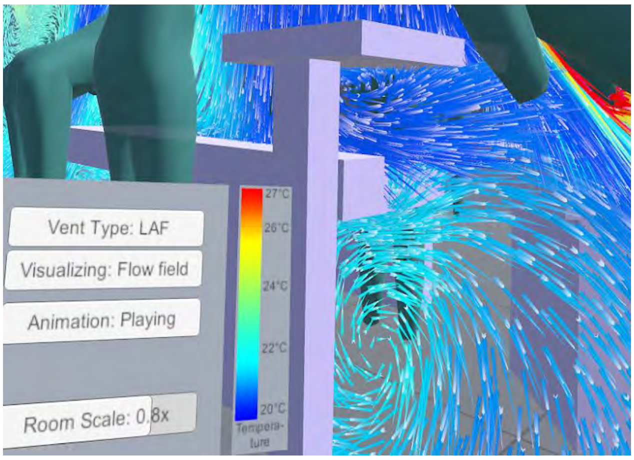

Figure 4. Details of the visual structure for the flow field.

The third visual structure provides two representations of individual particles dropped into the airflow field (Fig. 6). First, we visualize the individual particles as they move through space. We colour code the particles based on their speed, from red (0 m/s) to blue (32 m/s). Through the participatory design sessions we determined the scales and the mappings of all the visual structures. Finally, the second representation of air particles is the path that the particle travels from its source (the nose of the physician, for example) to its destination (the air ducts at the corners of the room). The user can view these paths from beginning to end and follow them closely. The paths are also animated by flowing a yellow-grey pulsating pattern down the length of the spline (path connected by discrete elements) (Fig. 6b).

The final decision in the design of visualization are view transformations. View transformations are the actions a user can take through interactive software to change what is visible about the data. In our project users can increase or decrease the field of view of the virtual camera, move in space, by teleportation in VR or by moving in physical reality, in order to inspect the details of a rendering or to get an overview. Users can change the scale of the colour mappings, alter the translucency of visual elements, filter particles based on temperature and speed and control the speed and direction of the animation. They can resize the room to focus on large-scale phenomena or minute details. Users can also select data from different simulations of different ventilation systems (Fig. 5). View transformations change the perspective of the visual structure to enhance human understanding of the data represented by the visual structure. In fact, visualization is a cognitive amplification through the interactive exploration of data through view transformations of visual structures.

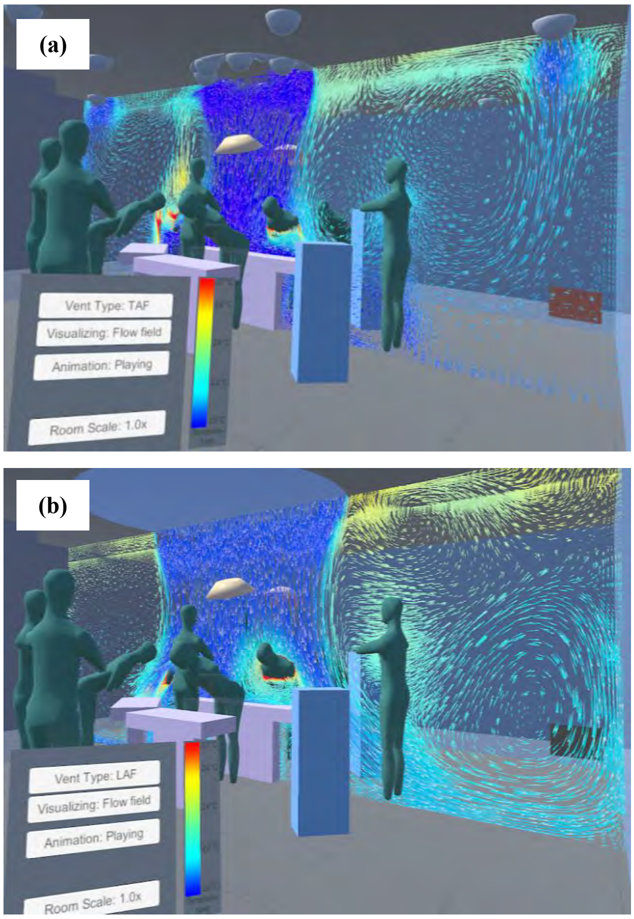

Figure 5. The airflow velocity vectors and temperature distribution in the OR with: a) TcAF, and b) LAF ventilation systems

RESULTS AND DISCUSSION

In order to visualize the CFD simulations, three scenarios were considered in the OR equipped with mixing, LAF and TcAF ventilation systems. In scenario one, the BCPs were released from the head of surgical teams; scenario two represented the BCPs release from the leg of manikins, and scenario three showed the particle distribution over the operating table when the surgeon is bent and releasing the BCPs. By applying the VR techniques the BCPs movement in the OR, temperature distribution and streamlines of the airflow were visualized. Figure 5 displays the airflow velocity vectors and temperature distribution in the OR equipped with TcAF (Fig.5 (a)) and LAF (Fig.5 (b)) ventilation systems. The colour of the velocity vectors were defined based on the temperature ranges, while the size of the velocity vectors was adjusted based on the value of the velocities.

The BCPs distribution around the surgeon is displayed in Figure 6. The movement of these particles was presented in the form of solid spheres (Fig.6 (a)) and streamlines (Fig.6 (b)). The colour of the animated particles were selected based on their velocity ranges.

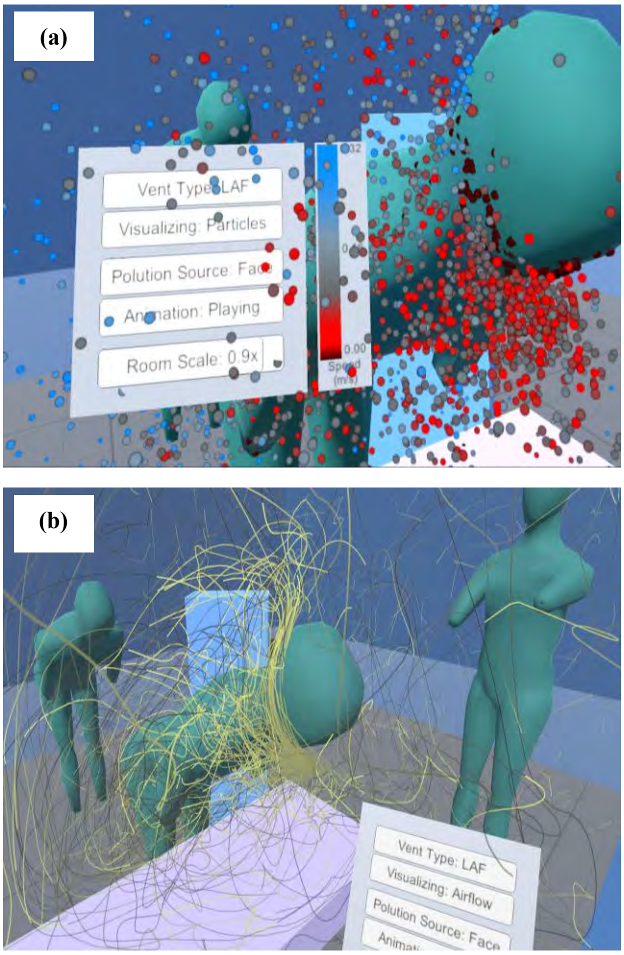

Figure 6. The BCPs distribution around the surgeon with: a) spherical shape and b) streamlines

We ran three summative evaluations of the system. First, we gave a lecture about computational fluid dynamics and the role of VR visualizations in understanding these simulations to a classroom of 70 master students in information visualization on 17th February 2020. Second, we ran a focus group with academic, governmental, and industry stakeholders on the same day. Third, we ran a focus group with domain experts from the healthcare industry (Figure 7-9).

The first summative evaluation was a live lecture using the virtual reality visualization of the CFD simulation in front of a live audience of 70 master students in the course DH2321 Information Visualization at KTH Royal Institute of Technology. For the lecture we prepared a set of slides explaining the users, the data, the tasks, the visual structures and the view transformations. We presented a number of images and videos explaining these concepts before delving into the interactive VR experience.

For the interactive VR experience we decided to split the task of navigating the immersive visualization from the task of explaining the data and the patterns within. We duplicated the perspective of the presenter onto a 4-meter 4K wall-sized display visible at high-resolution detail to everyone in the room (Fig. 8). One of the authors of the paper drove the visualization in VR. Because this researcher had to wear the heads-up display (HUD), he was situationally blind to the audience. He could not see what the audience was doing, read their expressions, or communicate non-verbally with them. For example, simple pointing gestures go unseen. For the task of explaining the data a second researcher shared the stage and spoke directly to the audience and to the first researcher driving the visualization. In order to share views for pointing and control, the researchers also split the controllers, so that both could point to regions of interest, both from within and from outside the VR. The researcher presenting the content pointed to patterns in the VR using the large screen. The researcher in VR simply pointed to objects directly in his field of view. The presenter outside VR communicated concepts to the audience and questions from them by directing the actions of the researcher in VR using language and pointing gestures with the controller.

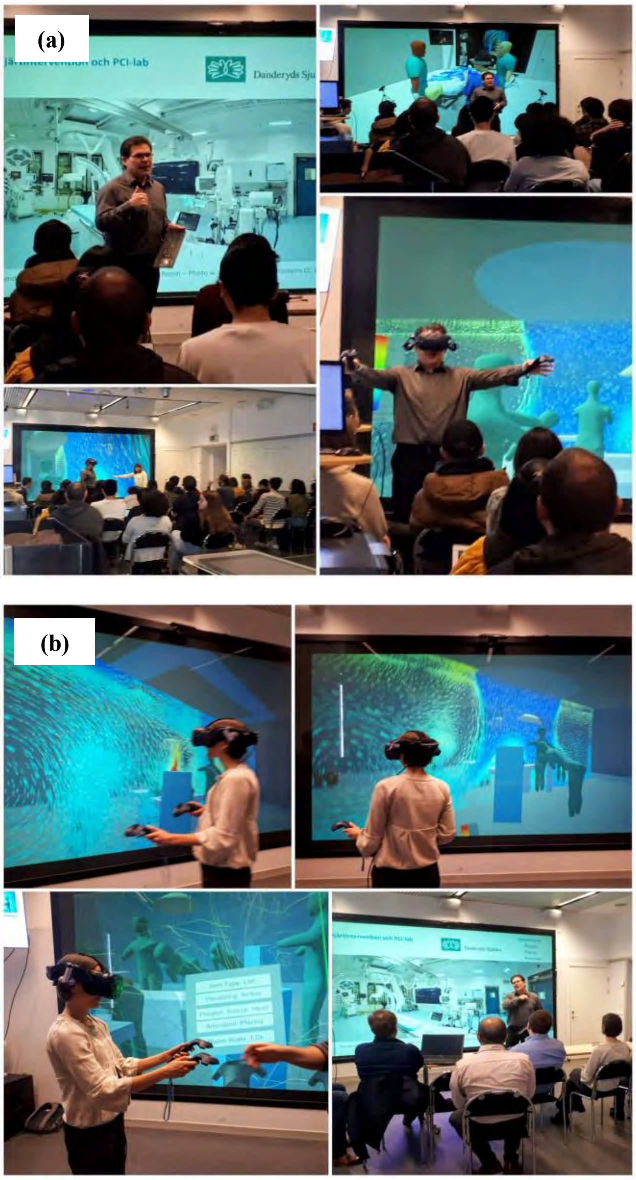

Figure 7. The interactive sessions for a) master students, b) academic, governmental, and industry stakeholders

Figure 8. The two presenters. One in VR; one in the classroom.

In Figure 8, the presenter on the left is in VR. The presenter on the right is guiding the actions of the presenter in VR through the control on her hand, which points, through the green laser, in the direction of the region of interest for the VR presenter. This presenter who is situationally blind, he can't see her or the audience. The controller is the medium for communicating pointing gestures. The presenter on the left is also pointing at the screen with her hand.

Figure 9. A student volunteer to run a user test live in front of the audience of other students.

Before the lecture we also trained for one hour six students to ask them to volunteer to drive the visualization and provide a think aloud evaluation in front of the audience. After the presentation by the two researchers concluded, we ran four think aloud sessions. The entire exercise lasted 2 hours.

After the lecture and user studies were over we discussed usability and effectiveness of the system in communicating patterns of airflow in operating rooms. We also collected a qualitative survey of the experience. Everyone found the system much more engaging than videos and images and all reported learning much better through the setup where people could ask the VR user to view a region of space and filter a data element and so on. The interactivity of the presentation experience allowed the audience to "feel much closer to the data and the patterns in it".

During the second and third summative evaluations we ran focus groups. In the first focus group we recruited eight executives from three agencies: the governmental funding agency of the project, FORMAS, the project's collaborating hospital, Danderyd, and the ventilation design and deployment industrial partner of the project, Avidicare (Fig. 7(b)). For the second focus group we recruited two medical physicians and researchers from Danderyd Hospital.

Similar to the experience in the classroom, we split the time into traditional slides describing the project, a live demonstration with the roles of presenting split between the same two researchers and a volunteer hands-on demonstration with participants of the focus group. In the focus group discussion, we identified a number of clear affordances and limitations with current technology. The clear affordances included the immersive first-person perspective of the outcome of the simulations. Air is not visible and people were truly shocked and intrigued by the visualization of moving particles. A common reaction was: "I never thought there could be so many particles moving all over the place, even while wearing surgical clothing". The ability to track individual particles and particle paths while controlling time was a powerful mechanism to understand and communicate transport of contaminants in the air. The participants were excited with the possibility to train nurses and medical doctors to understand the impact of their practices in the quality of air transport with the goal of reducing the risk of hospital-acquired infections.

The main limitation found in the discussions of the focus group was the single, static geometry. People wanted to be able to explore not just different ventilation systems scenarios, they wanted to investigate key moments during the operation procedure. A future work for our project is to detect, model and simulate key moments during specific operations in order to contain the computational cost of simulating entire operations, which is not a practical simulation as it would require thousands of hours of heavy calculations with supercomputers.

CONCLUSIONS

This study used a virtual reality interface to produce understandable animations from the CFD simulations of the airflow and BCPs movement in the OR. The CFD simulations predicted the airflow fields in the OR equipped with the mixing, LAF and TcAF ventilation systems. The 3D visualization environment was created by using the Unity game engine. Then, the interactive control for animations was provided in the virtual reality visualization of the model.

Overall, three interactive sessions were accomplished for evaluations of the system. In this regard, the sessions were ran for master students in informative visualization, a focus group with academic, governmental and industry stakeholders and finally a group of experts from the healthcare industry. During the sessions, one presenter was in the VR environment and the other one guided the actions of the presenter in the VR. The participants of the sessions found the system more engaging than videos and images. Furthermore, visualizing the particles' movement in the air was a powerful mechanism to understand the key points for reduction of the airborne contamination during the surgery. The participant were excited that the current system can help the medical team and nurses to have a clearer image about the impact of their behaviour in the OR, thus increasing the opportunity to reduce the infection risks caused by BCPs.

This study plans to work on detection, modelling and simulating of the key moments during specific surgeries to make the current system more applicable for medical education and training.

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