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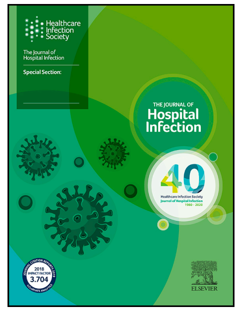

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Influence of the surgical team activity on airborne bacterial distribution in the operating room with mixing ventilation system: A case study at St. Olavs Hospital

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Summary

Background: Operating rooms (ORs) have strict requirements regarding cleanliness. While existing standards concerning the ventilation and staff guidelines are theoretically sufficient to subvert the threats posed by microorganisms within the room, there exists potential sources of contamination due to human activity around the area. Studies exploring this influence of human activity on distribution of microorganism contamination in ORs have relied on manual observations, or indirect methods such as number of door openings.

Aim: To utilize depth registration sensing technology to identify the activities of surgical staff and investigate their effect on the distribution of airborne microorganism contamination in ORs.

Methods: A mock surgical experiment was performed using a depth registration technique for the dynamic capturing of human presence and activity levels. Field measurements were carried out in one real OR to analyze its influence on the bacterial distribution in ORs with mixing ventilation system.

Findings: Bacterial contamination levels tended to correlate with higher activity levels, albeit with some inconsistencies. The highest activity levels were around the surgical bed when the patient was placed, and around the instrument table during the surgical procedure. Locations with obstructions had the highest CFU densities, indicating that airflow patterns are important in such spaces

Conclusion: Our activity monitoring methods demonstrate a novel means of studying the influences of human activities in hospital rooms.

Keywords: Surgical site infection; Hospital operating room; Hospital-associated infection; Human activity

Introduction

Operating rooms (ORs) in hospitals have to uphold the highest standards of cleanliness [1]. Introduction of bacterial contamination into the surgical wound, through direct airborne transmission or indirectly, e.g. through airborne contamination of instruments that then enter the wound, can cause infection [1], [2]. Theoretically, the installed ventilation system is sufficient to protect the surgical zone from any potential sources of contamination, with staff inside the surgical zone having limited contact with those outside the zone. However, in practice, the dynamic of the environment may change during the surgery, especially if there is poor compliance with OR discipline. Even when OR personnel are fully compliant, the transitions and movement inside the whole room can still be a source of potential contamination [3].

In modern hospitals, the most important source of airborne contamination is related to the dispersal of particles from persons present in the OR and their movements [4][5]. A high volume of staff movement and activities could play a role in higher risk for Surgical Site Infections (SSIs) [6]. Generally, staff movement can increase the colony forming unit (CFU) level by three means: (i) clothes rub against the skin, leading to increased shedding [7]; (ii) a pumping effect inside clothes that creates air streams that can transport skin scales into the OR air through pores in the fabric structure or from openings (such as the wrists, neck, ankles and the waist) [8]; and (iii) movement may cause settled particles on the floor and other surfaces to be re-suspended into the air [7].

A number of studies have explored influencing factors using various experimental methods. For example, You et al. utilized the emission rates of particles in a sealed chamber [9], whereas Scaltriti et al. focused on a recently built operating theatre using measuement of microbiological and dust contamination to assess the influence of human activity [3]. Andersson et al. investigated 24 orthopedic operations in Sweden and concluded that different activity intensities highly influence the CFU level [10]. However, these studies investigated the influence of human activity by relying on air quality data, correlating those with the occupancy, and the type of clothing worn, or the traffic flow within the operating room. In some cases, manual observations and door openings served as the basis for this comparison [10].The occupants in the room were not monitored individually, regarding their plocations or movement trajectories. Developments within the field of occupant monitoring in indoor spaces has allowed for much more sophisticated techniques of data acquisition [11], which have not yet been widely utilized for experimental procedures in operating rooms.

The objective of this study was to use of depth registration sensing as a tool to investigate the effect of surgical activities on the distribution of airborne microorganism contamination in ORs.

Methods

Three mock-up surgeries were performed with a controllable series of actions. The main monitoring parameters were dynamic registration of staff movement and passive air sampling, using downward displacement of air and enumeration of bacterial colony forming units (CFU), where these settle onto the surface of exposed agar plates, at floor height. Bacterial contamination was established by cumulatively exposing agar plates positioned inside surgical room and the surgical staff was monitored with the use of a depth registration camera. This method made it possible to assess the influence of medical personnel's activity, especially their movement, on the potential contamination.

Experimental Setup

Three mock surgeries were performed in the cardiopulmonary OR with a mixing ventilation system in St. Olavs Hospital, Trondheim, Norway. There were six participants in the study, one of whom represented the patient and the rest carried out the roles of five staff members (main surgeon, assistant surgeon, sterile nurse, distribution nurse, and anesthetic nurse). The layout of the room and the respective positions of each participant is shown in Figure 1. A total of twenty-four passive agar plates (internal diameter 85 mm) were used in six locations (A-F), placed around the surgical bed (Figure 1).

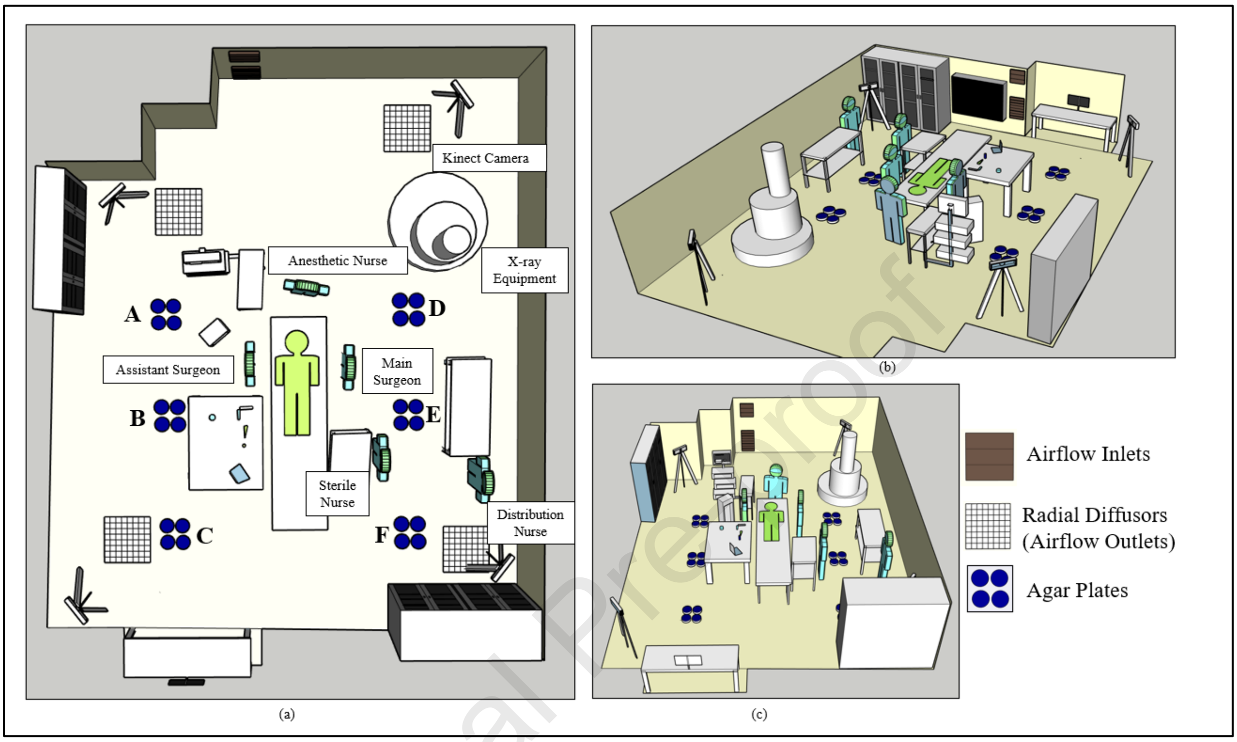

Figure 1. (a) Layout of the mock surgery experimental setup (Top View) (b) & (c) Bird's angle view of different perspectives of the setup

The experiment consisted of four different phases, and each agar plate group consisted of four agar plates. Each set of the agar plates was opened at the start of the different phases and kept open until the end of the experiment. 'Group' refers to the four agar plates present at each of the six locations, and 'set' refers to the plates from each group that would be opened at the start of specific phases. The first set of agar plates were open from Phases 0 to 3 (140 minutes), the second set were opened from Phases 1 to 3 (120 minutes), and so on (Figure 2). The durations of the phases were based on the timings of a typical hip arthroplasty procedure. The sampling windows for the agar plate groups is depicted in further detail in Figure 2. All the locations (A-F) followed the same pattern. Agar plates incubated for 48 hours at 35 +/- 2°C, followed by 24 hours at room temperature, before counting.

The clothing used by the staff was provided by and adhered to the standards of the hospital. The staff wore an EN 13796-compliant two-piece disposable nonwoven polypropylene suit. The main surgeon, assistant surgeon and sterile nurses wore surgical gowns outside the two-piece disposable nonwoven suit, which were made of nonwoven polyester/polyethylene and approved according to the EN13795: 2011 standard. The surgical masks worn by the staff were approved according to EN 14683 type II, which had double band, tie-on type and an integrated adjustable nose clamp. Latex gloves, surgical caps and hoods were also used to cover hands and the exposed parts of face. The patient worn a two-piece disposable nonwoven suit and a surgical cap.

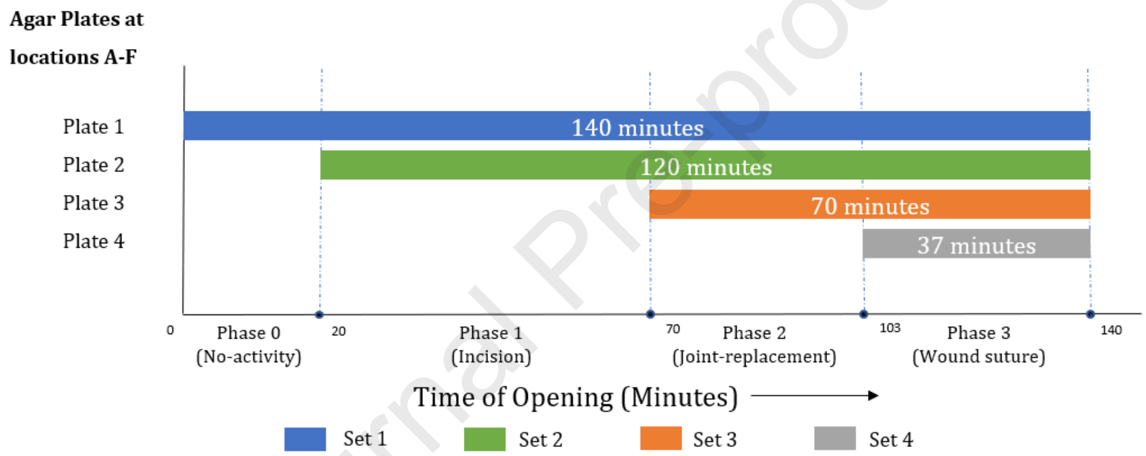

Figure 2. Sampling windows of the Agar Plates

Monitoring and Processing Movement of Participants

Participants were monitored using Microsoft Kinect Xbox devices, that use depth registration to capture geometric information about human activity [12]. The principle of depth registration is similar to a traditional projector, but visible light is replaced by an infrared beam. An additional sensor measures the time it takes for this incident ray to be reflected back to the camera, and this is used to gauge the distance of nearby objects. These measurements are recorded in a matrix array, which makes it possible to recreate a three-dimensional representation of the observed surface. If the human body is present within its Field of View (FoV), it gets processed with a Skeleton Model (SM), with 25 joints representing the human body in a three-dimensional matrix. For this trial, four cameras were used, each having a registration angle of 46 degrees in a 5-metre radius, and a 30Hz sampling rate. To cover the OR entirely and avoid occlusion, each device was placed in a corner of the room (Figure 1). Since all the devices have a capability of capturing up to 6 persons simultaneously, there was no possibility of misregistering any participant's activity.

Data processing consisted of unification of planes, data fusion, and plotting an activity heat map. Each device captured information according to its own local coordinate system. This had to be synchronized by selecting one device as referential and changing its horizontal plane to be parallel to the floor. The data from other devices were then accordingly adjusted and combined to create the final map. Based on previous studies [13], another significant component to validate the synchronization of the data is by using the most stable joints from the SM. The plotted map has a resolution of 5cm by 5cm. Each time the movement readings indicate a position in a particular cell of the heat map, it increases the value of this cell by adding one. After all the movement recordings are processed in that manner, a developed figure can show a spatial activity distribution. Static persons do not register any readings. With such filtering, it was possible to obtain a heat map of the staff activity in the OR during the experiments. This heat map represents the concentration of the activities within a particular cell.

Mock Surgery Procedure

Based on a typical hip arthroplasty procedure, a definite movement and action plan was formulated for each participant during the mock surgeries in the experiment. The mock surgeries (repeat thrice) were divided into three main phases: phase 1-incision (50 minutes), phase 2-joint replacement (33 minutes), phase 3 wound suture (37 minutes). In addition, 20 minutes non- activity and non-speaking phase (Phase 0) was added before the start of the mock-surgery to see the difference in CFU levels of activity compared with non- activity of the surgical team.

A detailed description of the activities performed by each participant during the mock surgeries is given in Table 1 and Figure 3. In addition to considering the body movement, the participants were also required to speak (by reciting the alphabet out loud every 7th minute), because speech can disseminate respiratory tract bacteria including important pathogens such as *Staphylococcus aureus* [14].

141 *Table 1. Movement and action plan for the surgical team*

Activity	Main surgeon	Assistant surgeon	Sterile nurse	Distribution nurse	Anesthetic nurse
1	**Body and arm movement**: Towards and away from sterile nurse (10 times)	**Arm Movement**: Continuous circular motions with one hand close to the wound (1 min)	**Arm movement:** Towards and away from main surgeon (10 times)	**Body and arm movement:** Towards and away the sterile nurse (10 times)	Sit still (1 min)
2	**Hand and Arm Movement:** Continuous random finger motions close to the wound (1 min)	**Body and arm movement**: Side to side (10 times)	**Body and arm movement:** Towards and away from distribution nurse (10 times)	**Body movement**: Walking to a cabinet and back again	NA (No Activity)
3	**Arm Movement:** Fast up and down movement of arm (10 times)	**Hand movement:** Holding a steady hand close to the wound (1 min)	**Arm movement:** Shaking arms continuously (1 min)	**Arm movement:** Twisting of hands in front of the chest (1 min)	NA
4	**Arm movement:** Shaking arms close to the wound - continuously for (1min)	**Body movement:** Squatting - 3times	NA	NA	NA
5	Resting position (1 min)	Resting position (1 min)	Resting position (1 min)	Resting position (1 min)	NA

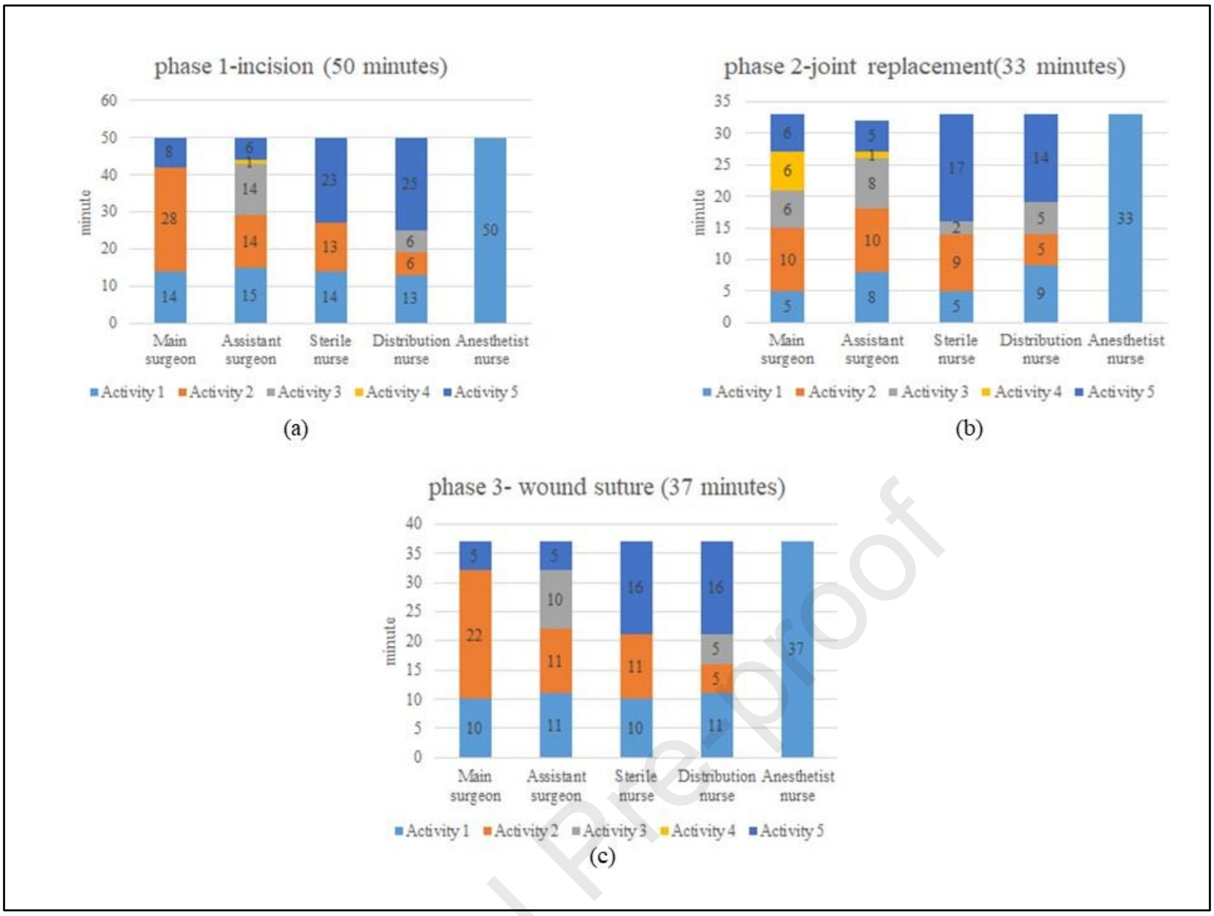

Figure 3. Distribution of activities within each phase, for each staff member

Since the measuring time is highly dependent on the type of a surgery, specifically the operating time, it is hard to compare the results with other different CFU standards by directly listing the CFU counts captured in the agar plates. Therefore, the measured data were normalized by transferring them to CFU density, which is formulized as CFU counts/agar plate area/measuring time (CFU/m2/h).

Results

Measured CFU levels with different activities

The CFU counts of three experiments are shown in Table 2. The observed amount of CFU counts were limited, with the maximum count being 8. Locations A, E, and F showed higher average counts with the first set of plates (open from Phases 0-3), while the location B and C showed the highest counts in the third set of plates (open during Phase 2-3).

Table 2. CFU counts of three experiments

Agar Plate Location	Experiment Phase	Phase 0-3	Phase 1-3	Phase 2-3	Phase 3
	Experiment NO.	CFUs			
A	Experiment 1	7	2	2	3
	Experiment 2	2	1	1	1
	Experiment 3	3	6	3	1
B	Experiment 1	5	3	6	1
	Experiment 2	2	5	3	0
	Experiment 3	8	8	8	2
C	Experiment 1	1	0	1	0
	Experiment 2	2	2	1	0
	Experiment 3	3	4	5	1
D	Experiment 1	1	1	0	1
	Experiment 2	1	2	0	0
	Experiment 3	0	0	2	2
E	Experiment 1	3	2	2	1
	Experiment 2	3	5	2	1
	Experiment 3	6	4	4	2
F	Experiment 1	3	2	2	1
	Experiment 2	4	2	0	0
	Experiment 3	1	1	1	0

The mean values for the normalized CFU density for each agar plate during different phases of the mock surgery are illustrated in Table 3. The CFU/m^2/h at locations B, E, A were higher than those at location C, F and D (Figure 4). The highest CFU/m^2/h was measured in location B during Phases 2 and 3. The highest value was observed as 1208.07. Very high values were observed in other repeated experiments, with 906.05 in the first experiment and 453.03 in the second experiment. The lowest CFU/m^2/h was measured several times at locations C, D and F.

Mapping of human activities

The human activity from the depth registration measurements was in the form of a spatial activity distribution map (Figure 4).

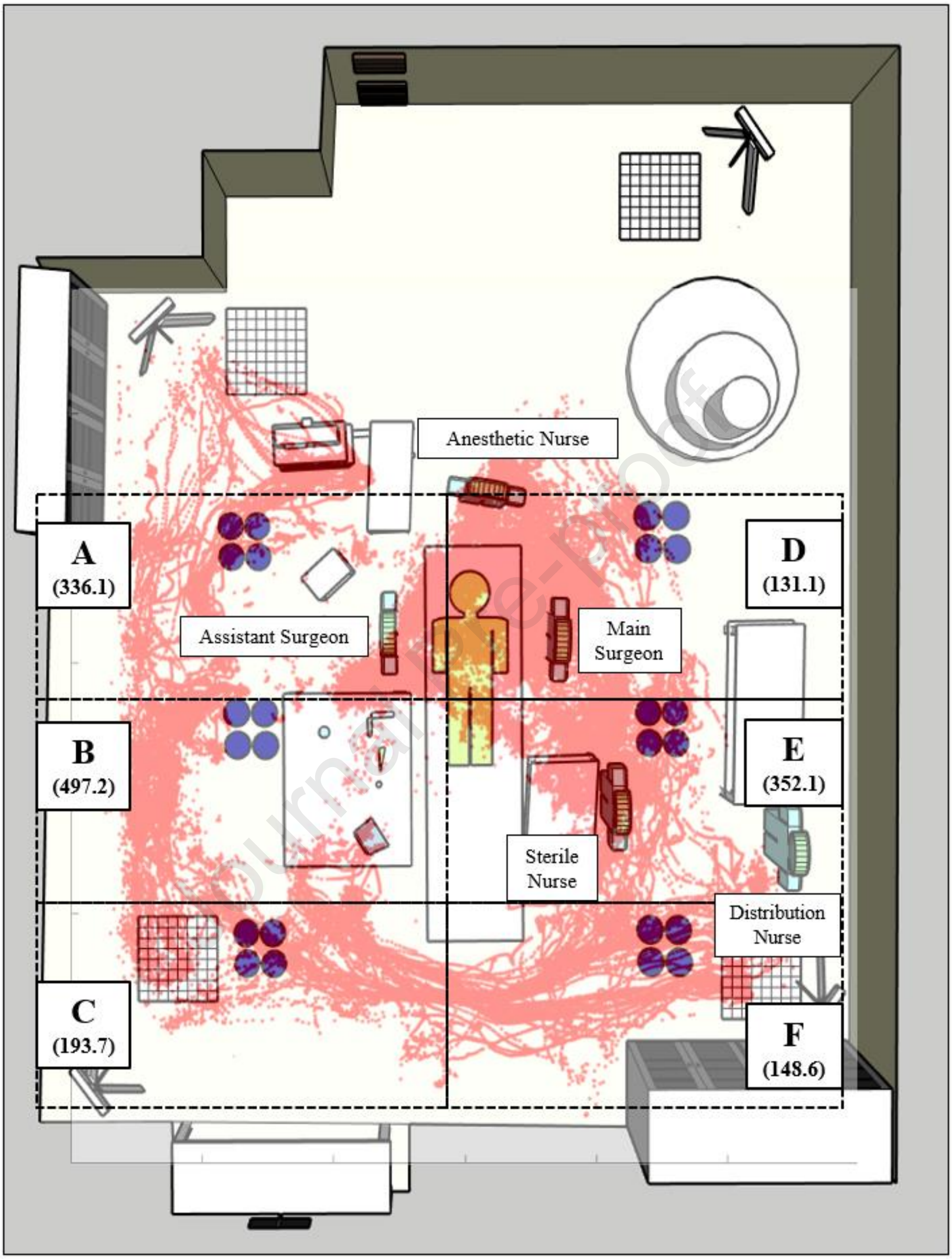

Figure 4. Activity levels around the surgical site. Each pink dot represents a single recorded activity. The average CFU measurements for each test location are also indicated

Table 3. CFU measurements and their corresponding activity levels

Experiment Phase	Phase 0-3		Phase 1-3		Phase 2-3		Phase 3	
Agar Plate Location	Activity Level	CFU/m2/h	Activity Level	CFU/m2/h	Activity Level	CFU/m2/h	Activity Level	CFU/m2/h
A	12.7%	302.15	20.9%	264.34	18 %	302.02	24.7%	**476.03**
B	0.5%	**377.68**	8 %	**469.94**	10.3%	**855.72**	10 %	285.62
C	1.3%	151.07	0.9%	176.23	0.5%	352.35	3.3%	95.21
D	23.9%	50.36	**37 %**	88.11	**36 %**	100.67	**30.1%**	285.62
E	**60 %**	302.15	31.5%	323.08	34 %	402.69	28.9%	380.83
F	1.6%	201.43	1.7%	146.86	1.2%	151.01	3 %	95.21

Discussion

Considering the activity levels associated with the CFU measurements in each location, it is clear that activity levels are not the only influencing factor on the distribution of airborne microorganism contamination. However, the area around location E had consistently high activity levels in different phases, a trend that was reflected in the CFU measurements as well. It might also be noteworthy that the Distribution Nurse was stationed near that area, and was the only one of the surgical staff that had to move across the room (Activity 2: walking to the cabinet and back), which would introduce particles from other areas of the room into the area near E, thus resulting in consistently higher CFU levels.

Measures in locations A, B and E reported higher CFU densities than C, D and F, which was consistent with the surgical staff within the respective region (main surgeon, assistant surgeon, sterile nurse) being more active than the anesthetist nurse. It can also be seen that there is a strong body movement (Activity 4: Squatting - 3times) of the assistant surgent in Phase 1 and Phase 2, which agreed well with high significance of CFU density for Phase 0-3, Phase 1-3 and Phase 2-3 in location B. In addition, the assistant surgeon during Phase 2 was responsible for opening the lid of the agar plates at location A, B and C. And the agar plates at location B were placed closer to the assistant surgeon. These reasons might be the cause of having extremely high CFU densities in location B.

Another possible explanation for the high CFU densities in agar plate location B is the obstruction caused by the amount of objects in that area. Most of the area around B is occupied by a large table, thereby obstructing the flow of fresh filtered air to that region. As such, measured CFU results may be influenced by both activity levels and airflow patterns within the OR.

However, there were unexpected findings. For example, it was expected that the CFU in location D would be high due to its close distance to the main surgeon and the sterile nurse. In addition, there was a walking movement by the distribution nurse with a path bypassing location D. It may be that different results would be obtained with a more sensitive bacterial sampling technique.

A significant limitation during this study was the over-estimation of the CFU counts in the experiments, especially the ones measured at the beginning of the experiment with no activity. While designing the experiment, it was expected that these CFU counts would be highly correlated to the activity level at a location, and it can be seen from the results that this was not entirely the case. Furthermore, the conducted surgery was a controlled imitation, which will undoubtedly contain significant differences from a real surgery.

Several studies have examined the efficiency of both active and passive air sampling, with variable results. Napoli et al. compared the results from active and passive sampling in 32 ORs with turbulent flows and concluded that both methods are applicable for monitoring of air contamination. However, it is pointed out that passive sampling, as we used, is more suitable in studies designed to monitor the risk of microbial wound contamination, whereas active sampling is more suitable for investigating the concentration of all inhalable particles [15]. In similar comparisons, other studies recommended the use of passive sampling for evaluating airborne risk of contamination, due to its relevance, simplicity and economy of use [16]–[18]. However, this technique also has its own limitations. Firstly, it may collect more relatively larger particles that are settled down mainly due to gravity, which has more influence than the indoor turbulent air. Secondly, ORs have surgical tables, X-ray equipment, and other facilities that pose as physical obstructions to the airflow and can have an impact on the CFU measurements. As mentioned previously, the second effect can be a significant factor in this study, considering the measured high CFU concentration around location B.

In order to overcome these limitations, future studies might include both active and passive techniques in order to provide a better comparison. The active sampler can also be programmed to be activated remotely, which would remove the need to physically interact with it, thereby minimizing additional contamination during measurements.

Since a vast majority (80%-90%) of post-surgical contaminants in wounds have their sources in ORs [19], it is imperative to discuss the significance of the ventilation system present in the study. The mock surgeries were performed in an OR with turbulent mixing ventilation (MV). Typically, the main types of ventilation systems employed to reduce the airborne bacterial load are Laminar Airflow (LAF) and MV. While many national standards considered LAF to be superior to MV in reducing the bacterial load, many recent studies have contested this claim [20], [21]. A systematic review of studies from 1990 to 2016 showed that LAF did not reduce the risk of SSIs in comparison with MV[20], which became the basis for new World Health Organization (WHO) guidelines recommending against employing LAF systems after total joint arthroplasty [22]. More recently however, these guidelines were again contested by several studies [23]–[25], providing the evidence that showed otherwise. In the light of these studies, it is even more important to have a detailed understanding of the influence that movement and activity can have on SSI. Taking these differences into account, future expansions of this study can include experiments performed in different ventilation systems to obtain a more detailed insight into the correlation between activity, airborne contamination and risk of SSI.

Conclusions

This study was designed to address the lack of dynamic capturing of human activity in experiments conducted in hospital rooms, which can be vital in investigating the standards of cleanliness, and other influences that human activity might have in such spaces. The results highlight trends of bacterial contamination in different locations. In general, higher activity levels correlated with higher CFU densities, but we also observed that locations near physical obstructions had the highest CFU densities, suggesting that airflow patterns might play in such spaces. Results from studies such as this might be used for implementing infection control practices concerning the staff activity and positioning of surgical instruments to optimize the airflow within the OR, because the current indoor environment design does not take into account the effect of human activities during real surgical procedures. We believe that dynamic recording of human activity, togather with reproducible techniques to measure airborne contamination and airflow patterns can provide val,uable information that could change operating theatre design and/or working practices.

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