CHALMERS
UNIVERSITY OF TECHNOLOGY

A Quantitative Analysis of Airborne Contaminants in an Operating Theater

Master's Thesis in the Master Degree Program Structural Engineering and Building Technology

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Division of Building Servicecs Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

A big problem in the health care sector today are the infections caused by airborne bacteria-carrying particles during surgeries. About 2 to 5 % of all patient undergoing surgery are affected by infections caused by the surgery. The aim of this paper is therefore to gather and then analyze data of particle concentrations and colony forming units (CFUs) during a surgery in a mixed airflow ventilated operating theater. The focus of the analysis was especially on the effect on the surgical smoke from diathermy and the emittance through surgical clothes.

The necessary particle data was acquired with three particle counters and one CFU-sampler during a rectum extirpation. Particles of sizes between 0.02 and 10 μm were investigated and five CFU samplings were performed during the surgery that took almost 4 hours. An air cleaner was also put on every second hour in order to see any improvements.

The report shows a higher CFU value before the surgery, during the patient preparation (13 CFU/m^3) than during the surgery itself (5 CFU/m^3), and a maximum particle amount of 102 120 per cm^3 was detected at a moment during surgery when electrosurgical equipment were in use. The smoke produced by electrosurgical equipment is hence one relevant factor for the particle impact on the environment.

The study concludes that the routines before the surgery needs to be optimized in order to minimize the infection risks from airborne bacteria. For example a "quiet minute" could be introduced before the body opening to let the ventilation dilute the room from hazardous particles from the preparations. Furthermore, a tendency shows that the clothing systems source strengths from previous research might be exaggerated, but further investigations are needed to confirm this.

Keywords: CFU, Source strength, Surgical Site Infections, Mixed airflow principle, dilution principle, airborne particles

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Martina Norén, Gothenburg, July 2016

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List of Abbreviations

ACH	Air Changes per Hour
CFU	Colony Forming Unit
ESU	ElectroSurgical Unit
HEPA	High Efficiency Particulate Air
HOR	Hybrid Operation Theater
MPPS	Most Penetrating Particle Size
OR	Operating Room
SSI	Surgical Site Infections

1
Introduction

1.1 Background

As well known, the objective of a surgical procedure is to cure or hinder a medical issue for the patient. We can therefore agree that surgeries that make the patient sicker than before the surgery are rather counterproductive. Such is the case when the patient is infected with a surgical site infection, a infection caused by bacteria, carried by airborne particles. These surgical site infections are quite common, and the risk of being infected from a surgical site infection is between 2 and 5 %, definitely not a negligible risk. It is therefore of great importance to minimize the amount of airborne particles in an operating theater to minimize the risk of unnecessary deaths due to surgical site infections.

A vital factor for the air quality in an operating theater is the effectiveness of the installed ventilation system and the principle of airflow it is based on. The latest technology in ventilation utilizes laminar air flows to effectively disperse the dangerous airborne particles; however, a lot of the operating theaters in use today were built in the middle of the twentieth century. These operating rooms often use a more primitive air exchange system with turbulent airflows that totally mixes the air in the room.

These outdated ventilators often cannot maintain the level of airborne particles to the high standards that exist today; thus, a more detailed analysis of what can be improved when it comes to procedures during surgery is therefore needed.

Numerous studies, such as those by Ljungqvist and Reinmüller (2010), Tammelin et al. (2012) and Erichesen Anderson (2013) among others have been conducted to study the effect the clothing system has on the concentration of airborne bacteria-carrying particles. However, these studies often examine the clothes during artificial surgical routines, and it remains relatively unknown if their results are optimistic or pessimistic when it comes to real-life scenarios.

From a broader perspective, the effect that different surgical routines have on the concentration of airborne particles is a subject rather unexplored but should be prioritized since routines can be changed relatively cheaply compared to building a new hospital or totally renovating the ventilation system in an existing hospital.

1.2 Aim

The aim of this Masters thesis is to analyze the concentrations of airborne particles during surgery in an operating room and suggest some suitable solutions concerning the ventilation system in order to enhance the air quality in the theaters. To succeed with this goal, CFUs will be considered as well as the effect that different types of surgical actions have on the amount of airborne particles in the operating room.

The focus is on two contemporary problems: The patient´s health and the staff´s health. Regarding the patient the main hazard is infections caused by bacteria that mainly originate from the staff's skin or from outside sources. For the staff, on the other hand, the main hazard is the working environment where dangerous chemical substances are dissolved in smoke generated from electrosurgical equipment used during the surgery. These two paths of danger are summarized in figures 1.1 and 1.2.

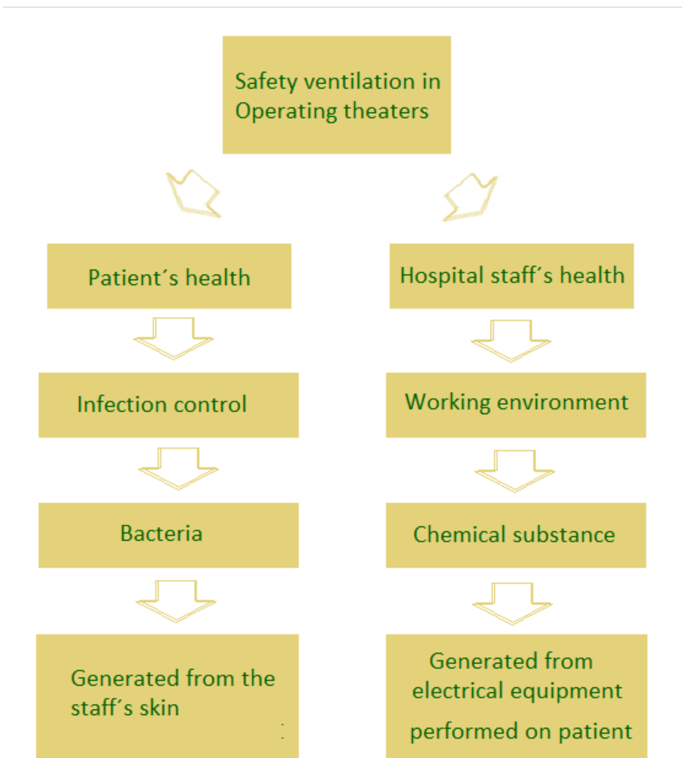

Figure 1.1: *A flowchart explaining the hazards during a surgery for the patient and the staff. It is these hazards that safety ventilation should prevent.*

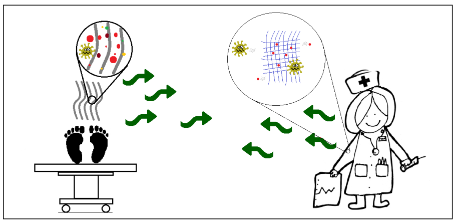

Figure 1.2: *A sketch of the direction of the contamination in the air*

1.3 Limitations

First and foremost, this thesis is based on one measurement session during a rectum extirpation in a specific operating room. The focus of the study will also be mainly on the surgical source strength from the surgical smoke and from the clothing system that the staff uses during the surgery. The study will also look at the effect of an air cleaner during the surgery. The CFU will not be measured continuously but rather be sampled for 10 minutes every hour.

The particles will be measured in the size range assessable by the particle detectors used. These detectors also measure the amount of particles over a span of time, to give the mean concentration during this period of time. This means that the direct response of the concentration will not be taken into account.

1.4 Problem Identification

The main problem is the infections caused by the airborne bacteria-carrying particles during the the surgical procedures. The secondary problem is the environmental contamination, dangerous for the staff's health.

1.5 Method

With medical support from the health care business a measure program was adapted in order to perform a qualitative analysis of a surgery. An advanced surgery process was observed in a conventional operating theater. Three particle counters were utilized together with a CFU-detector before, during and after the surgery to study the contaminations in the room. One particle detector tracked bigger particles in terms of size, than the other two particle detectors. The CFU-detector uses agar plates and was sampled one every hour.

After completion of the measurement program a comparison between the different medical phases in the studied surgery and the measured particle concentrations and, the CFUs was made. A literature study was performed for the theory part of the report.

2

Theory

2.1 Particles

Particles are specks of very small matter that exist all around us. They vary greatly in size, from the volume of a molecule to a grain of sand. Particles can also carry substances, such as microorganisms or contaminations.

2.1.1 Particle Sizes

Particles are classified by their aerodynamic diameter. This is the diameter of a spherical particle with the same density as a water droplet, 1 g/cm^3, and with a falling velocity in air equal to that of an actual particle. When a particle´s diameter is mentioned, it is the aerodynamic diameter that is referred to (Jordestedt, 2015).

Particles larger than 100 μm are considered as large and heavy. The gravitational settling has a big influence on these particles which makes them fall down quickly and sediment on horizontal surfaces with a downward velocity greater than 0.5 m/s (Allan, 1981).

Particles with a diameter between 1 μm and 100 μm are regarded as medium-sized particles. All the fragments in this range are affected by gravity, but with greatly varying downward velocities ranging from 0 m/s to 0.5 m/s. This means that particles with a diameter greater than 10 μm are still fairly affected from the gravitation, but in a slower manner than the heavy dust. The medium-sized particles smaller than 5 μm have a very small impact from the gravity and will stay floating in the air for a long time, mainly following the air movements until they settle down (Allan, 1981).

The small particles are particles with a diameter less than 1 μm. These fall very slowly and can take anywhere from days up to years to settle in a quiet atmosphere, and may never sediment in a turbulent environment. They are therefore assumed to be suspended in the atmosphere. The finest type of particles is the ultrafine particles which are defined as particles with a very small diameter, less than 0.1 μm. Around 99.9 % of all particles in the atmosphere are small or ultrafine. (Lundblad & Nilsson, 2013). Figure 2.1 shows the sizes of different particles in relation to the gravitational impact.

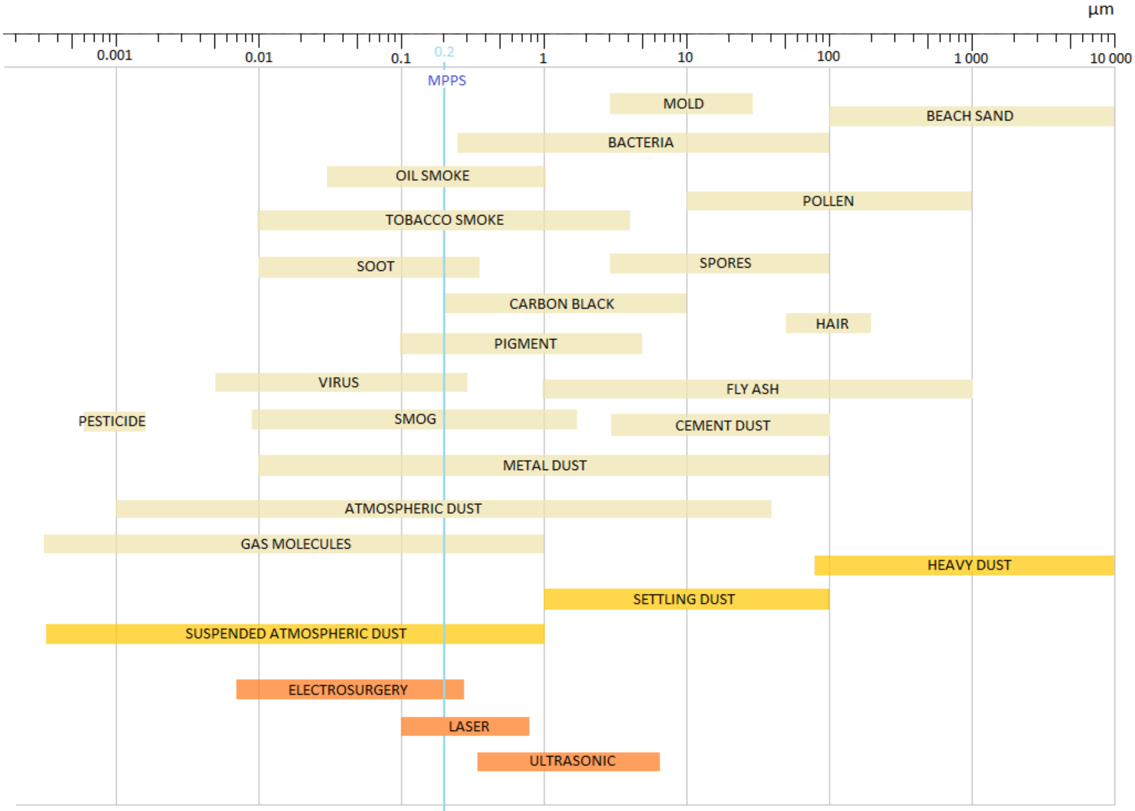

Figure 2.1: *This sketch shows the sizes of different particles. Depending on the particle size they can be categorized by their gravitational impact. The blue line shows where the most penetrating particle size is for particle filters, see section 2.4. The red markings show the types of surgical smoke generated from heat producing devices, see section 2.6.2.1*

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2.1.2 Dispersal

Airborne particles are transported in the air by sedimentation, diffusion and convection (Jordestedt, 2015). Sedimentation is the falling process caused by gravitational forces which in turn depends on the size of the particle. Diffusion is movements caused by concentration differences in the air, a movement from a region of high concentration to a region of low concentration. Convection is a rising air movement caused by temperature differences i.e., a motion from a warm zone to a colder zone. This transport mechanism tends to have a much stronger and more rapid impact, compared to the previous transportation methods, in situations with an air movement as a driving force, and will hence be the most crucial dispersal mechanism in a ventilated room (Jordestedt, 2015).

The ventilation in a room together with other possible driving forces, creates the airstreams that direct the airborne particles. We can hence neglect the gravitational settling in such a scenario. If the air in a room is totally mixed, we usually assume a more or less evenly distributed concentration of the particles in the room (Jordestedt, 2015).

2.1.3 Contagion

The most common contagion in the health care sector is through physical contact. Air contagions are transferred between people either by particles from the skin or by small droplets. The droplets come e.g., from a cough that either drops directly to the wound or dries up and forms an aerosol containing very small droplets with a diameter of less than 5 μm, a size that can be carried by the air (Vårdhandboken, 2015).

2.2 Bacteria

Bacteria virtually exists in all environments on the earth and are the smallest living microorganism, too small to see with the naked eye. The size range of bacteria vary between around 0.25 and 100 μm, see figure 2.1. Bacteria contain only one cell and comprise the essential components required for their own reproduction. They, thus, have the ability to survive in various conditions for many years and are highly adaptable to many environments (Aryal, 2015).

Bacteria appear in variations of three major shapes: cocci (spherical), bacilli (rod-shaped) and spirilla (twisted), see figure 2.2. Cocci is the most common type of bacteria and can operate in pairs, chains, groups or by them self. The majority of these bacteria have a diameter of between 0.5 and 2 μm and are found in the air. Bacilli appear mostly as single rods but can also gather in pairs or in chains. The average diameter is between 0.5 and 1 μm and a length between 2 - 5 μm. Bacilli are typically found in soil and are usually not harmful to humans. Spirilla acts as individual that consists of one or more twists. They vary in sizes between 2 and 15 μm and are normally found in aquatic environments (NE, 1990).

Viruses, which are smaller than bacteria, on the other hand, belong to non-cellular organisms since they are too simply built to be called cells and require a living host to survive (Jordestedt, 2015). Bacteria are therefore the most harmful microorganism and the one normally investigated.

Ultrafine particles with their minor diameter (< 0.1 μm) means they have a high ratio of the surface area to the mass. This attribute gives the ability to carry a significant amount of airborne substances, e.g., bacteria. The smaller the particle size, the further it has the ability to travel in the air, enabling bacteria passing into the lungs reaching sensitive targets. Ultrafine particles have shown to result in higher potential health risks compared to larger particles. Since bacteria are the smallest living microorganism, these bacteria are normally considered as the most harmful particle in the air (Lundblad & Nilsson, 2013).

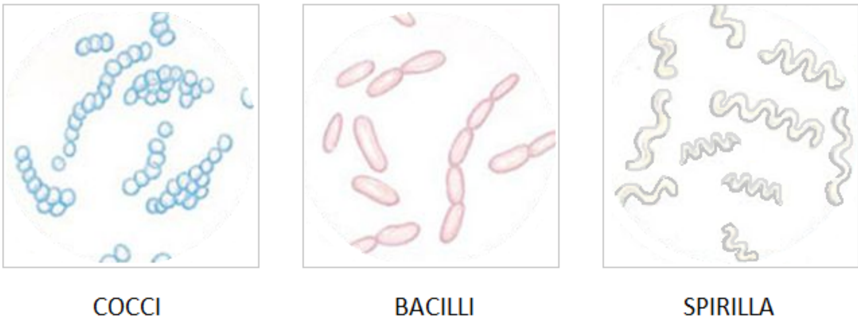

Figure 2.2: *The three most common shapes of bacteria.*

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2.3 Colony Forming Units (CFU)

A Colony forming unit, CFU, is a unit estimating the number of viable bacteria-carrying airborne particles. The estimation of the amount of contamination in the air is made by a cultivation of microorganisms. The colony forming unit is captured on agar plates during a predetermined time and then stored for a specific amount of time in a controlled environment with a certain temperature, humidity, and a given amount of available nutrients. The microorganisms start forming colonies, and this controlled reproducing of bacteria allows for easy determination of the number of colonies. The number of colonies presented on the agar surface is counted and is defined as the CFU value (Jordestedt, 2015).

There does not exist any direct connection between the amount of airborne particles and the amount of airborne CFUs. However an environment with a higher content of airborne particles usually contains more airborne CFU (Jordestedt, 2015). The amount of bacteria-carrying particles have been showed to have a correlation with the risk of infections during surgery (Lundblad & Nilsson, 2013), and the content of CFU within an operating theater is considered to be a good indicator of the infection risk (Jordestedt, 2015). The measurement of CFUs is therefore used as a tool to achieve ultra clean air and to reduce the bacterial burden in operating theaters (Lundberg, 2015).

For a controlled environment like an operating theater, a cubic meter of air with a content of 1 000 - 2 000 particles larger than 0.5 μm corresponds approximately to a CFU density of 1 CFU/m^3 (Lundblad & Nilsson, 2013).

The amount of CFU in the air is dependent on the number of people in the operating theater, surgery equipment, the amount of door openings, the staff clothing and the air movement, which in turn depends on the air flow.

2.4 Particle filters

Particle filters are commonly installed in ventilation systems, designed to trap contaminants from the air streams. For rooms with very high demands on the cleanliness, such as operating theaters and clean rooms, filters normally have very high demands on the filtration efficiency.

High Efficiency Particulate Air (HEPA) and Ultra Low Penetration Aerosol (ULPA) are two very effective air filters and are normally utilized in hospitals. HEPA has a filtration efficiency of minimum 99.97 % for particle sizes $\geq 0.3\ \mu$m. ULPA are closely related to HEPA filters but are an even more efficient filter, with a filtration efficiency of minimum 99.999 % for particles with sizes $\geq 0.12\ \mu$m (White, 2009).

HEPA and ULPA filters are composed of randomly arranged fibers, normally fiberglass, and trap particles in four different ways- sieving, diffusion, interception and impaction. However, the filter has a weakness in the size range between 0.1 and 0.4 μm. Particles less than 0.1 μm are easily trapped by diffusion, and particles larger than 0.4 μm are effectively trapped by interception, impaction and sieving. In between 0.1 and 0.4 μm, all catch techniques are comparatively inefficient. The weakest point lies around 0.2 μm and is hence called the Most Penetrating Particle Size (MPPS). -This is why HEPA has a specifying effectiveness of size 0.3 μm and larger (White, 2009). Figure 2.1 shows what kind of particles that is of concern around MPPS. The amount of particles that passes through is still however very low, and a HEPA filter is usually efficient enough in ventilation systems for operating theaters.

Since bacteria exist in sizes between 0.25 and 100 μm basically all bacteria will get caught in a particle filter.

2.5 Cleanliness recommendations for operating theaters

Requirements regarding allowable concentrations of bacteria-carrying airborne particles inside operating theaters are not prescribed by law. The Swedish standards institute has instead developed some guidelines regarding the cleanliness in operating theaters (Nordenadler, 2010). The guidelines separate these requirements of CFU depending on the surgical procedure. For "normal" non-infection sensitive surgery, the air should maintain a lower level than the limit < 100 CFU/m^3 air. The recommended value is < 50 CFU/m^3 (Nordenadler, 2010).

Infection-sensitive surgery, for instance orthopedic surgeries and implant procedures, has a much higher demand on the air quality, called ultra-clean air. This limit should be < 10 CFU/m^3 air. Further, a mean value is of < 5 CFU/m^3 a recommended guidance value and is becoming more and more common, partly to ensure that the limit of < 10 CFU/m^3 is maintained. This is usually achieved by using a parallel air streaming principle. With concerns regarding the fast growth of antibiotics resistance, the possibility of a limit of < 1 CFU/m^3 might be a reality soon (Jordestedt, 2015).

2.6 Source Strength

Source strength is defined as everything in the room that contributes to the airborne particles and consists mainly of:

- Persons and their clothing system
- Surgical procedure and medical equipment
- Disturbances
  (Reinmüller, 2011)

2.6.1 Persons and their clothing system

A great contribution to the source strength is the staff in an operating room, their movements, and the clothes that they wear. Skin particles are constantly released from a body and some of these particles carry bacteria from the skin through the clothes causing a source strength. The sizes of these fragments differ between 5 μm - 60 μm. The mean size is however around 10 μm which means they can either be carried by the air or settle down, depending on which driving force that tends to have the greatest impact for the moment (Jordestedt, 2015). Different factors contribute to how many particles a person emits, e.g., the movements, the skin type, the gender (men emits more particles than women), beard or no beard, and other factors that are different between persons. The movements result in the skin particles being emitted to the surroundings. But the factor that is universal between people of all shape and sizes, is the clothes that they wear.

Since the source strength is generated from the staff, the particles are transported further away from their source into the air. The harmful particles are therefore mainly effected by the patient, see figure 2.3.

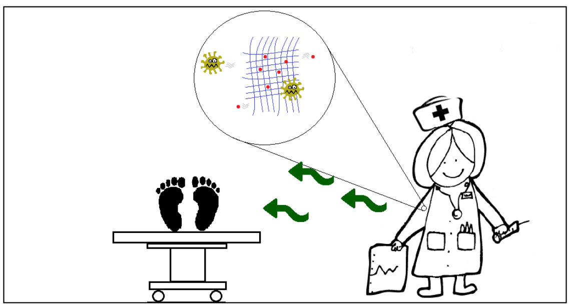

Figure 2.3: *A figure showing particles emitted from the clothes worn by the staff during surgeries. These particles are mainly harmful for the patient.*

2.6.1.1 Surgical Clothing System

There are mainly five different clothing systems used in hospitals. The two most commonly used systems are the clean air suit and the standard suit, also called Mertex. One system consists of single- use clothes, and the last two are high quality cleanroom clothing system, respective, OR clothes of cleanroom quality in combination with undergarments (Nordenadler, 2010). The two most common clothing systems are described.

2.6.1.1.1 70 % cotton 30 % polyester

The employees working in a surgical ward are required to wear a department bonded surgical operating suit during their working hours. This suit is regarded as the standard suit.

The surgical standard suit, called Mertex, has the purpose of preventing the transportation of infectious agents between patients and is hence not manufactured to prevent the transportation of particles through the fabric (Meda, 2014). The suit includes a pair of long trousers, a short-sleeved shirt, a single-use head cover and a pair of indoor shoes. Long-sleeved shirts are unacceptable since they can be a carrier of these infectious agents. The clothes are changed every day and can only be used in the working area. If the suit has been in contact with a patient or if the clothes get contaminated or wet, a change of clothes is required (Vårdhandboken, 2016).

Since the suit is not made to prevent particles from becoming airborne from the staff´s skin, the material of the suit is normally less penetration-dense. The trousers and the shirt are made of 30 % polyester and 70 % cotton (Vårdhandboken, 2016).

2.6.1.1.2 50 % cotton 50 % polyester

Surgeries with a greater risk of infections, e.g., orthopedic or liver surgeries, have to be performed with a special suit, called a clean air suit. Clothes used for these surgeries are meant to reduce the spread of bacteria compared to the standard suit and thus consist of a more compact woven fabric (Vårdhandboken, 2016) made of 50 % polyester and 50 % cotton (Meda, 2014). The blocking capacity of the suit mainly depends on the woven cloth´s density and the pore size, see figure 2.4.

This fabric, thus, causes a reduction of the bacteria-carrying particle diffusion from the skin to the air in the operating theater. Both single-use and reusable material exist together with wristlets at sleeves and ankles. All personnel in the operating theater have to use this type of special suit that always has to be changed before every high risk surgery (Vårdhandboken, 2016). This suit consists of a pair of trousers, a short-sleeved shirt, a single-use helmet covering the whole head and neck, a face mask and a pair of indoor shoes, the only garment that is also found in the standard suit (Meda, 2014).

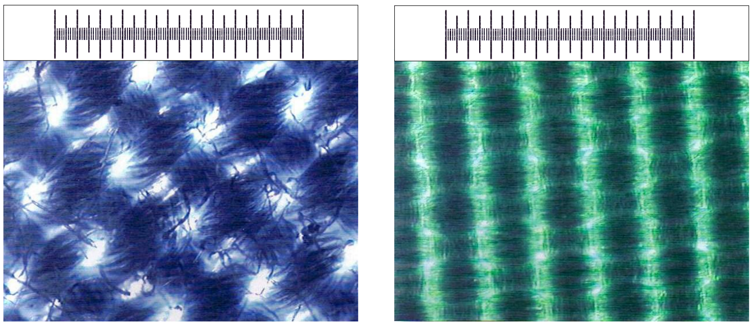

Figure 2.4: *A figure showing different types of fabric illustrating the difference in size of pores and woven density (Reinmüller, 2011).*

2.6.1.1.3 The clothing systems' source strength

The skin particles released from the doctors and the nurses penetrates through the surgical clothes, in different amounts, depending on the type of fabric. The fabric can hence be defined with a source strength value.

The source strength varies with the clothing system, and the chosen system plays a determining role for the room´s contamination level. The clothing systems are hence classified by the definition of their source strength of the CFU. The value is described as the number of CFU per second from one person. This means that the number of personnel present in an operating room is directly proportional to the amount of CFUs (Ljungqvist & Reinmüller, 2013).

Studies about the blocking capacity against airborne particles for different surgical clothing systems are made by measuring the CFU-values in the operating room during surgeries. These studies can also be performed in dispersal chambers where the test subjects (often men) perform a repeated cycle of movements. This cycle includes arm movements, stationary walking and knee bends at a set speed (Ljungqvist & Reinmüller, 2013). For clothes,the level of source strength increases with the number of washing cycles (Ljungqvist & Reinmüller). For a summary of found source strengths see table 2.1.

The values achieved in the chambers show a relatively big difference compared to the studies in the operating theaters. This probably depends on a few things. Firstly, the individuals representing the staff during the chamber tests were all men. Men are generally bigger than women, which means that their skin area is bigger and they also produce bigger movements. Secondly, the activity levels in the chamber tests were often higher than the activity level estimated in the operating rooms. This was probably done to be on the safe side. However, this caused skewed results.

Table 2.1: *Different studies of Source strength from clothing systems, mean CFU/second and person*

Clothing System	Chamber [1]	Study A [2]	Study B [3]	Study C [4]	Study D [5]
69 % Cotton, 30 % Polyester, 1 % Carbon Fibre	10.9	6.4	5	4.1	-
50 % Cotton, 50 % Polyester	1.7/4.2/9.0 [6]	2.0	-	-	1.9
100 % Polyester, without polyester undergarment	0.4/0.5/1.1 [7]	0.9	2.9	2.4	-
99 % Polyester, 1 % Carbon fiber, With 100 % Polyester undergarment	< 0.2	< 0.2	0.7	0.6	-
Single-use clothes made of Polypropylene	2.5	-	1.15	0.7 [8]	-

[1] Study in a chamber. By Ljungqvist, B. & Reinmüller, B. 2004
[2] Study in an operating theater. By Ljungqvist, B. & Reinmüller, B. 2010
[3] Study in an operating theater. By Ljungqvist, B. & Reinmüller, B. 2010
[4] Study in an operating theater. By Tammelin, A., Ljungqvist, B. & Reinmüller, B. 2012
[5] Study in an operating theater. By Erichsen Andersson, A. 2013
[6] Results from 1 wash, 25 washes resp. 50 washes
[7] Results from 1 wash, 25 washes resp. 50 washes
[8] Study in an operating theater. By Tammelin, A., Ljungqvist, B. & Reinmüller, B. 2013

2.6.2 Surgical procedures and medical equipment

The first big consideration when analyzing the source strength during a surgery is to look at the type of surgery that will be performed. Next, one has to look at the surgical procedures that the staff have before, during, and after the surgery, since usage of different types of medical equipment and repeated movements can generate a lot of airborne particles.

For example, in an surgery with a lot of diathermical procedures (see 2.6.2.2.1 and 2.6.2.2.2), the surgical smoke generated by such electrosurgical equipment is often a big contributing factor to the source strength.

2.6.2.1 Surgical Smoke

Surgical smoke is the gaseous byproduct created when tissue is heated and cellular fluid is vaporized by the thermal action of an energy source during a surgical procedure called diathermy. This smoke is generated at the patient´s wound, rising and spread to the environment in the operating theater. The surgical smoke is therefore mainly harmful for the staff, see figure 2.5.

The category of heat producing equipment consists mainly of monopolar electrosurgery devices, bipolar electrosurgery devices, lasers, ultrasonic devices and argon beam coagulation. The most common equipments are with no doubt the electrosurgical units (ESUs) (Sankaranarayanan, 2013).

Each type of device generates particles of different sizes. The ESUs stands for the production of the smallest sizes, a mean diameter of 0.007 μm. Since smaller particles can more easily penetrate through the surgical masks and have the ability to travel further in the air, these are the most harmful type of particles. Lasers generate mean particle diameters of μm 0.31 μm, and ultrasonic devices creates sizes between 0.35 - 6.5 μm, see figure 2.1. These bigger sizes are more easily hindered by the surgical masks and other filters (Ulmer, 2008).

The smoke generated has a big spread which means that the smoke not only affects the people close to the patient, but all personnel in the room are affected. The surgical masks are normally only designed to block particles bigger than 5 μm which means that surgical masks are not a complete protection since the particles smaller than 5 μm penetrate the mask pretty easily (Meda, 2014).

The smoke consists of 95 % steamed water and 5 % cellular matter composed of chemicals, blood, tissues, viruses and bacteria. The chemical composition contains around forty chemicals in different amounts. Two of the chemicals of concern are acrylonitrile and hydrogen cyanide. Acrylonitrile is a volatile and colorless chemical substance with the ability to be absorbed through the skin and the lungs. Acrylonitrile subsequently liberates hydrogen cyanide, which is a colorless toxic with the same ability of absorption. The harmful substances obviously pose a risk for health diseases and infections for both the patient and the surgical team and can in a worst case scenario lead to death (Ulmer, 2008).

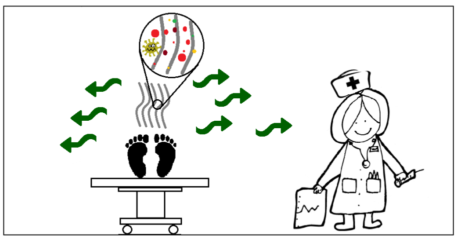

Figure 2.5: *A figure showing surgical smoke that mainly affects the staff´s well-being.*

2.6.2.2 Electrosurgical Units

ESUs have a lot of advantages compared with normal equipment such as scalpels, but are also the main contributor for the generation of fine particles in the OR (Bonomi, 2016).

Electrosurgery uses high-frequency alternating electric current to affect tissue in forms of cutting, coagulation, desiccation and fulguration. The source for the used current is an electrosurgical generator. This generator converts the standard electrical frequency from the wall outlet, which is 50 Hz, to 200 000 - 3 300 000 Hz. This higher frequency is important in order to minimize the nerve and muscle stimulation which occurs for electrical currents below 100 000 Hz. 200 000 Hz can therefore pass through the patient with minimal neuromuscular stimulation (Sankaranarayanan, 2013).

Electrosurgical generators are able to deliver different electrical waveforms, see figure 2.6. By changing the waveform, i.e., reducing the duty cycle or "on" time, different tissue effects are caused. In general, electrosurgical generators provide energy in two types of modes: continuous and interrupted (Massarweh, Cosgriff & Slakey, 2006).

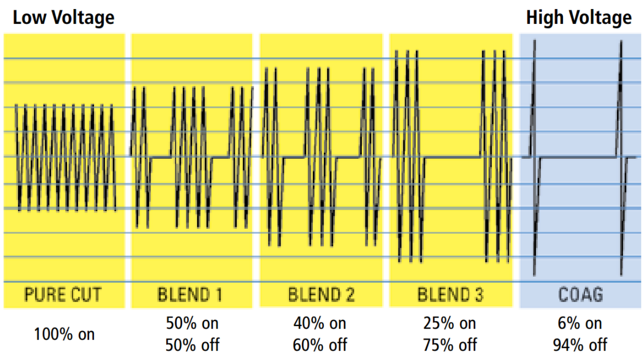

Figure 2.6: *The figure shows different duty cycles of the electrical current used by electrosurgical units in order to attain different tissue effects (Massarweh, Cosgriff & Slakey, 2006).*

The continuous mode of current output is referred to as the "cut" mode. Here heat is rapidly produced causing a large current concentration on a ESU with a pointed tip. To create a cut the electrode is held slightly away from the target tissue to create electrical sparks that direct the intense heat to a limited area of the tissue. This action produces a great amount of heat over a very short time, causing the tissue temperature to rapidly exceed 100 degrees. This results in an expansion of the liquid filled cells in the tissue leading to explosive vaporization (Massarweh, Cosgriff & Slakey, 2006).

The interrupted mode is referred to as the coagulation mode or "coag" mode. This mode has a significantly reduced time for the tissue exposed to the current, usually 6 %. In order to deliver the same amount of energy in the interrupted mode as the continuous mode a higher voltage is needed. The low duty time in "coag" mode results in a slow heating process for the tissue, forming a coagulum rather than a vaporization of the tissue (Massarweh, Cosgriff & Slakey, 2006).

Desiccation occurs when the active electrode on a blunt instrument tip is in direct contact with the tissue. This reduces the current concentration at the tip, causing less heat production. The area will dry out and a coagulum will form. Fulguration is usually performed in "coag" mode and with the electrode held slightly away from the tissue, causing sparks. Together, less heat, higher voltage and sparks make the tissue coagulate and reduces the remaining solid components of the tissue to carbon (Massarweh, Cosgriff & Slakey, 2006).

Modern electrosurgical generators can offer a wide variety of electrical waveforms. In addition to the pure “cut” mode, there are often blended modes that modify the degree of current interruption (duty cycle) to achieve varying degrees of cutting, see figure 2.6 (Massarweh, Cosgriff & Slakey, 2006).

2.6.2.2.1 Monopolar Electrosurgery

A monopolar electrosurgery, also called monopolar diathermy, uses the electrical frequency spectrum between 200 000 - 3 300 000 Hz. The energy is applied between two electrodes, one active and one neutral. The monopolar instrument is designed as a pen with an active electrode, see figure 2.7. This electrode transfers the energy from the surgical site through the patient further to the return electrode pad, which is attached to the body of the patient. From here the current is transferred back to the generator, see figure 2.8.

The active electrode that is placed in the entry site can be of any form, but usually a point, a hook or a blade. The sharp edges have a very small contact area and thus results in a very high current density. These are used for cutting whereas blunt edges are used for coagulation. The return electrode pad is attached to the skin of the patient. This pad has a wide surface area which disperses the heat and results in a low current density with no heating effect. This part is thus called the neutral electrode (Sankaranarayanan, 2013).

The monopolar pen is normally designed with a local exhaust on the handle to prevent the smoke from the vaporized tissue to spread in the operating theater, see figure 2.7.

Figure 2.7: *The monopolar electrosurgical instrument (the blue part) equipped with a local exhaust on the handle (the white part) in order to prevent the surgical smoke to spread in the operating theater. mod. (Lundblad & Nilsson, 2013).*

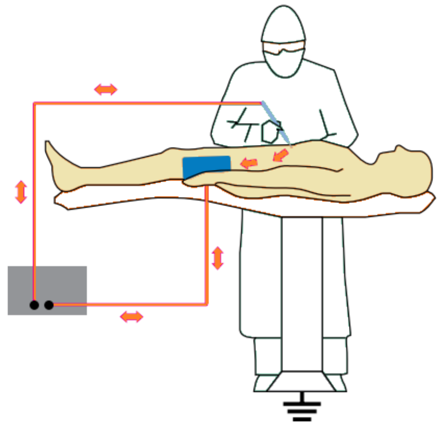

Figure 2.8: *The electrical circuit for a monopolar electrosurgery is transferred from a generator by means of a monopolar electrosurgical instrument at the surgical site, through the patient. The current continues to a return electrode pad that is attached to the body of the patient, and then further back to the generator (Massarweh, Cosgriff & Slakey, 2006).*

2.6.2.2.2 Bipolar Electrosurgery

Bipolar electrosurgery, also called bipolar diathermy, uses a handle designed as a gripper or a forceps. The two tines on this handle perform as the active resp. the return electrode, see figure 2.9. The electrical circuit is therefore closed by the tissue area that are grabbed between the arms of the electrodes (Massarweh, Cosgriff & Slakey, 2006).

Because of the short distance for the current, the bipolar electrosurgery requires lower frequencies than monopolar electrosurgery. Lower voltage results in a limited ability to cut but are better suited for uniform drying of tissues, which minimizes the chance of re-bleeding. this instrument is thus more suitable for coagulation or for procedures where tissues easily can be grabbed on both sides by the forceps electrodes(Sankaranarayanan, 2013). The design of the bipolar ESU results in a better control over the tissue area and thus helps preventing damage to other adjacent sensitive tissues. The bipolar electrosurgery reduces the risk of patient burns significantly and is also optimal to use in patient with implanted devices in order to prevent short-circuit or misfire (Bonomi, 2016).

Figure 2.9: *The bipolar electrosurgical instrument designed as a gripper (Elite Medical, n.d.).*

2.6.3 Disturbances

Disturbance in operating theaters relates to the remaining sources that contribute to the airborne contamination. Door openings are probably the most common disturbance, but other examples can be leakage between rooms, particle generated equipment or other machines that contribute to the airborne particles.

2.6.3.1 Door Openings

When a door opens or closes, air movements will be created from the door´s swinging action. This action generates unpredictable air vortices which are relatively short-lived as they abate after a couple of seconds to gradually fade away. The process only lasts for a couple of seconds, and the extensions of the air vortices reach up to 1 meter into the room (Nordenadler, 2010).

The air movement from doors can be neglected when having a temperature difference to the adjacent rooms of more than 3 - 5 degrees. Otherwise, the supplied amount of air to the room is proportional to the velocity of the door´s movement. The air volume contribution from a door opening is about 50 % of the door´s sweeping volume. For example, a door with a width of 1 meter, height of 2 meters and an opening angle of 90 degrees will give a supply of air volume of around 0.8 m3 (Nordenadler, 2010), compared to the door's sweeping volume of ca. 1.57 m^3.

2.6.4 Source Strength Calculation

Source strength is normally described as the mean value of the number of airborne CFUs generated per second from one person. This is assumed since bacteria are mainly emitted from the skin of the staff. Thus, this is a valuable tool in calculating the needed air volume flow or the number of persons that can be allowed in an operating theater (Nordenadler, 2010).

When calculating the necessary air volume flow in the operating theaters, a simple applicable expression can be derived which describes the relationship between the concentration of the airborne CFUs, the source strength in the room, the air volume flow, and the number of persons in the room. This equation is called the dilution principle and can be used when the air pattern in the room acts in a disordered way i.e., a total mixing of the air. A total mix of the air is normally established for systems with a mixed ventilation and for systems with a displaced ventilation. Regarding parallel airflow systems, a disordered airflow pattern in the operating zone is sometimes made to be able to use a simplified equation in order to estimate the values using the dilution principle, but they are not applicable in the same way.

With the assumption that there is no air leakage from the adjacent rooms to the operating theater and the HEPA-filters having close to 100 % efficiency, the dilution expression is applied in totally mixed air:

$$q_s = \frac{c \cdot Q}{n} \tag{2.1}$$

where

- q_s is the source-strength of the bacteria carrying particles from each person [CFU/s]
- c is the concentration of the bacteria-carrying particles [CFU/m^3]
- Q is the air volume flow [m^3/s]
- n is the number of people

2.7 Ventilation Principles

An air conditioning system in the ordinary facilities, like offices and schools, is designed to provide a comfortable environment with an acceptable level of air contamination, so called comfort ventilation (Lundblad & Nilsson, 2013).

The primary purpose of a ventilation system in an OR is to provide a secure area by protecting the patient against airborne bacteria-carrying particles, in order to prevent infections. Secondly, the aim of the ventilation is to achieve a comfortable environment for the patient and the staff. This type of ventilation is called safety ventilation (Lundblad & Nilsson, 2013).

To achieve the optimal cleanliness condition, it is necessary to have a negligible air inflow from the surrounding environment, control of the air movement and of the concentration of the contaminations in the air is (Lundblad & Nilsson, 2013).

There are three different air streaming principles: mixed airflow, displaced airflow and the parallel airflow principle.

2.7.1 Mixed Airflow Principle

A mixed airflow distribution is the traditional ventilation principle in an operating room. The air is supplied from the ceiling by an air supply device creating an effective mixing process, called a turbulent airstream. Because of this total blending of air, the temperature differences are small and the air contaminations are evenly distributed in the room. This, in turn, dilutes the airborne particles successively (Appengren & Erlandsson, 2012). The principle is shown in figure 2.10.

Due to the robustness of this ventilation principle, the air supply with a temperature below the room temperature but with a high velocity is possible, which also provides a high comfort level in the room. Another advantage is that the air stream is not as sensitive against either thermal or physical disturbances (Appengren & Erlandsson, 2012).

This kind of operating room is normally not constructed today because of the evenly distributed contamination generated in the air. The parallel streaming principle is normally chosen, if not the displaced airflow principle, which both give a much cleaner zone around the patient compared to the mixed airflow principle (Appengren & Erlandsson, 2012). Operating theaters built around the mixed airflow system are therefore usually found in older hospitals.

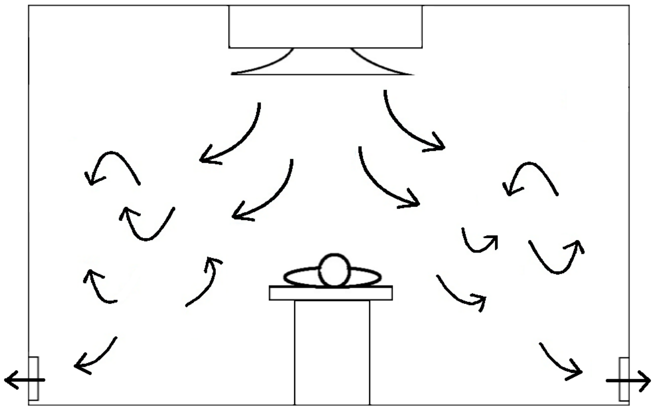

Figure 2.10: *A schematic picture of the mixed airflow principle for ventilation which is supplied from the ceiling. mod. (Appelgren & Erlandsson, 2012).*

2.7.2 Displaced Airflow Principle

The displaced airflow principle works by supplying air under room temperature in low velocities along the floor of the room. The air moves out over the floor where it eventually heats up from warm surfaces. This generates a convection movement due to the density differences of warm and cold air. The air rises toward the ceiling and is pushed out through the air-exhausts, see figure 2.11. When the physical activation in the room is created, the air is assumed to behave as a mixed airstream. The air pushes the airborne contaminations from the operating zone upward, creating an upper zone with more contaminated air than the zone at the floor level, called the lower zone. The boundary between these zones is desired to be as high in the room as possible, preferably over the breathing zone. A disadvantage of this principle is the risk that the supply air will introduce bacteria and other particles from the floor upward to the patient (Appengren & Erlandsson, 2012).

Since the air is supplied at the floor level, there is a risk of discomfort for the staff in the operating room due to the possible draught caused by a high air velocity. That is why displaced supply devices are relatively large, to give good conditions for larger airflows even though the supply air velocity is small (Appengren & Erlandsson, 2012).

The low level of inflow also makes the principle sensitive to disturbances from physical activity that can create both mechanical disturbances and a generation of heat in the air, which disturbs the desired thermal air movement from the floor to ceiling

(Appengren & Erlandsson, 2012). Another cause that distorts the intended air flow pattern is local obstacles like personnel and equipment (Nordenadler, 2010). These create vortices normally behind the causing obstacle. Vortices are unpredictable air movements causing uncontrolled dispersion of air contaminations, (Ljungqvist & Reinmüller, 2013).

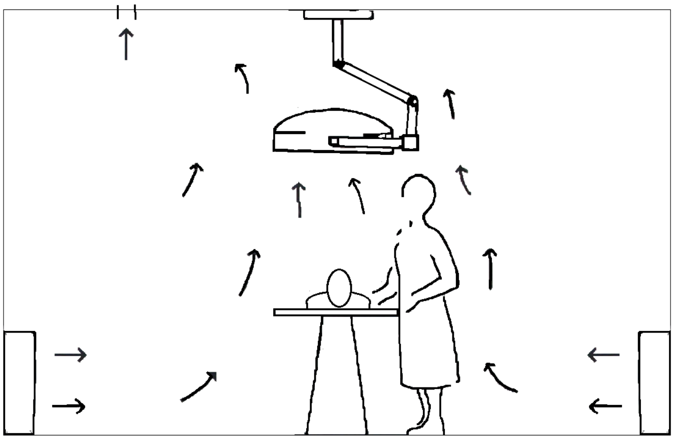

Figure 2.11: *A schematic figure of the displaced airflow principle, with air supplied at floor level and exhausted at the ceiling (Nordenadler, 2010).*

2.7.3 Parallel Airflow Principle

The parallel airflow principle exists in both a vertical and a horizontal manner. The vertical parallel air principle is the most common, also known as the unidirectional airflow system or laminar airflow system. It is a controlled air ventilation principle developed with a high amount of parallel supply air creating a controlled air distribution in an OR, see figure 2.12.

The concept is to create air movements with as few air vortices as possible since they have a negative effect on the safety ventilation. The most important component is the air supply device, which distributes and pushes clean air in a controlled laminar manner from the ceiling downward over the patient and further down to the floor level where it is exhausted. The supply device is usually built like a cylinder with a HEPA-filter which has a function to clean the supply air but also help with the air distribution. The airflow past the patient brings the contaminations with it on the way down from the operating area in a higher manner than the ventilations with a mixed air stream, since the air is distributed without vortices (Appelgren & Erlandsson, 2012).

This principle requires very high airflows, commonly between 10 000 - 20 000 m^3/h or 400 - 500 air changes per hour (ACH), which is about 5 -10 times higher than the airflow for the traditional mixed airflow principle, about 2 000 m^3/h or 16 - 20 ACH (Ljungqvist & Reinmüller, 2013).

When the air velocity increases, such as for this air distributing principle, the impact of the air vortices increases because of the decrease in the disturbance from physical activity. The airflow for a unidirectional principle is therefore optimized for preventing vortices in the airflow pattern. Obstacles like lamps placed over the patient, surgery equipment and the staff, however, are difficult to eliminate (Ljungqvist & Reinmüller, 2013).

Today, the vertical parallel streaming principle is normally used at new hospitals. The principle is built around the special false ceiling that creates the evenly distributed air flow. The false ceiling for the conventional rooms normally consists of perforated sheets with small holes, which is not efficient enough to create laminar airflow. Furthermore, this part is not that easy to change, since most operating theaters are mainly constructed after their ventilation system. Today, the false ceilings are almost entirely built with systems with the ability to create controlled laminar airflows (Appelgren & Erlandsson, 2012).

Since this ventilation principle results in such high air cleanliness in the OR, it is mainly used when the air cleanliness demands are high, such as for infection-sensitive surgeries. This principle is also used in hybrid operating theaters.

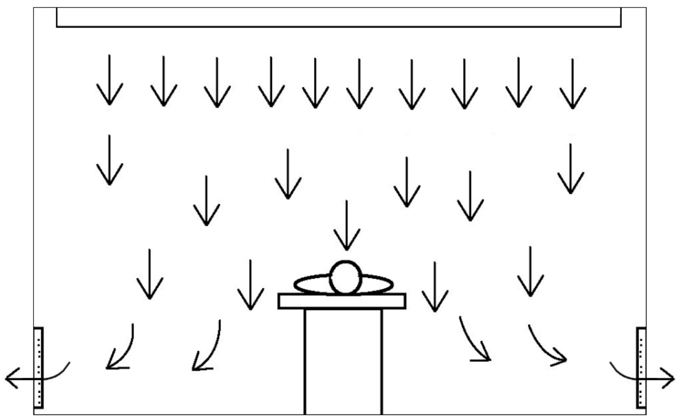

Figure 2.12: *A schematic figure showing the vertical parallel airflow principle, with supply air supplied from the ceiling. mod. (Appelgren & Erlandsson, 2012).*

2.7.4 Hybrid operating Theaters

Hybrid operating theaters (HORs) are a relatively new type of operating theater, built to be able to handle both surgical procedures and x-rays in the same room, maximizing space optimization in a hospital. The main advantage of a HOR compared to a regular OR is, of course, the built in automatic x-ray scanner that can give real-time visualization of the patient's anatomy during the surgery (Bonomi, 2016).

Even though HORs utilize space more efficiently than a regular OR plus an x-ray facility, they are larger than regular ORs. Commonly, HORs have an area of ca. 100 m^2, while normal ORs tend to have an area of approx. 50 m^2. This, of course, has to do with the needed space for the x-ray machine and other advanced equipment (Meda, 2014).

The surgeries often take place in a part of the HOR called the surgical zone. The surgical zone often has an area of around 10 m^2 where a laminated airflow is supplied in high velocities, making the risk of infections in a HOR very low (Lundblad & Nilsson, 2013).

2.7.5 Positive internal pressure

In order to prevent the air from the neighboring environments from being transferred into the operating theater, an positive internal pressure is maintained in the OR. This is done through ventilation by selecting a greater supply air flow than the exhaust air flow. When the door to the room is closed, the differential pressure will protect against air leakage from the outside. The suggested pressure difference between the OR and the adjacent rooms is suggested to be 5 -20 Pascal (Jordestedt, 2015). This is, of course, more important in surgeries with a greater risk of infection (Lundblad & Nilsson, 2013). In ultra clean air systems, the air is even more controlled and improved.

2.8 Risk of Infections

A human being´s skin has a natural barrier against infections. This means that any breakage of the skin in a surgery can cause surgical site infections (SSIs). A SSI arises after a surgery in the part of the body where the surgery took place (Medical center, 2016) and is one of the most common types of infection in the health care. The most harmful type of surgery is where unfamiliar objects for the body, for instance a hip prosthesis, are operated into the patient (Appelgren & Erlandsson, 2012).

2.8.1 Particle Transportations

The main cause for a surgical site infection is the airborne bacteria-carrying particles. These bacteria are transported in three ways: by physical contact, by droplets, or by the air.

The physical contact means a direct contamination from the staff to the wound at the operating table or indirectly via contamination from the instruments and/or other equipment used during the surgery. Reasons can be e.g., a cut in a glove, torn working clothes, or wet clothes. Droplets occur e.g., through coughing, sneezing, sweating, and speaking where the saliva drops directly into the wound (Appelgren & Erlandsson, 2012), (Lindblom, 2008).

The amount of microorganisms in the saliva is normally rather low and is not considered to be the major cause of the airborne dispersion of bacteria (Jordestedt, 2015). The amount of bacteria-carrying particles is about 10 000 for a sneeze, 100 for a cough, and 10 for speech (Lindblom, 2008).

Another possibility is that the droplets form an aerosol containing very small droplets that can be carried by the air (Vårdhandboken, 2015). The amount of such aerosols in the air is often small compared to the amount of skin fragments in the air, emitted from the staff (Appelgren & Erlandsson, 2012).

The amount of fragments a person emits during "normal" movements is considered to be around 10 000 per minute. Approximately 10 % of these are carriers of bacteria, which means that every person in an operating theater emits about 1 000 CFU per minute, or 2.7 CFU per second. The sizes of these fragments differ between 5 μm - 60 μm. The mean size, however, is around 10 μm which means they can either be carried by the air or settle down, depending on which driving force that tends to have the greatest impact for the moment (Jordestedt, 2015).

When comparing the airborne CFU-values with the droplet´s CFU-values, the skin particles show a considerably higher source strength; hence, they are considered to be the main source for airborne bacteria.

Another way for infection to spread is the situation where the bacteria come from the patient him or herself. These bacteria normally come from the skin of the patient and are easily transported to the wound, causing infections. surgeries in organs that normally contain bacteria, e.g., intestines or stomach surgeries have a higher risk of this situation than other types of surgeries (Appelgren & Erlandsson, 2012).

Thus, there are basically two ways to protect a patient from the airborne bacteria-carrying particles from the staff:

- Airtight clothing which prevents the particles from leaving the body and becoming airborne.
- Efficient ventilation which will dilute the concentration of the bacteria and prevent them from reaching the operating area.

2.8.2 Risk of SSIs

The risk for a surgical site infection complication after a surgery depends on the type of surgery. The average risk is however 2 - 5 %, which in turn causes an increase in the length of the hospital stay for the patient, with approximately 7 - 10 days. SSI also results in a 2 - 11 times higher risk for mortal outcome compared to patients without SSI (Anderson et al. 2008).

Today's increased expansion of multi-resistant bacteria makes an infection caused by multi-resistant bacteria a potentially deathly outcome. This is already an established problem (Anderson et al. 2008).

2.8.3 Cost of SSIs

The cost for the treatment of SSI varies, depending on the type of surgery and type of infecting pathogen. Independent of this, the costs are enormous. The United States has an estimated cost of between $3 000 and $35 000 in hospital fees for treatment of each patient. This results in an annual cost of $3 billion up to $10 billion in the US (Scott, 2009), (Anderson et al. 2008).

3 Method

3.1 Surgery at Östra Hospital

The hospital where the measurement took place was at Östra Hospital, which was inaugurated in 1978 and lies in the eastern part of Gothenburg, Sweden. This hospital, together with four other hospitals around Gothenburg, has been part of the Sahlgrenska University Hospital since 1997 (Björk, 2013).

At the time when the hospital was built, the standard operating theater were equipped with ventilation systems using based on the mixed air ventilation principle. The previous generation of operating theaters, however, is still the most common system existing today, and these rooms need to be updated to improve the cleanliness of the air in order to prevent the risks of infections for the patients. Today operation rooms (ORs) are, as mentioned before, normally built with a controlled laminar air ventilation systems or as hybrid rooms, but there are still a majority of ORs utilizing the mixed air ventilation principle in use today. Therefore, it is of great importance to minimize the contamination in the air in such ORs to reach the ever increasing requirements of cleanliness in the operating theaters but also, perhaps most importantly, to prevent the risk of SSIs for the patient.

In this thesis, the contagions from a Rectum Extirpation operation were studied at Östra Hospital.

3.1.1 Rectum Extirpation

Rectum Extirpation is a surgical procedure for patients diagnosed with rectal cancer or anus cancer. The procedure completely removes the distal colon, the rectum, and the anus through incisions made in the abdomen and perineum (Perry & Connaughton, 2007).

The incision in the abdomen is made at the pubis to just above the umbilicus.The small intestine is packed into the upper abdomen, which gives an adequate visualization and access to the cavity. After removing the rectum and the lower colon that is affected by disease, the end of the remaining colon is brought out permanently as an opening on the surface of the abdomen, called colostomy. This wound is closed by clips, which are removed after approximately 10 days. The lining of the colon on the abdomen is called a stoma. A colostomy pouch is applied to the skin around the stoma, and the pouch gathers stool and gases from the body. The stoma is usually placed in the lower left side of the abdomen, about 5 centimeters away from the belly button. The perineal area is the area between the anus and the reproductive organ. The removal of the rectum and the anus in this area results in an empty space between the buttocks. This space is closed by stitches (Perry & Connaughton, 2007).

The operation time may vary for this type of surgery, but is usually around 2 – 4 hours.

3.2 Experimental Procedure

The surgery where the measurements for this study took place was at Sahlgrenska University Hospital, Östra Hospital, at the central clinic (centralkliniken) in OP1 hall 4. A Rectum Extirpation operation was performed on November 24, 2015.

The room had a ventilation system based on the mixed airflow principle, but with a supply device extended along the top of the wall, instead of one single supply device. The floor area was 42 m^2 and the height of the room was 3 m. The room also had a dimensioned supply airflow of 2 100 m^3/h and an exhaust airflow of 1 600 m^3/h, corresponding to 0.58 m^3/s and 0.44 m^3/s, but the last control of the air-flow measured a supply airflow showed a value of 1 948 m^3/h corresponding to 0.54 m^3/s (CRC medical, 2015). The value of further estimations was also based on 0.54 m^3/s. The protocol also showed an positive internal pressure of 5.2 Pascal, while the measurement during the surgery showed an positive internal pressure of 7 Pascal. The direction of the flow was toward the patient's feet, and the two exhausts were on the side walls of the operating theater as far from the supply device as possible, see figure 3.2. The theater, shown in figures 3.1 and 3.2, had a wide double door on the short side opposite to the supply air, where the patient was rolled in on the operating table with wheels. On the opposite short side, there was a normal door that was used by the staff.

A small pre-treatment room was located between the corridor and the entrance to the operating room. Here, inter alia, the equipment were disinfected before the surgical procedures. This room is also used to reduce the impact from the atmosphere in the outer hospital area.

To get a reliable value of the air conditioning level, two of the particle detectors were placed by the two exhaust devices that existed in the room, measurement point 1 (MP1) and measurement point 3 (MP3). The sterile zone where the surgery took place is also an important area. Here, the open wound of the patient is exposed, and it is also the breathing zone for the doctors and nurses. Measurement point 2 (MP2) was therefore set just above the doctor´s head, approximately two meters high; MP1 and MP2 consisted of a P-Trak particle counter detecting the total amount of particles in the size range from 0.02 to 1 μm. The second particle detector was a TSI AeroTrak detecting the amount of particles in different ranges from 0.3 to 10 μm.

The detector referred to as MP4 was a device used for sampling the CFUs on the agar plates for 10 minutes every hour. The sampling started before the surgery and continued until after the surgery ended. These plates were then incubated for a couple of days and subsequently counted to evaluate the amount of CFUs per m^3.

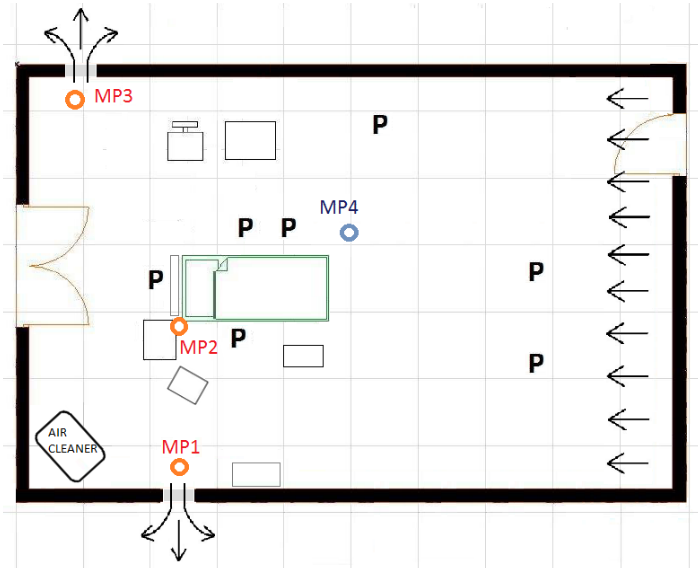

Figure 3.1: *A schematic birds-eye view of the operating theater where the researched surgery took place, based on plan material. The arrows show the direction of the air from the ventilation system further out through the exhaust devices. The P stands for the area where the staff normally stood.*

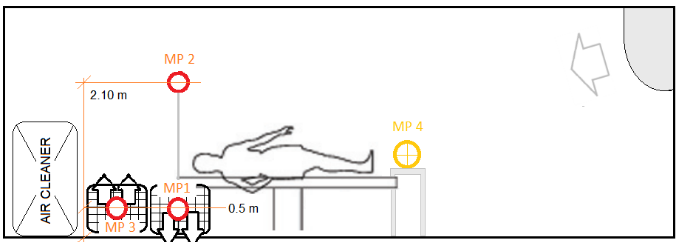

Figure 3.2: *A schematic side-view of the operating theater where the Rectum Extirpation operation took place. The arrows show the direction of the air from the ventilation system at ceiling level further out through the exhaust devices at floor level.*

The clothing used during the surgery was the standard suit, consisting of a long pair of trousers and a short-sleeved shirt made of 30 % polyester and 70 % cotton. The nurses in the room outside the clinical area wore this suit together with a single-use hat or helmet. The surgeons in the clinical area in close proximity to the wound also used a face mask, gloves, a single-use hat or helmet and a surgical coat on top of the suit.

3.2.1 Surgery Timeline

The timeline in figure 3.3 shows the procedure during the surgery. Before the patient arrived, the room and equipment were disinfected and prepared. Then during the surgery, a monopolar diathermy was used, which created a smell, due to the surgical smoke (as noted by the author of this thesis and noted in the figure).

Pauses were taken for the nurses to change the position of the patient, at which time the doctors were not present. The standard position is where the patient who is to undergo the surgery lies flat on his or her back on the operating table. The rectum position is equal to a normal gynecological check up position. During the pauses, the nurses also disinfected the area around the wound.

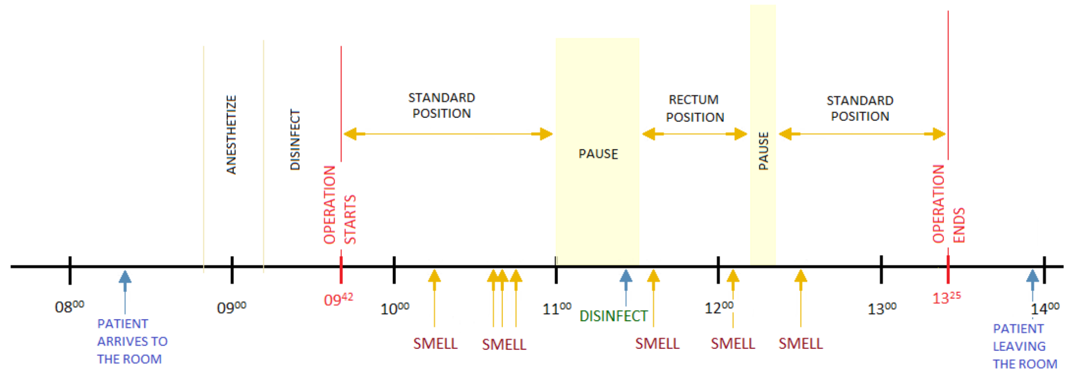

Figure 3.3: *A timeline of the studied surgery; the arrows noting the smells are the times during the surgery where the author of this thesis noticed a smell from the monopolar diathermy.*

In figure 3.4, the details of the usage of an air cleaner as well as the sampling times for the CFUs are shown. An air cleaner was placed in the operating theater in order to evaluate if and how much this contributes to the cleaning of the air.The air cleaner, as can be seen in the picture, was turned on every second hour and, as the particle detectors, were on before patient arrives to the room until a while after the patient left the room. The surgery took almost 4 hours.

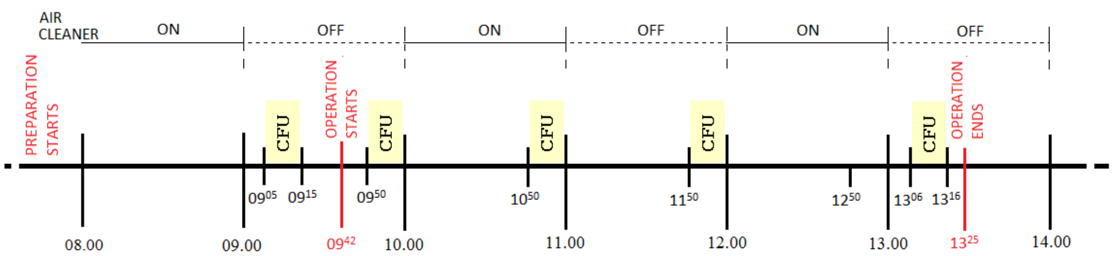

Figure 3.4: *A timeline of the studied surgery and the author's sampling of the CFU, as well as the air cleaners operational time.*

3.3 Air Cleaner

A DopAir air cleaner was used for the measurements in this thesis. DopAir is an air cleaner from the French company ATA Medical, shown in figure 3.5, which has designed air handling units for areas with high risk of infections for the last 30 years. DopAir is a mobile unit, with an adjustable airflow ranging from 600 to 2000 m^3/h; furthermore, it has an air change rate of 15 volumes per hour and does not need any installation work to meet the requirements regarding the air treatment (ATA Medical, 2013). The air cleaner was attuned on 1 100 m^3/h during the surgery.

Figure 3.5: *The air cleaner, DopAir used in this project (ATA Medical, 2013)*

The air cleaner uses two filters and a bioxigen system. The first filter, a F7, is a fine dust filter that operates over a very low pressure drop and with an average filtering efficiency of 80 - 90 % for particles with a diameter > 0.4 μm. The second filter, a H14 is a HEPA filter, which also operates over a very low pressure drop and with a filtering efficiency of 99.995 % MPPS for particles with a diameter > 0.3 μm (ATA Medical, 2013).

The remaining 0.005 % undesirable particles now pass through the bioxigen system where they are exposed to a set of condensators producing an electric field. This gives numerous chain reactions causing two main actions: a microbicide and a bacteriostatic action which together destroys the remaining bacteria, fungus, mould, yeasts, pollution, pollens, steam and smoke (ATA Medical, 2013).

3.4 Measuring Instruments

Three particle counting instruments of two different types were used during the measuring: two P-TRAK® 8525 Ultrafine Particle Counter (UPC) and one AeroTrak™ portable particle counter 9310. The tools are briefly described below.

3.4.1 TSI P-TRAK® 8525

The P-trak counter (figure 3.6) registers ultrafine particles with sizes between 0.02 μm and 1 μm and register particles in the range of 0 to 500 000 particles/cm^3. When the sample is collected, a mean value over a selected time is recorded. The minimum interval is 5 seconds, which is also the interval the author chose due to the aim of recording as accurate values as possible (TSI, 2016). Particles are drawn to the instrument with an air flow rate of approximately 100 cm^3/min thanks to an inbuilt pump. The air passes through a saturator tube where it is mixed with alcohol vapor, which makes the air condensate on top of the particles in a condenser tube. This causes the particles to grow into larger droplets. By passing through a laser beam, flashes of light are produced and a photo detector counts the concentration (TSI, 2012).

Figure 3.6: *TSI's P-Trak Ultrafine Particle Counter (TSI, 2016)*

3.4.2 AeroTrak™ portable particle counter 9310

A TSI AeroTrak™ 9310 portable particle counter (figure 3.7) generates a flow rate of 28.3 liters/min. The sample inlets are located on the top of the instrument and counts the particles passing through into six different size channels: particles larger or equal to 0.3, 0.5, 1.0, 3.0, 5.0, or 10.0 μm. The sampled air is exhausted through a pump exhaust diffuser placed at the back of the instrument. This air is HEPA filtered before it is exhausted back to the room. The counting data is viewed on a touch screen display and up to 10 000 registered data points can be stored in the AeroTrak™s internal memory. The results can be downloaded or printed directly by the integrated printer. The gauge can be used alone or integrated into a facility monitoring system (TSI, 2009).

Figure 3.7: *TSI's AeroTrak™ portable particle counter 9310 (TSI, 2009)*

4 Results

4.1 CFUs

The CFU measurements from the performed surgery are presented in table 4.1. The agar plates were normally exposed during the last ten minutes of every hour except for the first and last agar plates. See the table-caption for details.

Table 4.1: *The detected CFU-concentrations during the surgery; Agar plate 0 was sampled between 09:05 and 09:15 during the patient's preparation period, Agar plate 1 was sampled between 09:50 and 10:00 during the body opening, Agar plates 2 and 3 were sampled between 10:50 to 11:00 and 11:50 to 12:00 during the surgery, and the final agar plate, number 4 was sampled during the body closure, between 13:06 and 13:16.*

Agar Plate	Phase of operation	CFU/m^3
0	Patient Preparation	13
1	Body Opening	10
2	Surgery	5
3	Surgery	5
4	Body Closing	6

4.2 Particles

The results from the first two gauges (1 and 2) in the measurement of the particle concentration during the surgery are shown in figure 4.1. The plots show the total amount of detected particles in the range 0.02 - 1 μm.

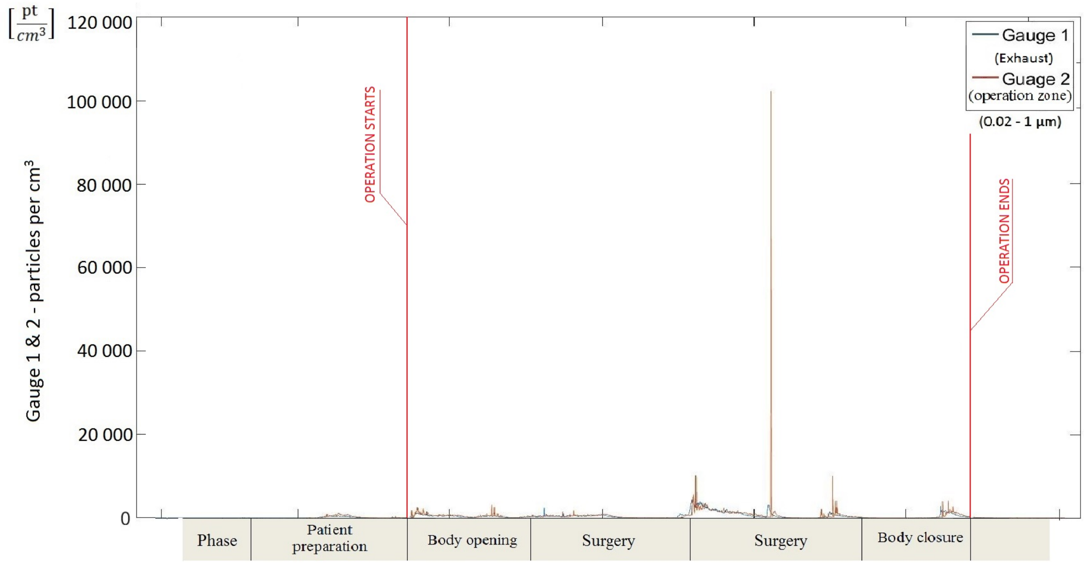

Figure 4.1: *The results detected from gauges 1 and 2.*

This graph shows one very large particle concentration of 102 120 particles per cm^3 in the sterile zone (gauge 2) at the time 12:06 during the surgery phase. Since the other values are much lower, a zoomed graph without this peak value is shown in figure 4.2. This graph shows a better overview of the measured results where two peaks are seen with values around 10 000 for gauge 2.

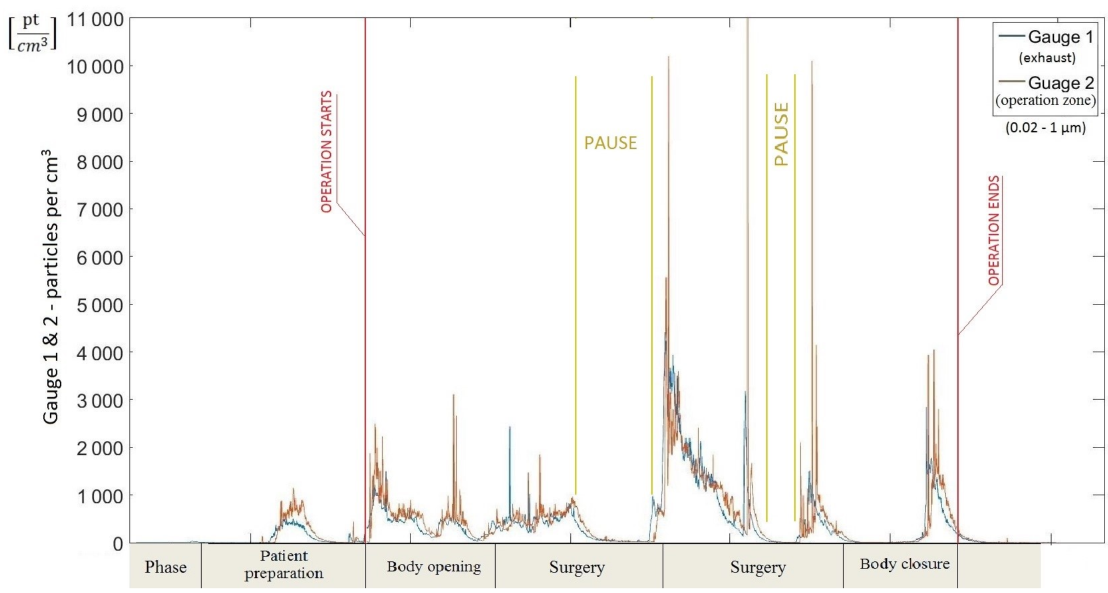

Figure 4.2: *A modified graph of the results detected from gauges 1 and 2 (the extreme value is ignored).*

Particle detector 3, the AeroTrak, is now added to the results. As mentioned in the theory, the AeroTrak detects particles of greater sizes (0.3 - 10 μm) compared to the size range for gauge 1 and 2 (0.02 - 1 μm). Figure 4.3 shows the particle amounts for all three gauges and gauge 3 here appear as a green line along the x-axis. This line can be hard to notice in the figure and it is hard to clarify if gauge 3 acts or varies at all. Figure 4.4 therefore shows a zoomed graph of the results. Notice that the x-axis is moved upward in order to see the results from gauge 3 (green line) more clearly.

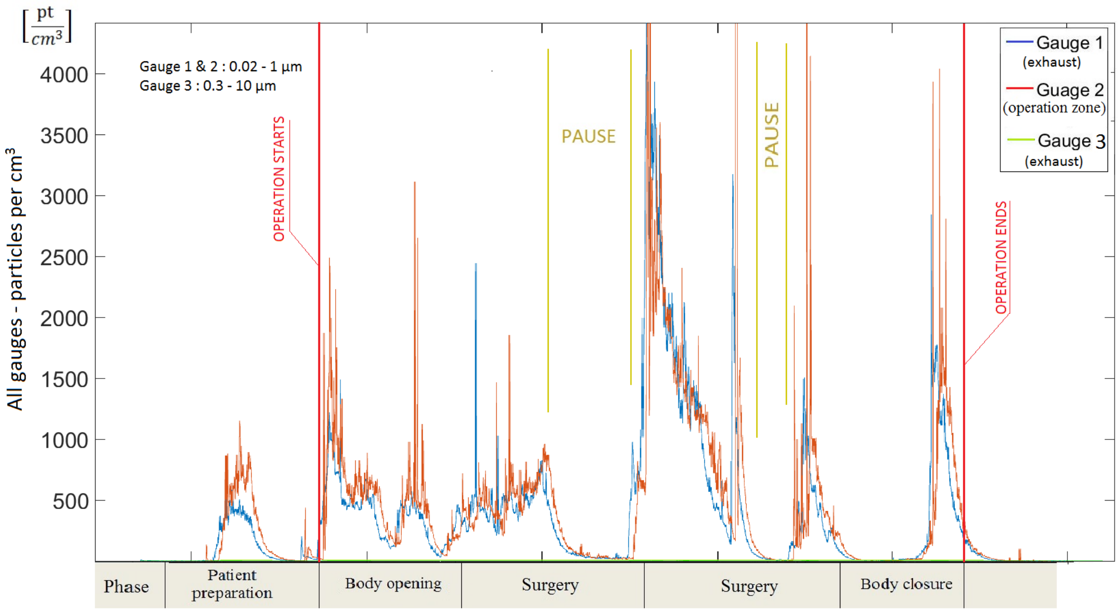

Figure 4.3: *Results from all gauges*

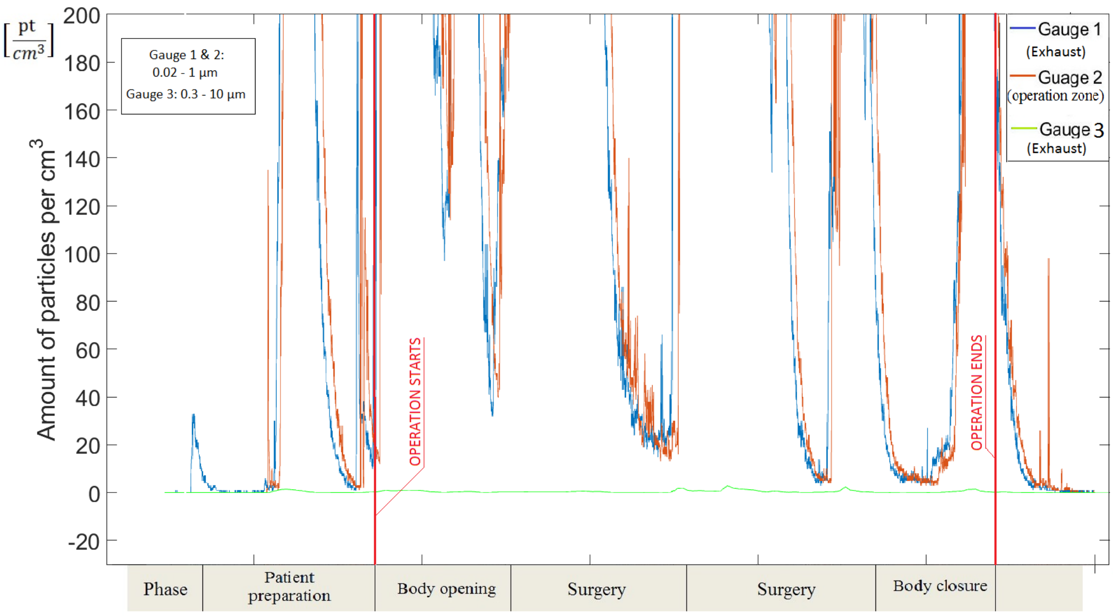

Figure 4.4: *Results from all gauges in a zoomed version and moved x-axis*

Figure 4.4 shows that gauge 3 at least moves a bit. In order to see a fair comparison of the different results figure 4.5 shows a graph of the total particle concentrations for all three gauges where the results from gauge 3 are plotted on a separate y-axis. These values are now displayed with the unit particles per dm^3. This figure has also omitted three large values from gauge 2, one at around 100 000 and two at around 10 000, with the intention of increasing the readability of the graph.

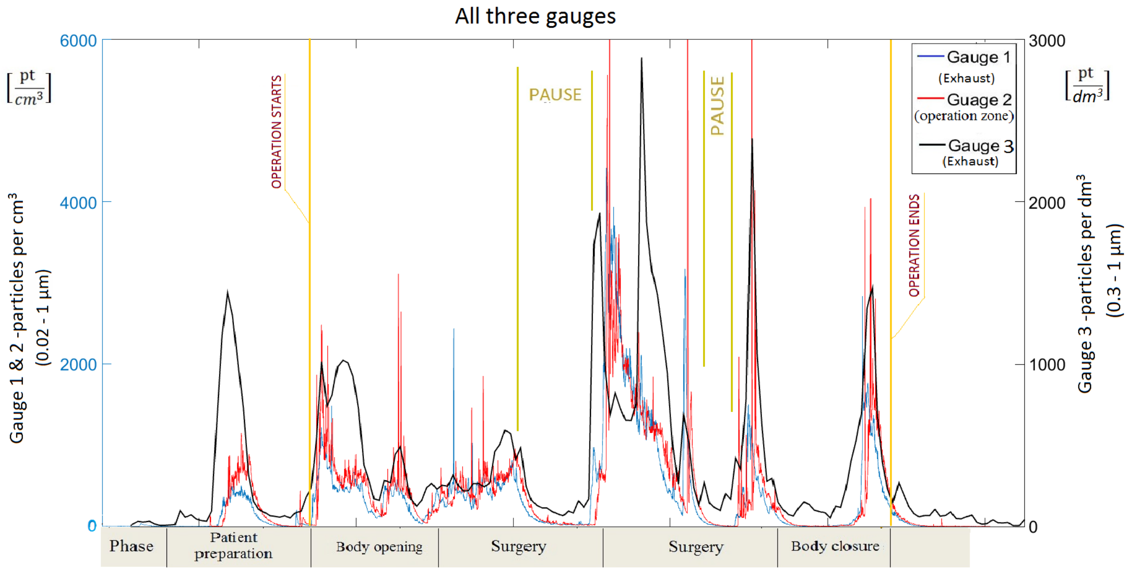

Figure 4.5: *A graph showing the detected amount of particles from the different particle detectors as a function of the time in the room. Note that gauge 1 and 2 have the left y-axis in the unit particles per cm^3. Gauge 3 has the right y-axis with the unit particles per dm^3 in order compare the amount of particles for all gauges. Note also that three large values from gauge 2, one at around 100 000 and two around 10 000, have been omitted to increase the readability of the graph.*

Since the AeroTrak (gauge 3) range the particle amounts in different sizes, 0.3-0.5, 0.5-1, 1-3, 3-5, 5-10 & >10 μm, it can be interesting to see the variation in concentration for the different ranges. The concentrations of these different sizes of particles are shown in figures 4.6, 4.7 and 4.8. Figure 4.6 shows all ranges and the total amount of particles. Figure 4.7 excludes the total amount and the range 0.3 - 0.5 μm. Figure 4.8 also excludes the particle range 0.5 - 1 μm. Every graph is also zoomed in according to the amount of particles in the different ranges.

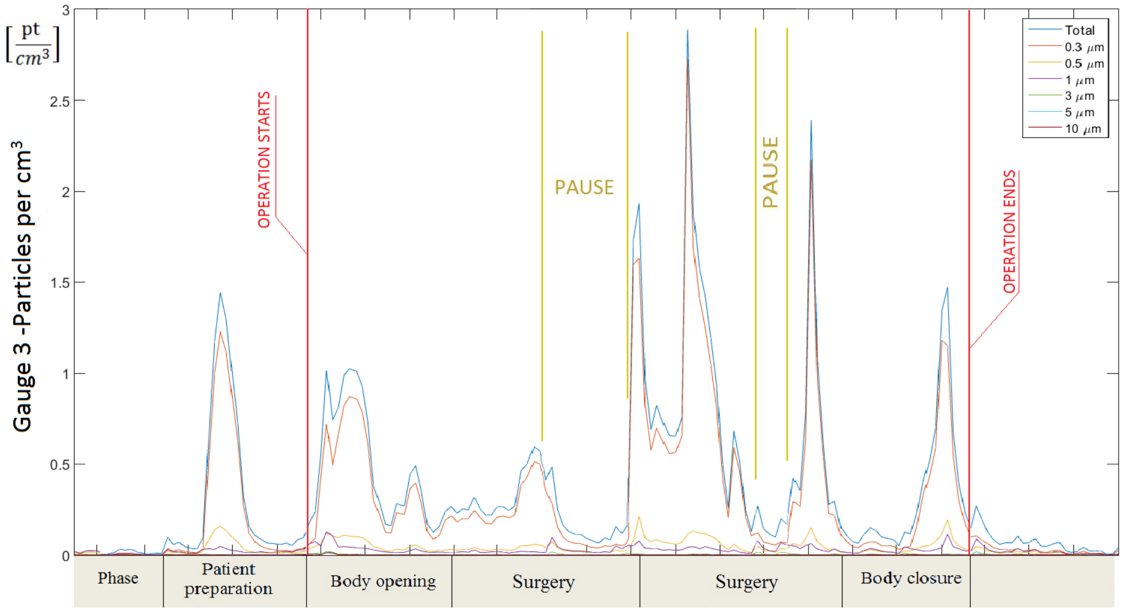

Figure 4.6: *Gauge 3 detects particles ranging from 0.3 μm to 10 μm in size. In this figure, the particle concentrations of all size ranges and the total amount of particles are shown as a function of time.*

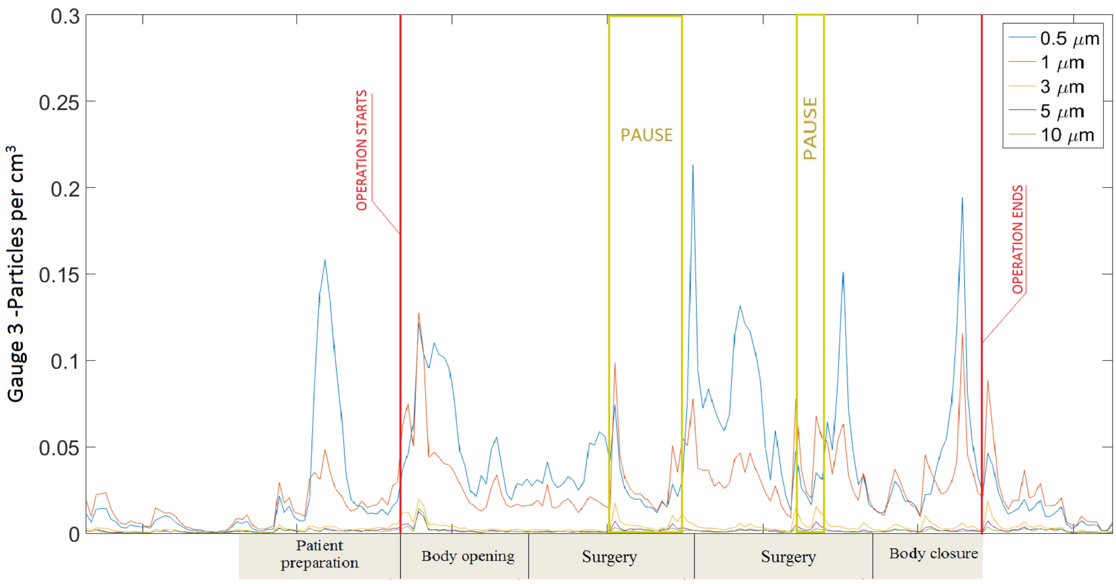

Figure 4.7: *Gauge 3 detects particles ranging from 0.3 μm to 10 μm in size. In this figure, the concentrations of particles with a size of 0.5 μm to 10 μm are shown as a function of time.*

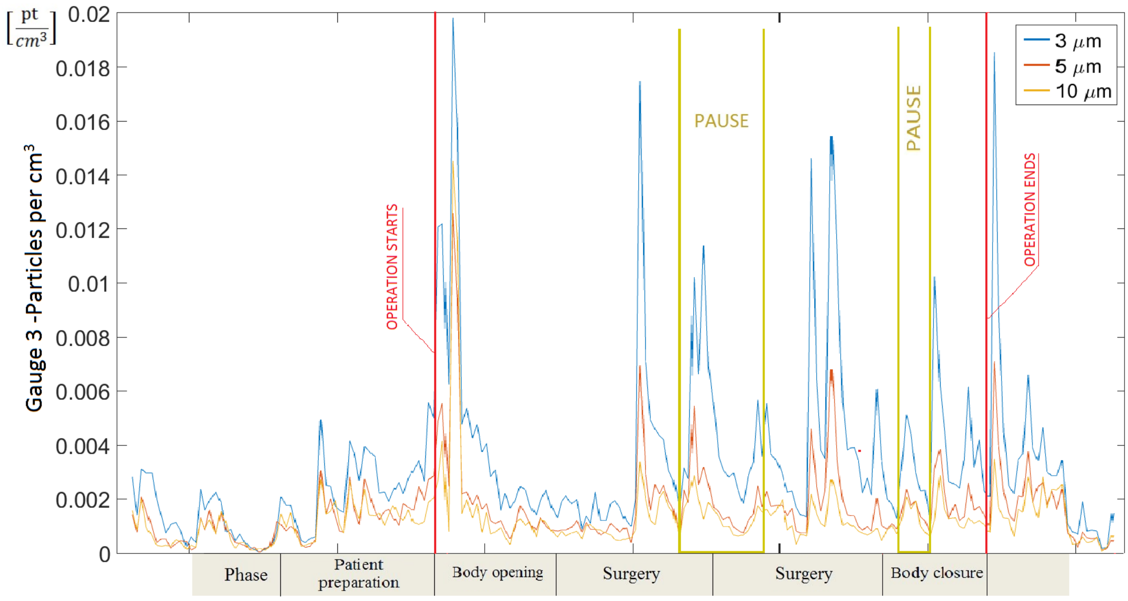

Figure 4.8: *Gauge 3 detects particles ranging from 0.3 µm to 10 µm in size. In this figure, the concentrations of particles with a size of 3 µm to 10 µm are shown as a function of time.*

4.3 Air cleaner

To study the effect the air cleaner has on the particle concentrations, modifications have been made to the graphs in figures 4.2, 4.5, 4.6, 4.7 and 4.8 to show when the air cleaner is on. These updated graphs are shown as figures 4.9 to 4.13

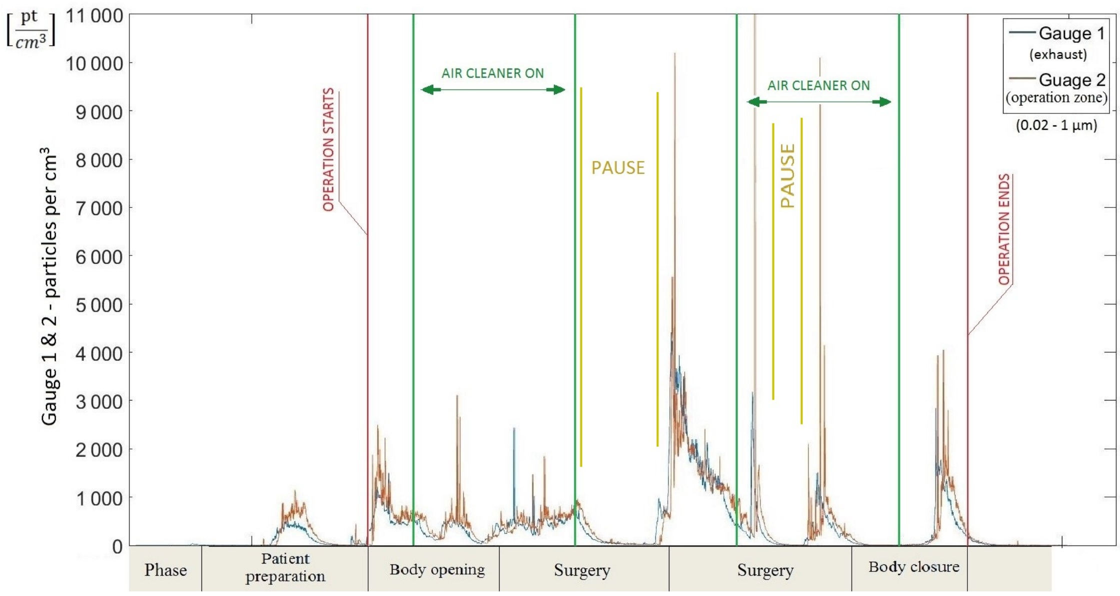

Figure 4.9: *The results detected from gauges 1 and 2 with notations when the air cleaner is on and off.*

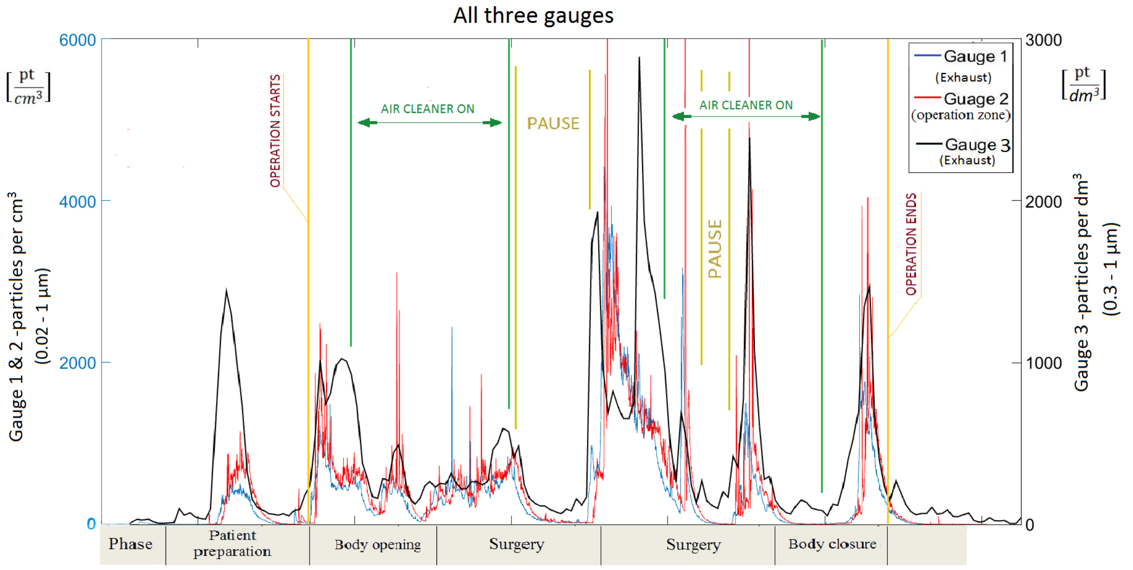

Figure 4.10: *The graph shows when the air cleaner was on and off for the detected amount of particles of all gauges. Gauge 3 has its own y-axis in the unit dm*^{3}*. The reason for the different unit and for omitted 3 large values is due to ease the readability of the graph.*

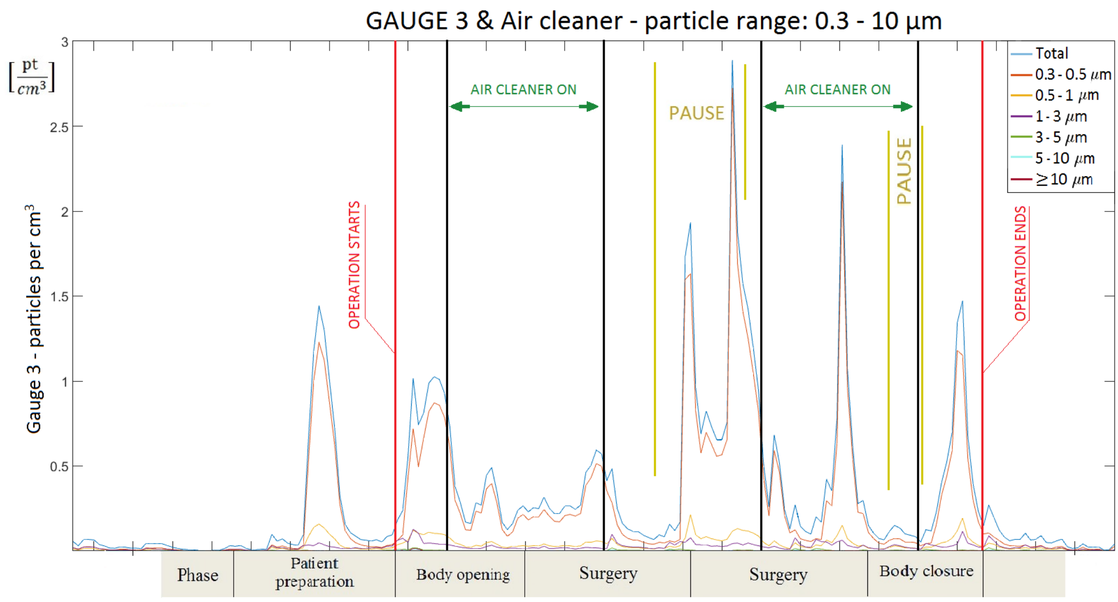

Figure 4.11: *The figure shows the total amount of detected particles and all the size ranges from gauge 3 during the surgery together with the noted air cleaner transfer.*

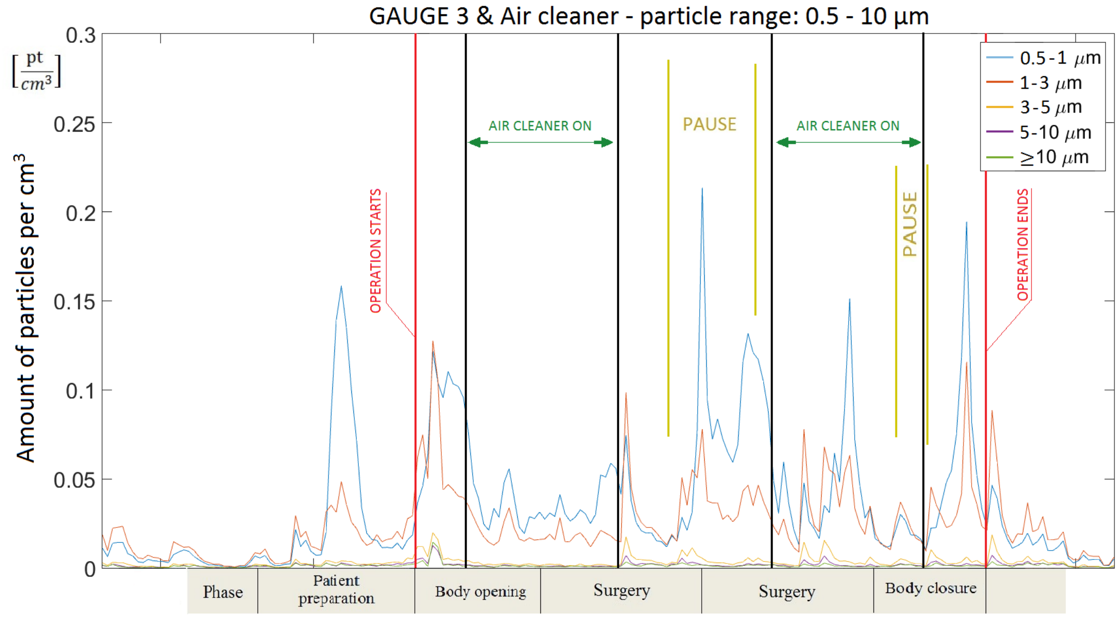

Figure 4.12: *The figure shows the detected particles in the size range 0.5 to 10 µm and when the air cleaner was on and off.*

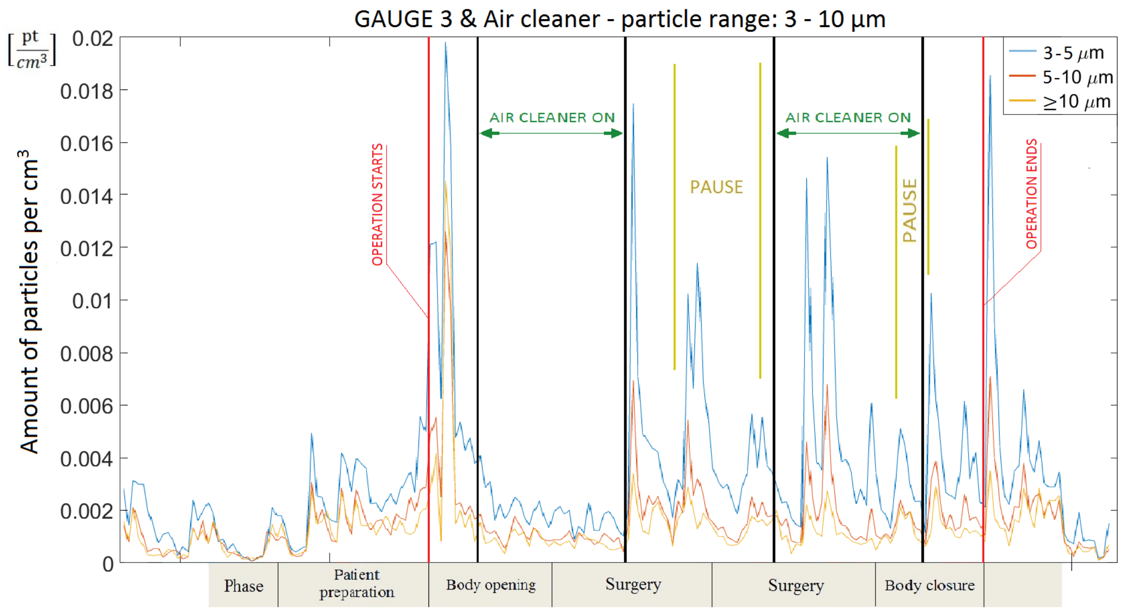

Figure 4.13: *The figure shows the detected particles in the size range 0.3 to 10 µm and when the air cleaner was on and off.*

4.4 Summary

In summary, the CFUs, the data from gauges 1 and 2, the air cleaner's "on"-times, observations, surgical phases and the surgery timeline are shown together in figure 4.14.

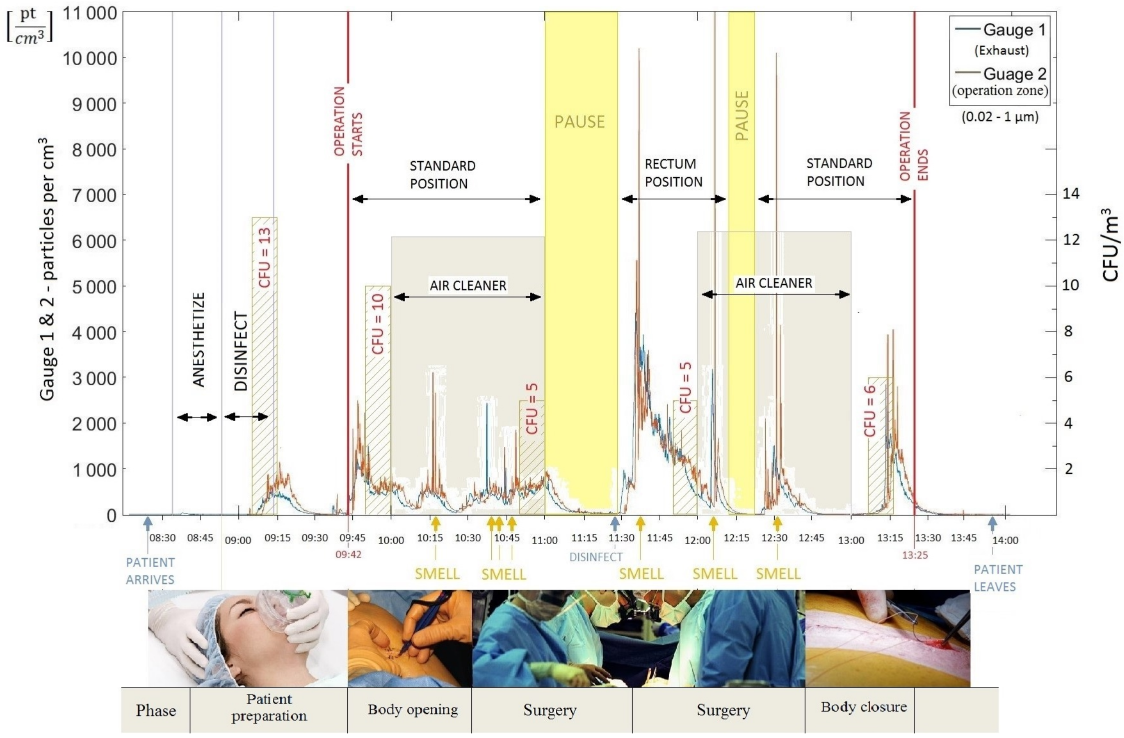

Figure 4.14: A summary of the surgery procedure, the experimental procedure and the detected concentration from gauges 1 and 2; for a bigger replica of this diagram, see Appendix A.

5 Analysis

5.1 CFU

To analyze the acquired CFU-data, a theoretical reference level may be used. Accordingly, the used clothing system's source strength is needed. An estimation of this source strength can be found in the data in table 2.1 and by taking a mean value of the data for the two most common clothing systems, a chosen value can be found.

These mean values are summarized in table 5.1. The studies performed in a chamber, which is an artificial environment, showed higher values compared to the studies performed during real surgery. The procedure in the chamber included a high amount of pre-determined movements performed by the test subjects, compared to the "regular" studies, which probably explains the higher values of source strength in the chamber. Table 5.1 therefore shows the mean values both with and without the chamber studies.

Table 5.1: *Estimated mean source strengths q_s (CFU/s and person) taken from studies described in table 2.1 in section 2.6.1.1.3. C = Cotton, P = Polyester, C-F = Carbon Fiber, P-UG = Polyester Undergarment, PP = Polypropylene.*

	Final mean values of source strength from studies				
CFU/s per person	69 % C, 30 % P, 1 % C-F	50 % C, 50 % P	100 % P, 0 % P-UG	99 % P, 1 % C-F, 100 % P-UG	Single-use clothes made of PP
Chamber Excluded	5.1	1.95	2	0.5	0.9
Chamber Included	6.6	3.8	1.4	0.4	4.35
Chosen Values	4	2	-	-	-

The chosen source strength to be used in further analysis for the standard suit and the clean air suit are also presented in 5.1 as 4 resp. 2 CFU/s. At a first glance one might find the chosen value for the standard suit to be quite low. This is correct, since this value was deliberately adjusted downwards to better adapt to the relevant conditions for the surgery performed.

The chosen values for the source strength of the clothing systems can now be used in a re-formulation of equation 2.1 where c_{est}, the estimated CFU concentration, is the unknown to get an estimate of what the CFU concentration during different phases of the surgery should represent. The q_s-value 4 was used since the staff used the standard clothing system during the surgery (30 % polyester and 70 % cotton). The calculations can be seen in table 5.2.

Table 5.2: *Estimated concentration c_{est} [CFU/m^3] during different phases of the surgery. n equals the number of persons in the room, q_s is the source strength for the used clothing system 70/30 (see section 2.6.1.1.1), and Q is the latest measured supply airflow, which in our case is 0.54 m^3/s*

	Estimated CFU-concentration			
Phase	Patient Preparation	Body Opening	Surgery	Body Closure
n	8	9	9	7
q_s	4	4	4	4
$c_{est} = q_s n/Q$	59.3	66.7	66.7	51.9

Finally, when the estimated CFU-values are found, they can easily be compared with the measured CFU-values from table 4.1. This, very interesting, comparison can be seen in figure 5.1. The comparison shows that the estimated values are remarkably higher than the measured values.

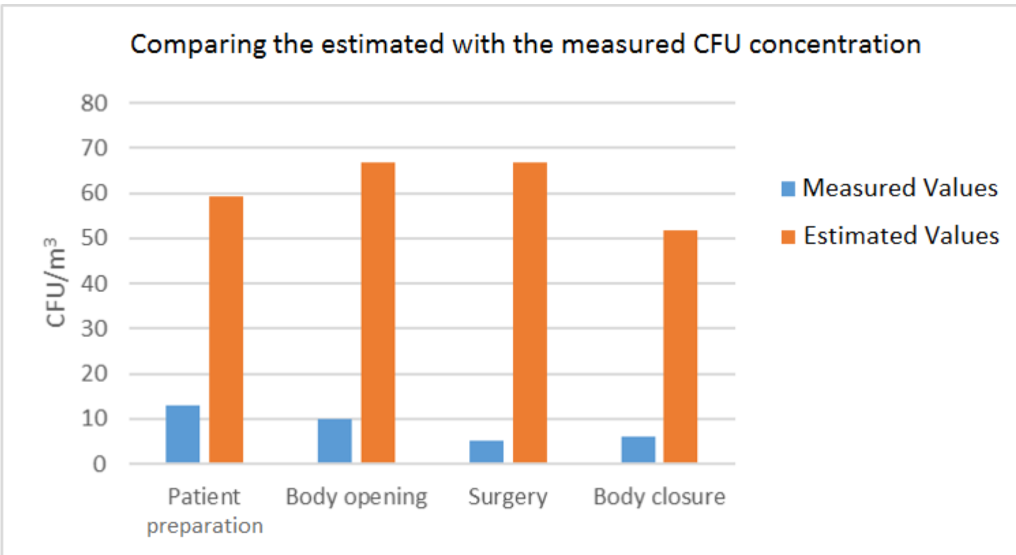

Figure 5.1: *This figure compares the estimated CFU concentrations with the measured CFU concentrations during the surgery.*

In fact, the estimated CFU compared to the measured CFU was during;

Patient preparation:	4.6 times higher
Body opening:	6.7 times higher
Surgery:	13.3 times higher (!)
Body closure:	8.7 times higher

To further use the measured CFU in order to estimate the source strength q_s is equation 2.1 applied again. The following values are obtained in the different phases:

Patient preparation:	$q_s = 0.9$
Body opening:	$q_s = 0.6$
Surgery:	$q_s = 0.3$
Body closure:	$q_s = 0.5$

These results indicate that something is not quite right. The found soruce strengths from the clothing systems are far lower than the ones presented in table 2.1

The graph in figure 5.2 compare the measured CFU concentration during the surgery in this study with two other air flow principles. The two compared ventilation airflow are displaced airflow and a hybrid room with laminar airflow. These values are taken from a parallel study done by Bonomi (2016).

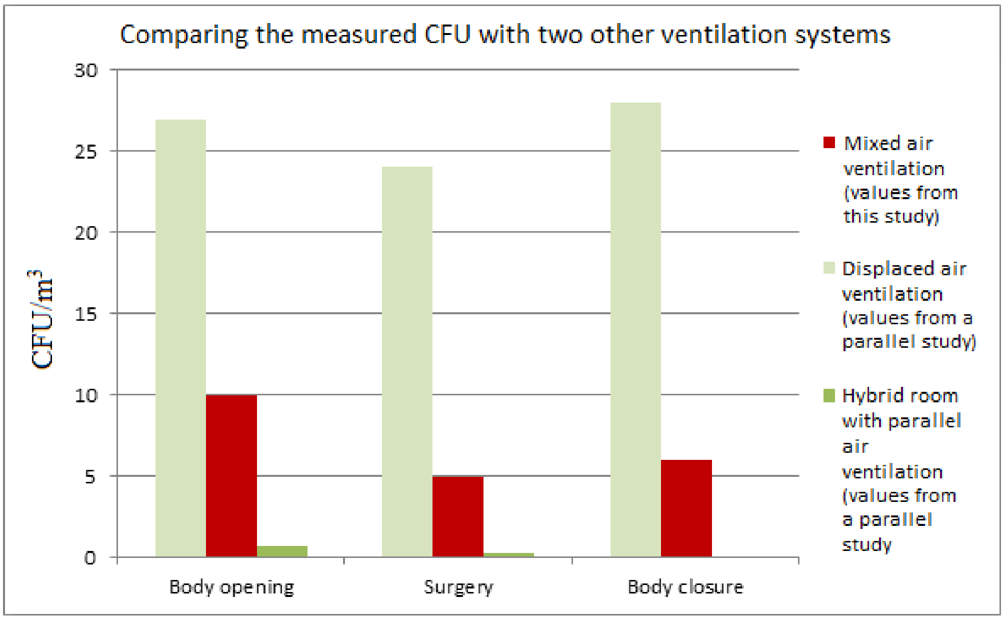

Figure 5.2: *The figure shows a comparison between the measured CFU concentrations during different phases of the surgery with the CFU concentrations measured during two other airflow principles by Bonomi (2016). The two other airflow principles are displaced airflow and a hybrid room with laminar airflow.*

The following airflow for the three different airflow principles: To relate the results be able to interpret this comparison the supply airflow for the different ventilation principles are needed:

Hybrid airflow	1700 l/s
Displaced airflow	560 l/s
Mixed airflow	541 l/s

The figure shows a quite big difference between the different air ventilations. The hybrid room which uses a very high amount of air, about three times more than the conventional rooms, result in CFU-values close to 0. Those values are really good. The two other conventional operating theaters use similar amounts of airflow but the figure shows quite different results of CFUs for these two. The operating theater with displaced airflow shows very high values of CFU, way higher than the limit for an advanced surgery (10 CFU/s).

The operating theater utilized in this study used a special kind of supply device, namely an extended supply device along the top of the wall. Compared to "normal" mixed ventilated rooms that usually use one single supply device, this extended supply air might create a more parallel-like airstream in the room, which enables the CFU values to be lower. Displaced airflows are also sensitive to obstacles, which are almost unavoidable since a lot of equipment is needed during a surgery.

5.2 Particles

As seen in the results regarding the particle-figures 4.3 to 4.5 a common trend between the three gauges can be observed. Although the trend is equal, the AeroTrak (gauge 3) shows a much smaller amount of particles compared to the P-trak counters (gauges 1 and 2).

Upon a closer look into the different particle ranges of gauge 3 (0.3-0.5, 0.5-1, 1-3, 3-5, 5-10 & >10 μm), a much bigger amount of the smaller particles are shown. In fact:

- about 98 % of all particles are in the range between 0.3 and 3 μm.
- about 91 % of all particles are in the range between 0.3 and 1 μm.
- about 80 % of all particles are in the range between 0.3 and 0.5 μm.

This means that the smaller particle sizes exist in much larger amounts in the air than the bigger particles. As mentioned before, the P-Trak measures particles in the sizes 0.02 - 1 μm. Obviously, the difference between 0.02 and 0.3 μm is quite big which explains the large difference in the amount of particles detected in between the different types of gauges (due to the smaller more common particles, detected by the P-Trak).

The measured mean amounts of particles for sizes between 0.02 and 1 μm during the different phases of the surgery is shown in table 5.3. The table shows that the highest mean amount of particles occur during the main surgery, which was quite predictable. The body opening showed a slightly higher amounts of particles than the body closure phase, probably because of the electrosurgical equipment used during the body opening. The phase of patient preparation, is in this purpose, restricted to the time from when the patient arrives to the room until the surgery is started. The mean amount of particles for this period showed a level of 150 particles, which is quite high since no real surgical procedure had started.

Table 5.3: *Table showing the mean amount of particles in the particle range 0.02 - 1 μm in different phases of the studied surgery.*

Phase of surgery	Mean amount of particles
Patient Preparation	150
Body Opening	432
Surgery	756
Body closure	339

These mean amounts of particles for a mixed air ventilation principle in this study is in figure 5.3 compared with two other ventilation principles, displaced air- and parallel air ventilation principles. These values are taken from a study made by Bonomi (2016) that used the same particle counting instrument, a TSI P-Trak, which means that all particles are in the same size range, 0.02 - 1 μm.

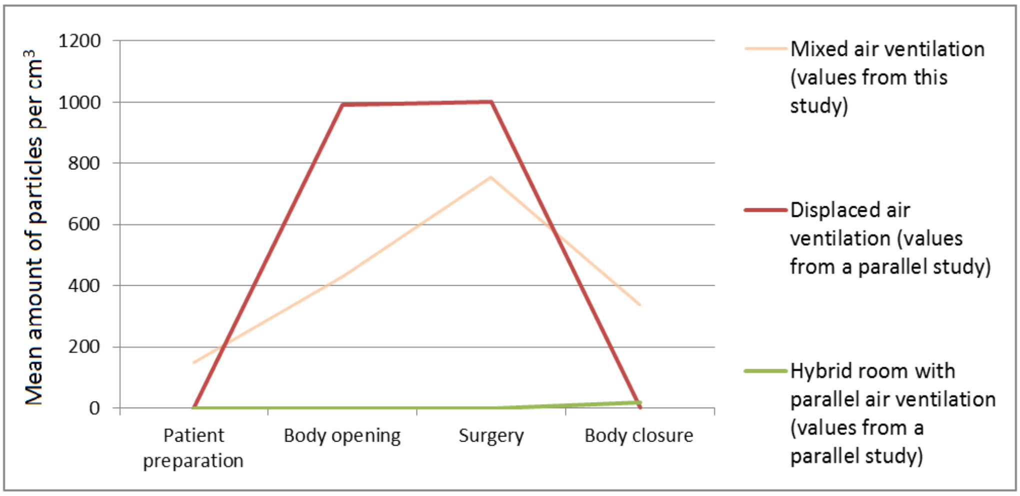

Figure 5.3: *The graph shows the measured mean amount of particles during the surgery with a mixed airflow principle together with two other air flow principles measured by Bonomi (2016). These two airflow principles are the displaced airflow principle and a hybrid room with a laminar airflow principle. Bonomi used the same measurement equipment as used in this thesis, which means that all particles are in the same size range.*

As for the compared CFU-data, the hybrid room is totally dominant when it comes to preserving a good air quality. When looking at the difference between this work and Bonomi's measurements from an OR utilizing a displaced air ventilation one can note that this study had a higher average amount of particles in the air during patient preparation and body closure, which is very interesting. This difference indicates differences in operational routines for different kinds of surgeries.

5.2.1 Effect of Door Openings

One source of contamination in an OR can be particles slipping into the operating theater from the air outside the theater with door openings. To see if the many door openings affect the particle concentrations in the operating theater during the surgery, the number of people in the room is plotted on a graph showing the detected amount of particles from gauges 1 and 2 in figure 5.4. In this graph, a door opening corresponds to a change in the number of people in the room.

Fortunately, figure 5.4 can be used to analyze a lot more than the door openings. For example, the figure shows the number of people and the activity of the people (a lot of door openings, a lot of activity) during the different phases of the surgery, and this data can be looked at together with the plotted CFU values or the concentrations from gauges 1 and 2 to acquire new insights. A lot of activity was observed, actually 144 door openings from when the patient arrived until the end of the surgery were noted.

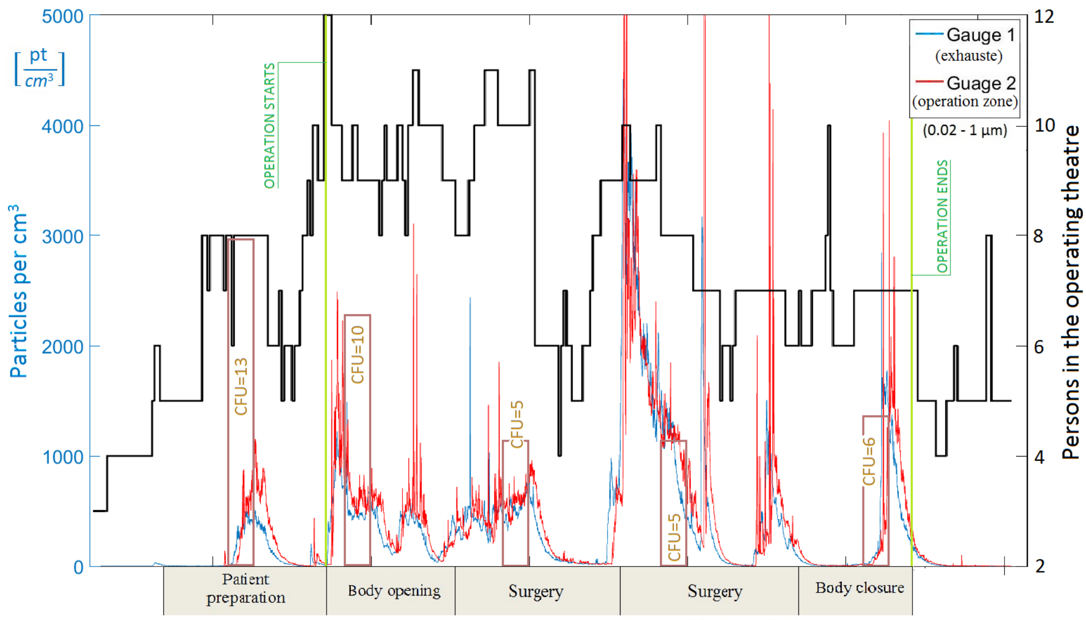

Figure 5.4: *In this figure the number of people in the room is plotted as well as the amount of particles detected by gauges 1 and 2 to study in part the effect of the door openings and in part the effect that the number of people in the operating room have on the amount of particles in the air.*

Another way to see the correlation between particle concentrations and the door openings is to note the amount of particles during the minute where at least one door opening occurs. Figure 5.5 considers the mean amount of particles during that minute, and figure 5.6 instead consider the maximum value of particles during the concerned minute. For example in figure 5.5, the top dot to the far right, which is red, shows that gauge 2 observed a mean amount of about 700 particles during a minute where five door openings occured during that specific minute.

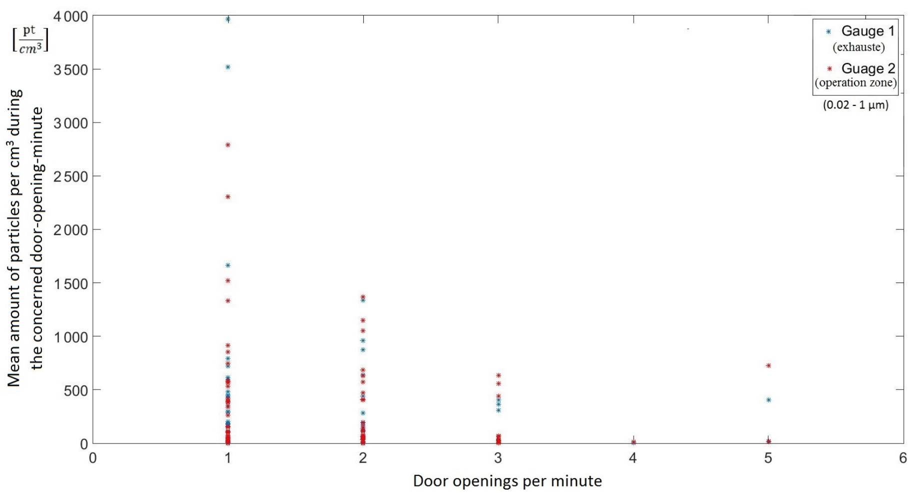

Figure 5.5: *The figure shows the mean amount of particles detected by gauges 1 and 2 during a time period of one minute, during this minute at least 1 door opening occurs. The x-axis shows the amount of door openings during the minute*

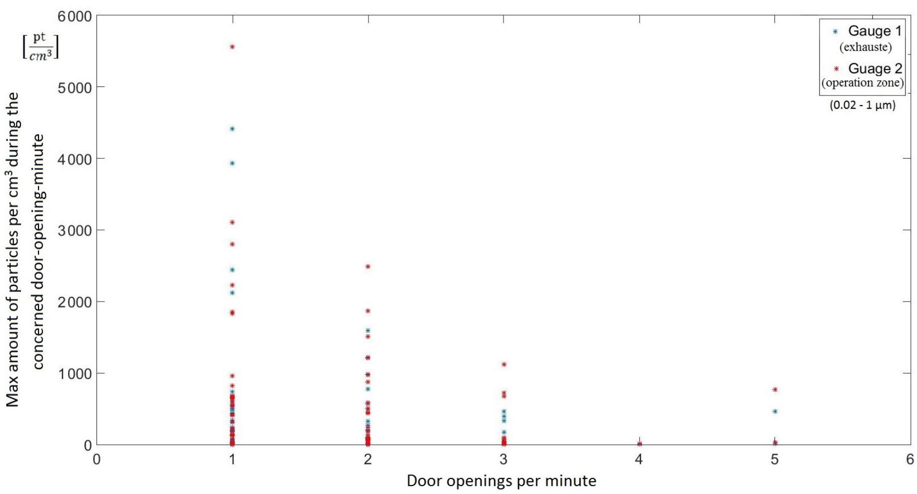

Figure 5.6: *The figure shows the max value of particles detected by gauges 1 and 2 during a minute, for the minute where at least 1 door opening occurs. The x-axis shows the amount of door openings during the minute*

Figures 5.5 and 5.6 both show the same story; that no correlation between the amount of door openings and the particle concentration can be observed. If a correlation between the amount of particles and the amount of door openings existed, the dots would create a fairly linear y=x curve. These figures instead show almost opposite results, which clarifies that the door openings, probably, had no impact on the amount of particles during this surgery.

5.3 Effect of Air Cleaner

The figures in section 4.3 show the amount of particles when the the air cleaner was on and off. When looking into the air cleaner´s influence on the amount of particles, a positive effect from the air cleaner is hard to verify, An effect is hard to detect for the amount of particles detected by gauges 1 and 2. Perhaps the figure showing the amount of bigger particles from gauge 3, figure 4.13, indicates a greater effect from the air cleaner, especially during the first "on"-period of the air cleaner. This, apparently, needs further studies since no real conclusions can be drawn.

The air cleaner had an airflow of 1 100 m^3/h. This, together with the operating theater´s supply airflow of 1 948 m^3/h, theoretically one should expect that 56 % of the air in the room passes through the air cleaner, i.e., the air cleaner corresponds to about 56 % of the room´s air change. This assumes a total mix of the air so that all air is available for the air cleaner at all times. Since this seems not to be the case, according to the non-effecting air cleaner-results, the placement of the aggregate becomes a factor of vital importance (to maximize the amount of air processed through the air cleaner).

A possibly better placement for the air cleaner is towards the center of the "entrance area" which would make the air cleaner more "available" for the surrounding air. This should improve the airflow in a cleaning point of view. Though, this requires a clear pathway for the air in order to pass the air through the machines.

6

Discussion

This thesis, based on advanced surgery, elucidates a number of interesting aspects that are worth taking an extra look at.

Firstly, the air cleaner situated in the operating theater had an air exchange amount off about 56 %, which means that a cleaning effect should be shown in the results. The explanation for a lack of such is probably due to the placement of the air cleaner, shown in figure 3.1. The air cleaner was actually placed in a corner, but still in a preferable distance from the supply devices and exhaust devices. However, since the operating theater included a lot of things, e.g., tables, chairs, computer, machines, and other equipment, the placement options were few, and the place that was chosen was probably the best of the alternatives. The obstacles probably also disturbed the regular air path, thus, hindering the effectiveness of the air cleaner.

To get a better cleaning effect, the air cleaner should be standing at a place more "available" to the surrounding air which partly means unblocked air paths. The optimal placement for the air cleaner would therefore probably be on the entrance-short side, opposite to the supplied air. This corresponds to a placement as far away from the supply device as possible and closer to the exhaust devices. In this way the supply air transports the air contamination from the surgical zone to the air cleaner, right before vortices are created that direct the contaminated air back to the surgery zone, which is not desirable. Of course, to for sure know where the best air cleaner placement would be a more extensive analysis on the air movements in the room would need to be conducted.

The door openings do not seem to affect the environment during the surgery, since no correlation was found between the length of time of a door opening and the concentration of the particles in figures 5.5 and 5.6.

The explanation for this is probably the adjacent pre-treatment room that worked as an airlock, thus, minimizing the amount of "dirty" corridor air that reached the OR itself. A lot of door openings occurred during the surgery and especially right before the surgery during patient preparation, actually 144!, (figures 5.4, 5.5 and 5.6). Therefore the staff in the operating theater should be blessed that they had this pre-treatment room. One can only imagine the rise in CFU and in the amount of particles from 144 door openings if the pre-treatment room hadn't been present.

Even though the door openings seem to be negligible in this study, other studies have shown the relevance of minimizing the amount of door openings during open body surgeries. It is therefore of great concern that the surgery in this study had so many door openings, especially during the body opening! Should this be allowed?

Unfortunately, most ORs today are built without this pre-treatment room. Not because of costs or space saving or other building reasons, but due to other esthetic reasons. The author hopes that future ORs will be built with specific airlocks or with adjacent pre-treatment rooms to minimize the danger of bacteria leaking in from the outside.

Not only do the movements of the staff through doors affect the particle concentrations, but also the effectiveness of the clothes they wear affect the concentration. In figure 5.1, the estimated CFU-values are compared to the measured values, and a huge discrepancy between these two series of values shows that something is different between estimation and practice.

On the one hand, these differences can be caused by a way too pessimistic view of the CFUs emitted through the surgical clothes from the particles cited in this thesis. For example, surgeons often use special surgical cloaks over their regular surgical suit that further blocks CFUs from escaping into the air, and surgery routines have maybe become more precise and effective.

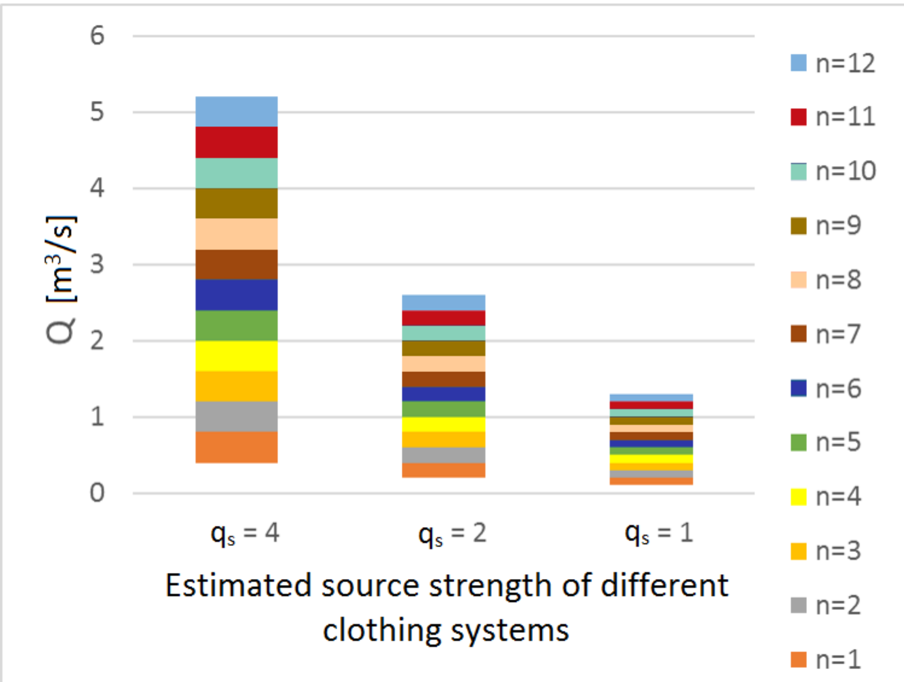

Figure 6.1: *The figure shows the estimated required airflow in relation to the number of people in the operating theater for different estimated clothing source strength in order to fulfill the requirement for high-risk surgery of 10 CFU/m^3.*

On the other hand, these differences could be caused by using the dilution principle in a situation where total mixing of the air is not present, i.e., using the dilution equation made for ideal condition in non-ideal conditions. Since this is not too hard to imagine, the equation should maybe be taken with a grain of salt, that is, not be viewed as law in all ventilation principles but rather as an estimate for dimensioning new ORs.

A further perspective that supports this trail of thought is the data in figure 6.1, where the estimated values are further investigated to see the needed airflow for meeting todays standard of CFU concentration, 10 CFU/m^3 for high-risk surgeries. When comparing these needed airflows, e.g., for 8 persons, which was the mean amount during the surgery, it shows that the airflows required are far larger than that of the studied operating theater, even if we change the clothing systems source strength to 2 or even 1 CFU/s. Recall that the CFU-measurements were under the limit when the patient was under the knife and that the staff was wearing a clothing system that theoretically was estimated to a source strength of 4 CFU/s.

If the surgery is viewed as a whole, it becomes quite apparent that the routines during the preparation are far from optimal, since:

- The greatest CFU value during the whole measurement occurs during the patient preparation time
- Most amount of door openings
- Most amount of people in the operation room (at the end of the preparations)
- A significant peak in particle concentration without any diathermy being used.

This tendency is shocking but maybe not surprising. During the preparation, the staff is often more relaxed than during the surgery itself since the body is not open, which makes them more likely to move around more carelessly and release particles and CFUs into the air. This is, of course, a huge problem since particles and CFUs can linger in the room even when the patient is open and exposed.

7 Conclusion

Firstly, The air cleaner seems to have a small effect on the bigger particles, but it is still hard to clarify an statistically significant effect. This is mainly because of the placement of the air cleaner which is far from optimal. A more optimal placement would be more at the center of the back wall.

The main conclusion in this thesis is the importance of the considerations taken during the phase just before the body is opened. It is important to consider the preparation time to be at least as important as the rest of the surgery. Having a lot of door openings right before the incision is understandable, but in that case the staff should take a couple of minutes to regain calmness before the storm since particles can stay in the air for some time before the safety ventilation gets rid of them.

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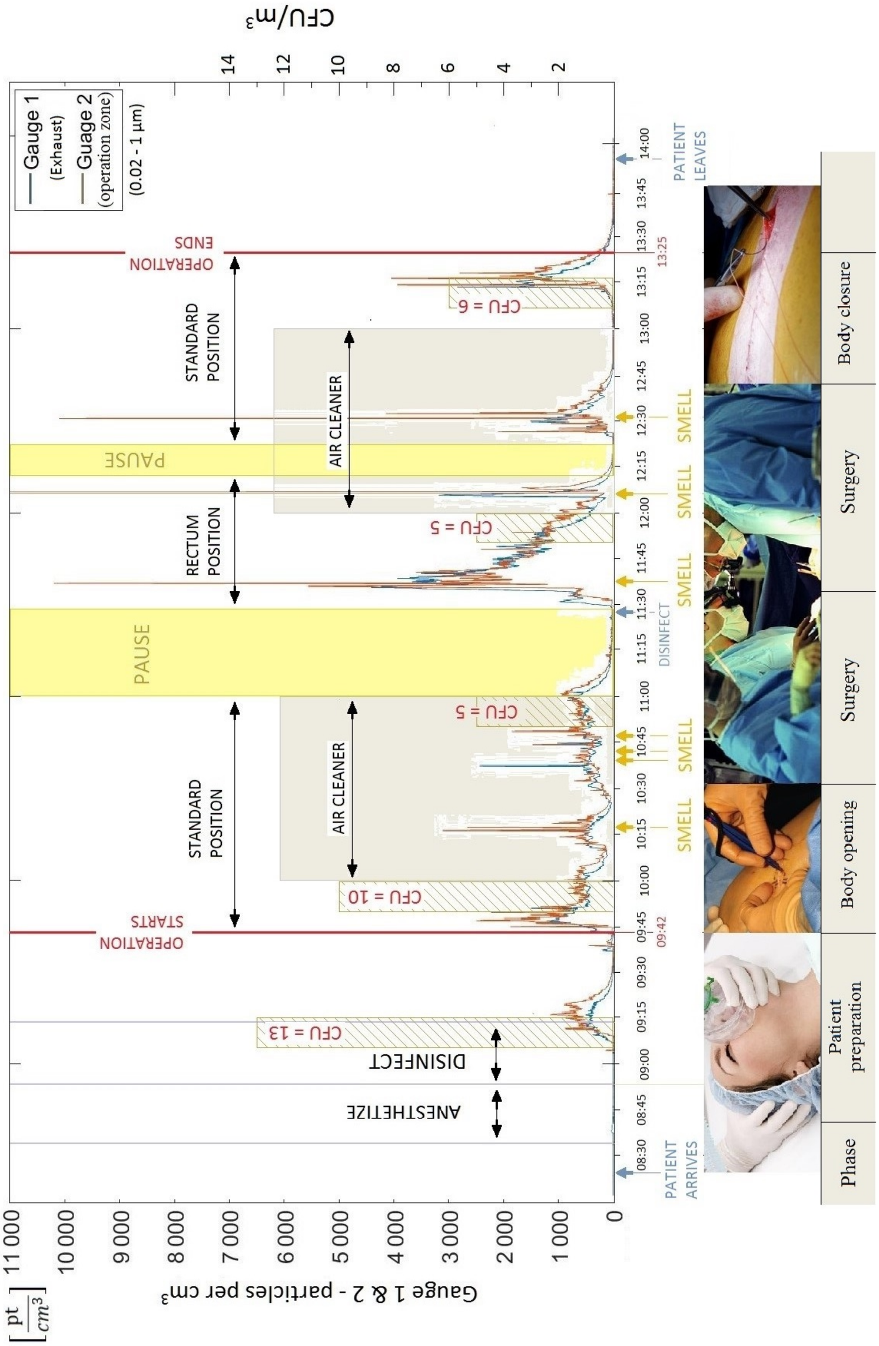
A

Appendix 1


CFU/m³
Gauge 1 & 2 - particles per cm³
Gauge 1 (Exhaust)
Guage 2 (operation zone)
(0.02 - 1 µm)
ANESTHETIZE
DISINFECT
CFU = 13
OPERATION STARTS
09:42
CFU = 10
STANDARD POSITION
AIR CLEANER
CFU = 5
PAUSE
DISINFECT
RECTUM POSITION
CFU = 5
PAUSE
AIR CLEANER
STANDARD POSITION
CFU = 6
OPERATION ENDS
13:25
SMELL
SMELL
SMELL
SMELL
SMELL
PATIENT ARRIVES
PATIENT LEAVES
Phase
Patient preparation
Body opening
Surgery
Surgery
Body closure