CHALMERS
UNIVERSITY OF TECHNOLOGY

Electrosurgery and Surgical Smoke in Operating Theatres

Conditions for Removal of Surgical Smoke through Local Exhaust Ventilation Focusing on Argon Beam Electrosurgery

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

JAKOB LUNDGREN
PER PETERSSON

Department of Civil and Environmental Engineering
Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Master's Thesis 2015:08

Master of Science Thesis in cooperation between Chalmers University of Technology and Sahlgrenska University Hospital

This thesis is a part of a work environmental project at Sahlgrenska Univeristy Hospital, Göteborg. Project leaders for this work environmental project are Christina Ekroth and Steven Muskantor, stationed at OP1/OP2. Ekroth and Muskantor have contributed significantly in making this thesis possible to perform.

MASTER'S THESIS 2015:08

Electrosurgery and Surgical Smoke in Operating Theatres

Conditions for Removal of Surgical Smoke through Local Exhaust Ventilation Focusing on Argon Beam Electrosurgery

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

JAKOB LUNDGREN

PER PETERSSON

Department of Civil and Environmental Engineering

Division of Building Services Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2015

Electrosurgery and Surgical Smoke in Operating Theatres
Conditions for Removal of Surgical Smoke through Local Exhaust Ventilation
Focusing on Argon Beam Electrosurgery

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

JAKOB LUNDGREN

PER PETERSSON

Examensarbete 2015:08/ Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2015

Department of Civil and Environmental Engineering

Division of Building Services Engineering

Chalmers University of Technology

SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
The use of argon beam electrosurgery on calf liver during test in hybrid operating theatre at Sahlgrenska University Hospital.

Name of printer or Department of Civil and Environmetal Engineering. Göteborg, Sweden, 2015

Electrosurgery and Surgical Smoke in Operating Theatres

Conditions for Removal of Surgical Smoke through Local Exhaust Ventilation Focusing on Argon Beam Electrosurgery

Master's thesis in the Master's Programme Structural Engineering and Building Technology

JAKOB LUNDGREN
PER PETERSSON
Department of Civil and Environmental Engineering
Division of Building Services Engineering
Chalmers University of Technology

ABSTRACT

When electrosurgery is used to cut and coagulate tissue, surgical smoke is generated and the particle content increases in the room. The purpose of this study is to describe the conditions for the development of a local extractor adapted to the activity and to develop a prototype.

The activity during surgery is the most limiting factor and must be carefully considered. Operations have been observed through visits at Sahlgrenska University Hospital and several tests have been performed. These include smoke tests, measuring of capture velocities and sound level tests in the test hall at Chalmers together with particle measurements in the hybrid operating theatre at Sahlgrenska. The tests were carried out with the prototype and a new product called minisquair.

The results show that both the prototype and the minisquair lowers the particle content in the room but that the capture ability is highly dependent of several factors, the main ones being flow and distance. Other measurements are needed to determine if an extractor is a possible solution to the problem. However it is still clear that if so, significantly larger capture ability is required in order to ensure a good working environment. Higher flows are therefore something that should be tested before an absolute answer can be given.

A higher flow in the extractor does however create other issues that any further studies should take into account. How are the pressure conditions in the room affected and how is the air flow pattern changing?

Key words: Argon beam electrosurgery, Surgical smoke, Capture ability, Hybrid operating theatre, Local extractor

Diatermi och operationsrök i operationssalar
Förutsättningar för bortföring av operationsrök genom punktutsug med fokus på argondiatermi

Examensarbete inom masterprogrammet Structural Engineering and Building Technology

JAKOB LUNDGREN
PER PETERSSON
Institutionen för Bygg- och miljöteknik
Avdelningen för Installationsteknik
Chalmers tekniska högskola

SAMMANFATTNING

När diatermi används för att skära och koagulera vävnad sker rökutveckling och en ökning av partikelhalten i rummet. Syftet med detta examensarbete är därför att beskriva förutsättningarna för utveckling av ett verksamhetsanpassat punktutsug samt att ta fram en prototyp.

Aktiviteten i salen är den mest begränsande faktorn och måste tas i noga beaktande. Operationer har studerats via platsbesök på Sahlgrenska Universitetssjukhuset och flertalet tester har utförts. Dessa inbegriper röksimuleringar, mätning av uppfångningshastigheter och ljudnivåer i försökshallen på Chalmers samt partikelmätningar i hybridoperationssal på Sahlgrenska. Testerna genomfördes med prototypen och en ny produkt kallad minisquair.

Resultaten visar att användningen av minisquairen och prototypen båda sänker partikelhalten i salen men att uppfångningsförmågan är starkt beroende av flertalet faktorer, varav de främsta är flöde och avstånd. Fler mätningar behövs för att kunna avgöra om ett punktutsug är en möjlig lösning på problemet. Det är dock tydligt att det i så fall krävs en betydligt större uppfångningsförmåga för att kunna säkerställa en god arbetsmiljö. Högre flöden är därför något som bör testas innan ett klart besked kan ges.

Ett högre flöde i punktutsuget skapar dock andra frågeställningar som i eventuella fortsättningsstudier bör beaktas. Hur påverkas tryckförhållandena i salen och hur förändras strömningsbilden?

Nyckelord: Argondiatermi, Operationsrök, Uppfångningsförmåga, Hybridsal, Punktutsug

Contents

Preface

This study, covering 30 credits, is a part of the master program Structural Engineering and Building Technology at Chalmers University of Technology. It is performed at the department of Civil and Environmental Engineering, at the division of Building Services Engineering.

The study is carried out from January to May 2015 and covers a general background about local exhaust ventilation and electrosurgery, together with tests performed both in laboratory and at Sahlgrenska University Hospital. It is a continuation on previous studies made regarding electrosurgery and surgical smoke in operating theatres.

During observations and measurments at Sahlgrenska we have come across a lot of interested people that have been very supportive and helpful, without them this study would not have been possible. Special thanks to Christina Ekroth, surgical nurse/technical manager, and Steven Muskantor, nurse anaesthetist, for the extra guidance along the way. Because of the technical support received we would also like to thank Anders Löfström and Peter Thyberg, working at Medical Technology at Sahlgrenska.

We would also like to thank Bengt Dahlgren AB for having us during this study and Christoffer Isaksson who has been our mental support. Also thanks to Håkan Larsson for helping us rebuild the test hall at Chalmers where several tests were performed.

Finally we would like to thank our supervisor Jan Gustén, professor at Chalmers, for taking time to advice and guide us during the entire study.

Jakob Lundgren and Per Petersson
Göteborg, June 2015

1 Introduction

1.1 Background

Electrosurgery is a method to cut, coagulate or destroy body tissue. This is achieved by an electrical current that is lead through the body tissue and thus producing heat. One complication with the method however is that it generates surgical smoke. Surgical smoke brings about an acrid smell and increases the particle concentration in the room air. The issue has also been raised in several reports concerning the hazardous effect of the smoke on staff and patients, though the health implications are yet uncertain (Blom 2008; Lundblad & Nilsson 2013; Meda 2014).

Operating masks and local exhaust ventilation are two methods that try to prevent the effects of the smoke and were also suggested as possible solutions in the previously referenced reports. Operating masks does however only concern the staff's health and even then it has a bad filtering capacity for the most crucial particle dimensions.

Local exhaust ventilation is a better alternative that tries to handle the problem at its source by removing the smoke before it is spread out in the room. The exhaust device has been integrated with the electrosurgical instrument, placing the exhaust nozzle just millimetres apart from the source of the smoke. This has resulted in very good capture efficiency and is today frequently used at the Sahlgrenska University Hospital and many other hospitals.

This type of exhaust device does however not work for all types of electrosurgical instruments. Argon beam electrosurgery uses argon gas that is shot out from the instrument to surround the electric arc. This method entails certain benefits and is commonly used during surgery, especially during liver resection surgery. If the exhaust nozzle were to be placed too close to the source of the argon gas, it would suck up the gas before it could spread out and fulfil its purpose.

The apparent predicament is thus to develop a local exhaust device that effectively removes the surgical smoke close to the source without also sucking up the argon gas from the argon beam electrosurgical instrument.

1.2 Purpose

The purpose of this thesis is to:

- investigate the prerequisites for development of a local extractor to remove the surgical smoke mainly from the argon beam electrosurgery
- develop a prototype based on the acquired results
- evaluate the prototype and the minisquair

1.3 Scope

The analysis will be based on experiments and measurements and not with numerical methods such as Computational Fluid Dynamics (CFD).

Since this report is focusing on argon beam electrosurgery, which is most frequently used during liver resection surgery, the types of surgery considered is limited to the abdomen (between thorax and pelvis).

Particle measurements are conducted and used as indicator; however suitable level of limiting value is not investigated.

1.4 Problem

Capturing the particle contaminants when argon beam electrosurgery is used is not problematic if no other factors were taken into account. The difficulties lie in the following aspects that have to be considered due to the working environment of the staff and the health of the personnel and the patient:

- Distance
- Size
- Sound
- Hygiene

The design must not cause any hygiene problems. Also the size should not interfere with the on-going surgery, meaning it cannot be too big. However if it has a small opening the velocity needs to be increased which may cause sound problems. Regarding the distance, the local exhaust cannot be placed too far away from the source in order to capture the contaminants, but placing too close will ventilate off the argon.

1.5 Method

A literature study was done as a first step towards understanding the problems that can occur while using argon beam electrosurgery. The study also included reviewing of existing standards and assessment criterion for measuring of capture efficiency. A recently developed extractor named minisquair was found during this study and one copy was acquired for testing.

Contact with Sahlgrenska University Hospital was initiated early for acquiring of information and to plan testing in operating theatre at later stage. Information from the hospital was gathered by interviews and study visits during on-going operations.

Ideas began emerging of which one was chosen to be further developed in contact with the hospital. One prototype was made to allow for testing.

A replica of an operating theatre was set up in a lab environment for testing. Several tests and measurements were performed, mostly there but later also in a hybrid operating theatre at the hospital. The results from these tests of the two local extractors were analysed to determine how well they lived up to the criterion.

1.6 Report structure

After the introduction and to highlight the problems with electrosurgery, a short presentation is given of previous works made on airborne particles generated by electrosurgical procedures in operating theatres. Basic theory of local exhaust ventilation follows, that is based on the literature study. Different measuring methods are described to widen the perspective of local exhaust ventilation, together with a unit existing on the market.

Chapter 4, based on the literature study and the observations, describe the hybrid operating theatre. First the layout of the hybrid operating theatre and the ventilation principles commonly used in operating theatres are presented. The medical instruments and the principles thereof are described together with the retractors-regarding the technique behind the electrosurgery equipment together with the use of retractors will be described. Also the activity during the on-going surgery is described to point out the problems and aspects that need to be considered.

Chapter 5 introduces the prototype and highlights the considered aspects when developing the prototype. The second part of the chapter gives a more detailed description of the developed prototype, and the steps in designing.

Chapter 6 covers the prerequisites for the tests in the test hall at Chalmers and describes the tests. Chapter 7 presents the results of the tests and includes shorter analyses. The process and the results are discussed and conclusions are stated in Chapter 8.

2 Earlier Studies

This master's thesis is a continuation of previous works made on the airborne particles that follow from electrosurgical procedures in operating theatres. *Modern surgery environment and ventilation* (2008), Blom, is a study made to see the correlation between argon beam electrosurgery and contamination spread out in the room and how it affects the personnel working in the room. The study is based on six real operations made with the use of argon beam electrosurgery at one of the operating theatres at Sahlgrenska University Hospital. Particle measurements were performed during these operations.

The conclusion from Blom was that measurement showed an obvious connection between the increase of the particle content and the activation of the argon beam electrosurgery. The study also showed a decrease in particle concentration with increasing distance from the source, however the acrid smell was experienced in the whole room and also in the adjoining corridors.

Diathermy and airborne particles in operating rooms (2013), Lundblad and Nilsson, is another measurement study but with the main focus to show the magnitude of the particle spread in the room based on equipment and activity. The study is based on the results from three particle counters placed in operating theatres during operations at Sahlgrenska University Hospital.

From this study the result shows that the particle concentration between the entrance zone and the surgical zone differs much when the argon beam electrosurgery is used but also that it get mixed quickly when the argon diathermy is turned off. So with the argon beam electrosurgery tops excluded the two measuring points show a similar pattern in particle concentration. *Air Contamination Control in Hybrid Operating Theatres* (2014), Meda, is another measurement study that focuses on the particle content caused by different surgery methods.

Based on these previous studies, there is a true indication that the use of electrosurgical instruments increases the particle content and affects the work environment. The previous works have focused on highlighting the problem with increased particle content in the operating theatres and therefore this study aims to look at a way to take care of the contamination caused by argon beam electrosurgery.

3 Local Exhaust Ventilation

There are two options when it comes to removing a contaminant from a room. The first option is to let the contaminant spread from the source into the room air and dilute through general ventilation. This results in a low concentration of the contaminant in the room air. The contaminant will thus expose the personnel, often with a high level if the person is close to the source.

The second option is to install local exhaust ventilation that removes the contaminant close to its source. This will prohibit the contaminant from spreading into the room, protecting the personnel from high exposure. The ventilation will also be much more effective in removing the contaminant, since the concentration is much higher close to the source. This reduction of the total ventilation air flow entails a decreased energy demand. There is however still a need of general ventilation for other reasons, e.g. removal of the contaminants that are not taken care of by the local exhaust.

3.1 Theory

Local exhausts can be classified into three categories, depending on the placement of the hood. The hood can be placed around the contaminant source and completely shielding it, partially surrounding it, or the contaminant source could be placed outside the hood (exterior hood). The latter is the least effective but still commonly used since the other options prohibit access to the working place. Since access is vital for surgical activity, exterior hoods are exclusively considered in this study.

The problem with local exhausts and particularly exterior hoods is that they have poor range, in other words the velocity rapidly decreases with the distance from the opening. The air velocity v caused by a point exhaust opening in stagnant air can be described as

$$v(x) = \frac{1}{4\pi} \cdot \frac{q}{x^2} \tag{1}$$

where q is the airflow through the opening and x the distance from the opening. The velocity is in other words inversely proportional to the square of the distance from the opening and proportional to the airflow. Because the exhaust hood is modelled as a point, the equation gives a velocity tending towards infinity close to the opening. To account for this, the opening area A is added to the denominator. Hence, the velocity in the opening becomes the opening mean velocity q/a:

$$v(x) = \frac{q}{A + 4\pi \cdot x^2} \tag{2}$$

The rapid decrease of velocity with the distance of the opening means that the exhaust opening must be placed close to the source of the contamination. One way to extend the range of the exhaust is to add flanges to the opening, see Figure 1. Their function is to reduce suction of air from behind the opening and should therefore be as large as possible.

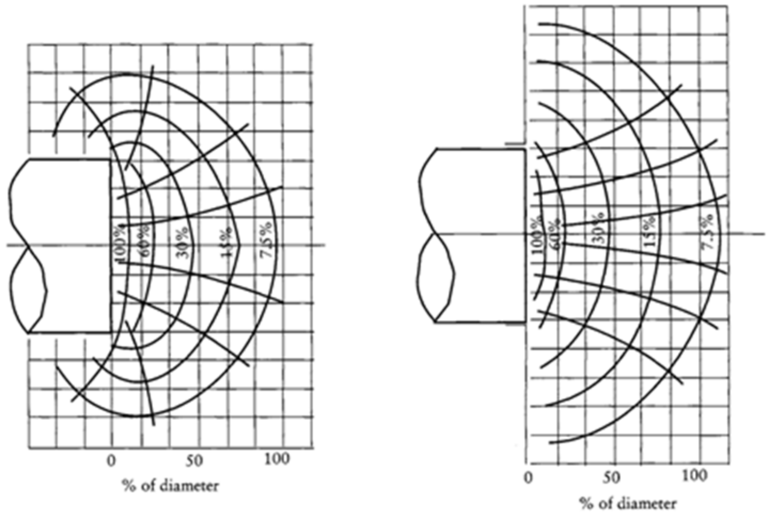

Figure 1 The effect of flanges on the capture velocity (Dalla Valle 1952).

The contaminant is often produced with a certain velocity. If possible, this given direction of the contaminant should be used and not counteracted. For example, smoke is normally generated with an upward direction why the hood's most suitable position in this aspect would be above the generation point.

3.2 Measuring methods

There are several methods of measuring the performance of an exhaust hood, varying in cost, accuracy and prerequisites (Olander 2001). The evaluation could either be done using the actual contaminant or using a tracer gas as substitute. Preferable is to use the contaminant, but if a tracer gas is used it should be as similar to the contaminant as possible, i.e. properties like density should be as similar as possible. This is to reduce the deviation in measurements.

Initially it is advisable to perform a smoke test to determine the general airflow pattern. More detailed measurements can follow, but it is difficult and very impractical to determine the general airflow pattern based on detailed measurement data. This is because the measurements are taken in points in a rather coarse grid and thus allow for uncertainties. The grid must be very fine to get the same level of accuracy of the general airflow pattern as a simple smoke test.

3.2.1 Capture velocity

The capture velocity can be described as the velocity that is generated by the exhaust hood at the point of the source. To get an idea of the capture velocity, measurements need to be made in order to establish the velocity contours of the hood. Since mathematical solutions are difficult to make for the contours, it is based on experiments. To determine the velocities by measurements, they need to be done with sensitive instruments where the total pressure and the static pressure can both be measured. For this the pinot tube is often used and with the difference between total pressure and static pressure the dynamic pressure can be calculated and from that also the velocity (Dalla Valle 1952).

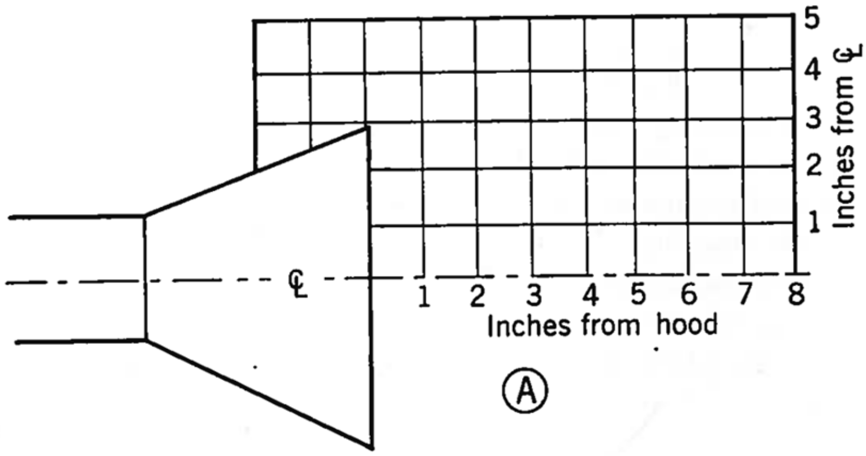

Figure 2 Coordinates at which readings are made (Dalla Valle 1952).

In Figure 2 the coordinates for the velocity contours are shown where the coordinates are based on the number of inches from the hood and the number of inches from the centre line. By measuring the velocity at different positions and distances from the hood a percentage of the average velocity at the opening can be obtained at each position, shown in Figure 3. From this figure the velocity contours can be drawn, shown in Figure 4.

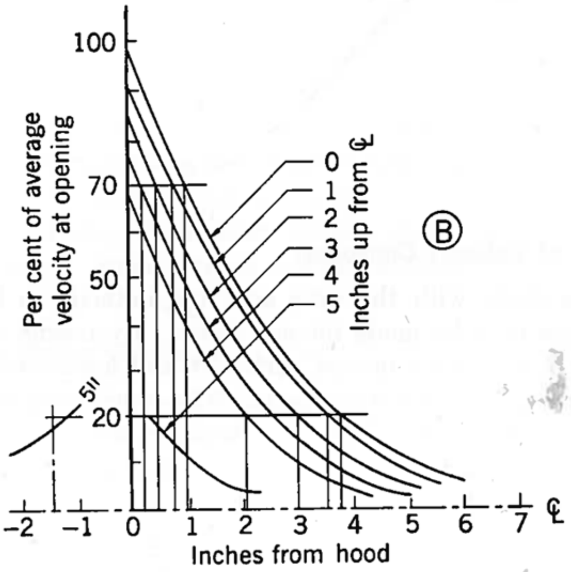

Figure 3 *Readings plotted, representing percentage of velocity at opening based on distance from origin (Dalla Valle 1952).*

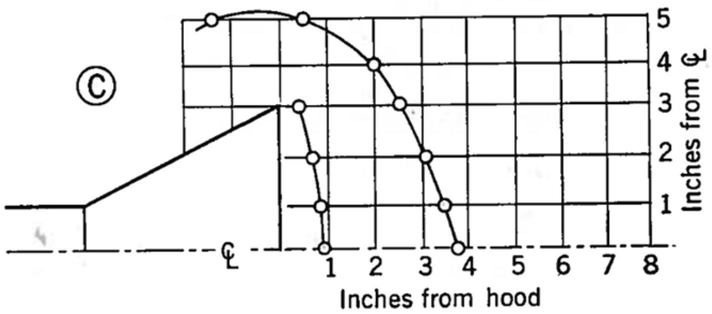

Figure 4 *Velocity contours (Dalla Valle 1952).*

In order to capture the contaminants, the velocity of the exhaust air generated by the extractor should be higher than the velocity of the contaminant and any disturbances and opposing air currents, such as cross-drafts. This disturbances are often caused by equipment or movements by the working staff and are therefore difficult to put a number on. Placing the extractor in a position so that the exhaust air have the same direction as the contaminants will help improve the performance of the exhaust. However this does not equal protection for the staff but could be complemented by capture efficiency and occupational hygiene efficiency, as described in following sections (Dalla Valle 1952).

3.2.2 Capture efficiency

Capture efficiency is defined as the ratio of the flow rate of directly captured contaminants to the total flow rate of released contaminants. Directly captured imply that the contaminants captured after dilution into the ambient air are excluded. Otherwise the capture efficiency would always be close to 100 %, depending on the flow rate of the general ventilation, and the measurement would be useless (Jansson 1982; 1990).

The capture efficiency could in principle be determined as

$$\alpha = \frac{q_\alpha \cdot C_\alpha}{\dot{N}} \tag{3}$$

Where $\dot{N}$ is the emission rate of the contaminant, q_α is the exhaust air flow through the extractor and C_α is the concentration in the same. The emission rate is however difficult to measure, though methods exist. Often a tracer gas is used instead.

The room air is usually not well-mixed and so the contaminant concentration differs spatially. Determining the concentration is therefore not simple but there are two typical approaches. First is to measure the concentration level in the general exhaust with the assumption that it is a good average for the room air. Second is to measure the concentration in a grid of points in the room and calculate their average.

Another method to calculate the capture efficiency is to measure the difference in contaminant concentration in the general exhaust between having the extractor operating and not operating. The contaminant generating source is running at a constant rate and measurements are taken when the concentration has reached steady state. Because the contaminant concentration is measured in the general exhaust, it corresponds to measuring $1 - \alpha$ and so to get the capture efficiency the result must be subtracted from one:

$$\alpha = 1 - \left(\frac{q(C - C_b)}{\dot{N}}\right)_{on} \Big/ \left(\frac{q(C - C_b)}{\dot{N}}\right)_{off} \tag{4}$$

where C_b is the background concentration in the room.

3.2.3 Occupational hygiene efficiency

The occupational hygiene efficiency is used to determine the effect of the hood on the operator's breathing zone. It is defined as

$$\eta_h = (C_{br} - C_b)_{on} / (C_{br} - C_b)_{off} \tag{5}$$

where C_{br} is the concentration in the operator's breathing zone. It is best determined by measuring the actual contaminants concentration, though a tracer gas can be used but with the loss in accuracy as stated earlier.

3.3 Commercial extractors

Local extractors are commonly used in industry and laboratory environments to extract dust and gases. There is therefore a large supply of products on the market. The underlying theory to local extraction is simple and so the product solutions available are quite alike, though some different solution strategies can be picked out.

Figure 5 Left: hose with external support (Fumex a), right: jointed pipes (Fumex b)

The main division is between using either hoses with added support or jointed pipes that support themselves, see Figure 5. The support for the hoses can be external or internal, i.e. outside or inside the hose. There are of course some solutions that does not conform to this division or that are hybrids of the two. One alternative solution is pipes that have hoses as joints, supported by springs. The pipe dimension is normally in the interval of 75 mm up to 200 mm and usually made of plastic or aluminium.

The solution becomes somewhat simpler if the hood can be fixated, removing the need of an extending arm. This is probably the best solution for an extractor of surgical smoke. The minisquair is a newly developed smoke capture device developed for medical use with surgical smoke in mind, see Figure 6. It started distribution in the EU in 2015, but was first released on the American market, where it also was developed during four years (Nascent Surgical 2015a; 2015b).

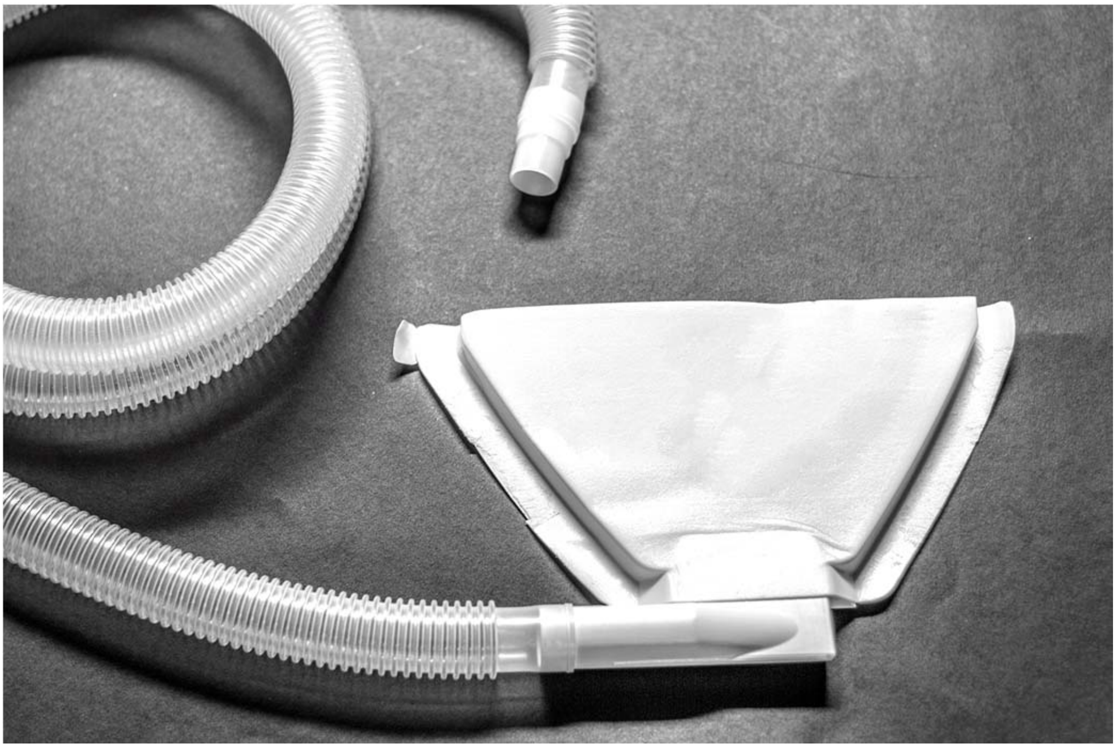

Figure 6 The minisquair.

The device is shaped similar to the nozzle of a vacuum cleaner, though the intake is at the longer end and not at the bottom. The shape is oblong and thin to minimise the obstruction of space above and around the incision and thus allowing the surgeons to move freely. However, the device must be placed close to the incision in order to maximise the capture ability. The back of the device is adhesive so that it can be applied directly to the skin or on the surgical drapes.

The device is made out of soft cell foam which makes it fairly flexible so that it can be placed on parts of the body that are not flat. The nozzle is stuffed with a coarse filter also made of cell foam which provide a pathway for suction and keeps the construction intact. In addition, this allows the minisquair to be cut and reshaped to fit around certain body parts.

The tube has a connection with a radius of 32 mm, which is larger than the standard connection of 22 mm. This is to allow for a higher airflow rate through the nozzle and thus a higher capture efficiency, without increasing the generated noise in the tubing. However the possible airflow rate depends on the pressure drop available in the system of the operating theatre. If there isn't a sufficiently high pressure drop available in the system, the airflow rate cannot be increased, regardless of the tubing.

4 Operating Theatre

The operating theatre is a unique environment; therefore the aim of this chapter is to give an overview of the room. Both the ventilation principles and the hybrid operating theatre are described, but also some medical instruments and the activity during surgery.

4.1 Ventilation principles

At Sahlgrenska University Hospital there are two kinds of ventilation principles in use in the operating theatres. One is displacement ventilation and the other is Laminar Air Flow (LAF) ventilation. They are used in rooms where high demands on air quality are required, in operating theatres to reduce the risk of airborne infections. Both ventilation principles are described, however focus in this study is on the LAF since all tests are done in rooms with this type of ventilation.

4.1.1 Displacement flow

With displacement ventilation the air is supplied at floor level with a lower temperature than the ambient air temperature, see Figure 7. The lower temperature causes the air to spread over the floor and when heated it rises to the exhaust diffusers placed in the ceiling. The inlet air is supplied with a low speed through large areas to the room. This principle of ventilation reduces the mixing of the air, creating a better air quality at lower flows. One problem at Sahlgrenska University Hospital is the need of much equipment in a relatively limited space, affecting the ventilation of the room with placing of objects in front of the supply diffusers.

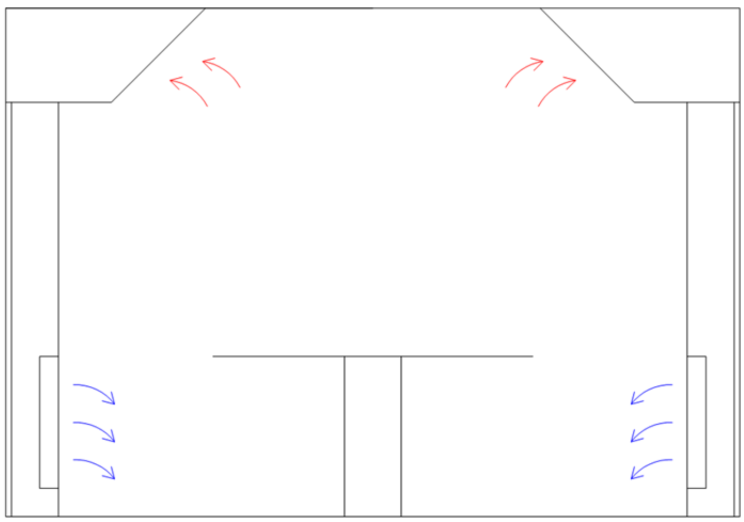

Figure 7 Principle of displacement flow. Blue (bottom) and red (top) arrows represent supply and exhaust air respectively.

4.1.2 Laminar air flow

LAF ventilation is a principle where the air moves parallel in the room either from wall to wall or from ceiling to floor, see Figure 8. In operating theatres the air is supplied from the ceiling and ventilated through the exhaust diffusers placed by the floor. In operating theatres this principle is used with an LAF ceiling where the air is drawn through a high performance filter in order to remove the airborne contamination. Presuming that the air is supplied from the ceiling, one complication can be disturbances from lighting and x-ray machines causing whirls and spread of contamination in the room.

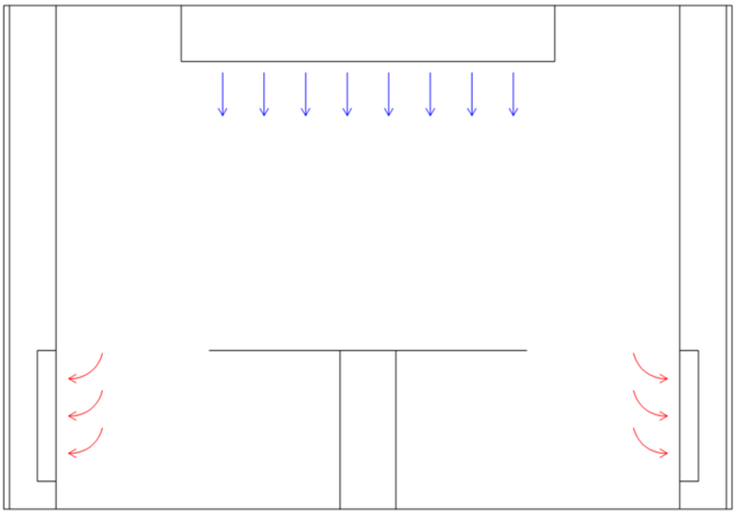

Figure 8 Principle of laminar air flow. Blue (top) and red (bottom) arrows represent supply and exhaust air respectively.

4.2 Hybrid operating theatre

This section aims to give an overview of the hybrid operating theatre at Sahlgrenska University Hospital and by that enhance the understanding of the following sections and chapters.

The hybrid operating theatre is 100 m² and thereby the largest operating theatre at Sahlgrenska. It is equipped for simultaneously performing radiology during surgery, which gives the possibility to perform all kinds of surgery in the same room. Regarding the general ventilation of the room it uses a LAF ceiling with a filter of type ULPA (Ultra Low Particulate Air) to secure a good operating environment.

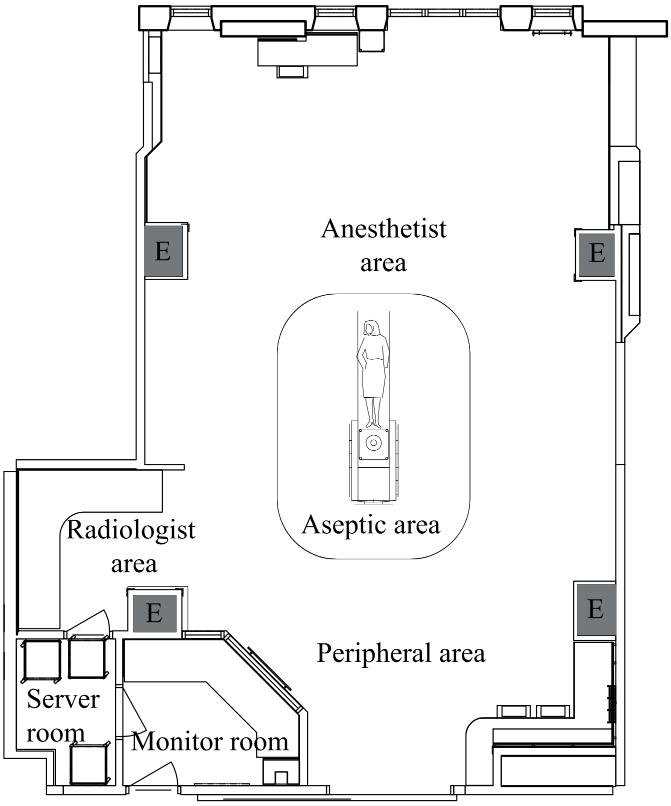

Figure 9 Plan view of hybrid operating theatre with the different areas marked. The areas marked E represents the exhaust devices.

In Figure 9 an overview of the hybrid operating theatre is shown with the different areas. The line surrounding the bed indicates the LAF ceiling that covers the aseptic area, also known as the clean zone. By the head of the patient is the anaesthetist area, where the nurse anaesthetist supervises the patient during surgery. Surrounding these areas is the peripheral area where the assistant nurse can move more freely gathering equipment needed by the surgeons. Apart from all monitors and surgical equipment there are several radiology screens to protect the personnel when the x-ray arm is active. The radiology is supervised from the radiologist area and in the monitor room the entire operation can be supervised and is therefore often used in educational purposes as well.

The exhaust air is extracted through four devices, see Figure 9. The airflow rates in the operating theatre are unknown, though there is a surplus of air supplied to the room. This is to generate an overpressure relative to the ambient environment, preventing infiltration into the room. However the same demand of no infiltration is true for adjacent operating theatres and no pressure difference between them must be aimed at to satisfy the demand for all rooms. This is important to be aware of when planning for a local extractor. The airflow rate of the extractor is minor compared to that of the general ventilation, however when instead compared to the surplus in the supply air, it suddenly becomes significant.

Figure 10 shows an overview of the hybrid operating theatre when it is not in use. As can be seen there is a lot of monitors and medical equipment stationed in the room at all time. When personnel and additional equipment is added the 100 m² becomes crowded and not as spacious as can be seen in the figure.

Figure 10 Overview of the hybrid operating theatre, taken from entrance.

4.3 Medical instruments

The purpose of this section is to describe the medical instruments frequently used and mentioned in this study. Therefore the different electrosurgery equipment used and the purpose of the retractors are presented here.

4.3.1 Electrosurgery

Diathermy, from Classical Greek meaning "through heat", exists in many variations and with different purposes but has the common denominator that it utilizes electrical current to generate heat in the body. Electrosurgery, also known as surgical diathermy, produces high-frequency alternating electrical current to coagulate, cut or destroy body tissue. The function is determined by modulating the waveform of the current (Davison & Zamah 2008).

There are two types of electrosurgery that are frequently used, monopolar and bipolar. Argon beam electrosurgery is a monopolar modification, and is the cause and focus of this study.

A beep is signalled when the electrosurgery is turned on and off. The sound differs between the types of electrosurgery and whether it is switched on or off. The purpose of the sound is to work as an audible feedback for the staff.

4.3.1.1 Monopolar Electrosurgery

The surgeon uses a single small probe as active electrode, which looks like a pen, see Figure 11. This is why this type of electrosurgery is called monopolar. A metal plate is attached to the patient and acts as the return electrode. The current flows from the probe through the body tissue and to the return electrode.

Figure 11 Monopolar instrument (Medtronic a).

A high current density is produced close to the probe, resulting in a heat build-up and tissue destruction (Gallagher et al. 2011). The current rapidly dissipates when entering the body, preventing heat build-up in unwanted places. Heat build-up is also prevented close to the return electrode by having a large surface area of the metal plate.

The monopolar instrument usually has a local exhaust installed, see Figure 12. It is placed very close to the electrode which maximises its capture efficiency. The exhausted smoke is led through the device and removed by a tube. This solution entails a widening of the instrument which therefore becomes a little less flexible.

Figure 12 Monopolar instrument with integrated exhaust (Safeair).

The exhaust is either constantly on or simultaneously activated with the electrosurgery and automatically turned off about one second after. The latter is most commonly used at Sahlgrenska University Hospital.

4.3.1.2 Bipolar Electrosurgery

In bipolar electrosurgery the surgeon uses a forceps where the two tines are connected to the active electrode and the return electrode respectively, for example see Figure 13. Because of the law of least resistance, the electrical current flows through the, of the tines, intervening tissue and not to a potential monopolar return plate (Gallagher et al. 2011). The bipolar electrosurgery affects the intervening tissue evenly and has a minimal effect on surrounding tissue.

Figure 13 Bipolar forceps (Micromed).

There are also other types of bipolar instruments, for example scissors or clamps. However the underlying theory is the same, two tines with current passing through intermediate tissue. There is no commonly used local exhaust ventilation solution available for the bipolar electrosurgery.

4.3.1.3 Argon Beam Electrosurgery

Argon beam electrosurgery is a modification of monopolar electrosurgery. The instrument can be used as a regular monopolar, but the difference is that argon can be ejected at the nose of the handle. Argon is an inert gas and also non-combustible. When it is influenced by an electrical current it becomes ionised, which creates a plasma cloud. “The thermal effect occurs at the time when a spark jumps from the active electrode tip to the tissue” (Emed 2014). It has no contact with the tissue and the distance can vary up to 5 mm, depending on power, resistance and argon flow rate.

Figure 14 Argon beam instrument (Medtronic b).

The advantages of using argon beam electrosurgery is that less power is needed compared to other methods. This minimises the depth of the thermal effect making coagulation of thin walled organs easier, the argon also helps to coagulate larger areas. The blood loss and tissue damage is also decreased compared to conventional electrosurgery, which makes the healing process quicker (Blom 2008). These are some reasons why the argon beam electrosurgery is so frequently used during liver resections.

Other types of electrosurgery can have extractors located on the instruments, which help to remove the contaminants caused by the electrosurgical procedure. However, this does not work for argon beam electrosurgery since a local extractor placed to close will also ventilate off the argon gas.

4.3.2 Retractors

Retractors are usually used during surgery to separate the edges of a surgical incision so that the surgeons can work unimpeded. They exist in many forms and variations depending on the type of operation and size of incision. Some are hand-held and others are self-retaining, which sometimes imply that they are tightened by fixation to a stand. See Figure 15 for some typical variants.

Figure 15 Variations of retractors, from left to right: Volkman (hand-held), Weitlaner (hand-held but self-retaining) and Balfour (self-retaining and fixated to a stand).

The retractor used during liver resection surgery is the Rochard abdominal retractor, Figure 16. The width varies from 90 mm up to 155 mm. It is fixated via a jointed extension to a horizontal traction bar, which is placed above the patient’s head.

Figure 16 Rochard abdominal retractor.

Two retractors were always used during the liver resection operations studied, though they sometimes were of different sizes. The abdominal retractors are put around the ribs and tightened, pulling the ribs and tissue and thereby widening the incision. The tension is directed slightly upwards since the retractors are fixed to the traction bar above the patient, causing the surrounding tissue to also rise somewhat.

After the retractors have been put into place, they are not moved during the operation. Because of the position of the traction bar, they are only put on one side of the incision. When the surgeons need more view or access they use their hands to temporarily hold back tissue. This happens fairly frequently.

4.4 Activity during surgery

The activity during surgery is the most limiting factor for development of a local extractor and thus very important to investigate and take into account. This subchapter is based on observations made during visits to Sahlgrenska University Hospital. Information was also gathered through questioning of the personnel.

Figure 17 Overview of the hybrid operating theatre, taken from radiologist area.

An operating theatre not in use is easily perceived as large and spacious, see Figure 17. However, the complete opposite is true during surgery when the operating theatre is full of personnel and equipment. The number of people and the amount of equipment used varies, depending on the type of surgery and what stage the procedure is at. The basic setup of personnel is 2-3 surgeons, 1 surgical nurse, 1 nurse anaesthetist and 1 assistant nurse[1]. See Figure 18 for their respective position in the operating theatre.

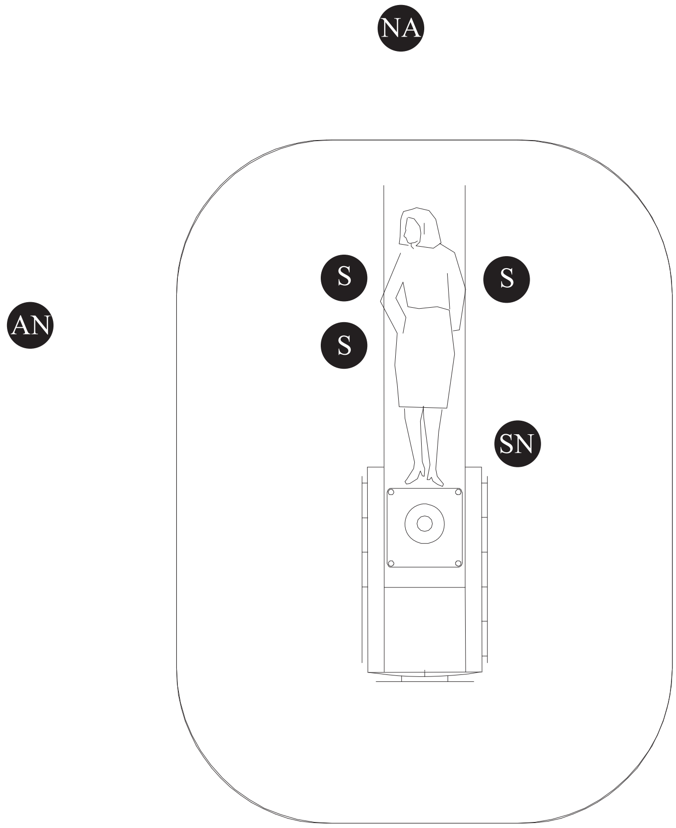

Figure 18 Position of surgeons and nurses in an operating theatre. Surgeons (S), surgical nurse (SN), assistant nurse (AN) and nurse anaesthetist (NA).

Closest to the patient are the surgeons, one on each side of the operating bed. During more complex operations where a third surgeon is required or if a student is present, they are two on one side. The surgeons are very active, though they mostly stand still.

Their work requires much focus and they constantly need to change their angle to find the best view. Several tasks are usually being carried out simultaneously, e.g. mono- and bipolar electrosurgery can be performed while a sucker is used to suck up blood and keep the incision clean. At least three hands are required for the mentioned tasks, but often even more for keeping back tissue and holding organs in the right position. Bearing in mind the size of the incision, it is clear that there is a lot of activity going on in a very small area, see Figure 19. This in combination with the seriousness of the procedure entails that the surgeons can be very sensitive when it comes to disturbances.

[1] Christina Ekroth (Surgical nurse and technical manager, Sahlgrenska University Hospital) 2015-05-18

The surgical nurse stands within reach of the surgeons at level with the patient's feet. In her immediate proximity are two tables which are prepared with instruments (retractors, scissors, etc.) that may come to use during the operation. The main task of the surgical nurse is to assist the surgeons with instruments and preparations during the procedure.

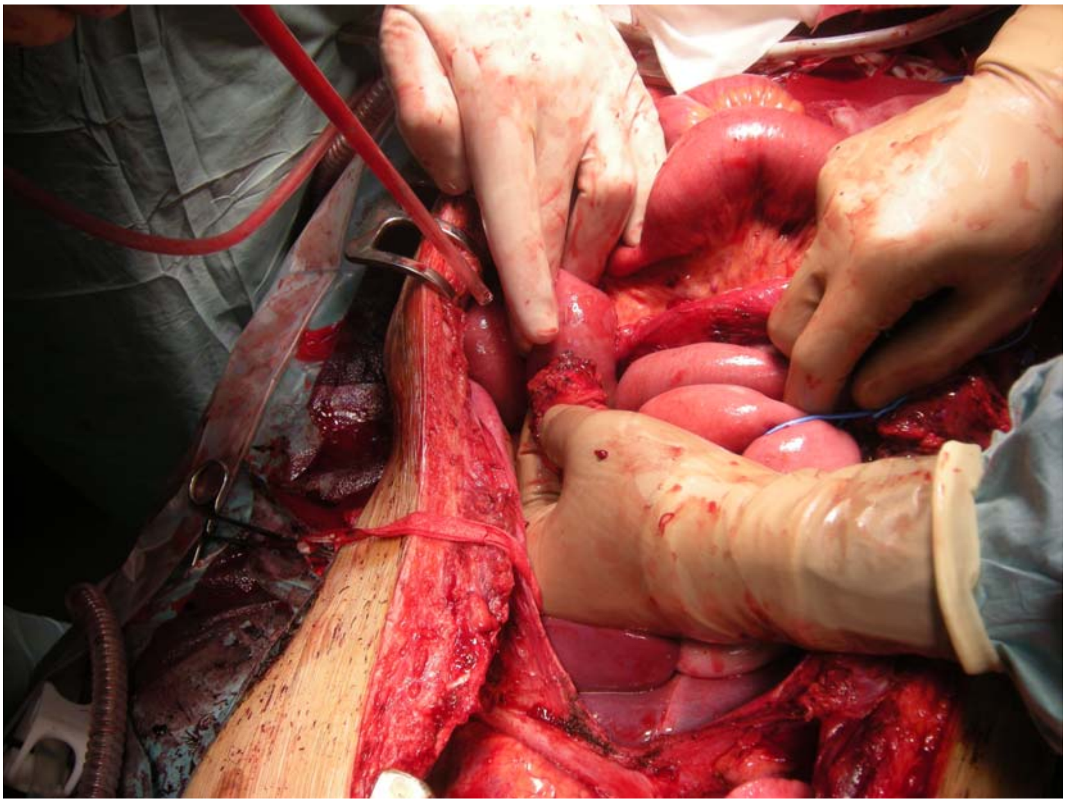

Figure 19 Incision showing a lot of activity with many hands involved. (Photo: Christina Ekroth)

The nurse anaesthetist sits above the head-side of the operating table and supervises the anaesthesia and the status of the patient. The work is usually independent from that of the surgeons but some communication may be required, e.g. if the procedure strongly affects the status of the patient.

The assistant nurse is outside the clean zone and assists the surgical nurse by fetching items from cabinets and other non-sterile work. During short periods the nurse must also leave the room to deliver a sample for testing. Additional personnel may be required at certain operations, e.g. a radiology nurse will attend during a cancer operation.

Because argon beam electrosurgery is mostly used during liver resection surgery, this section describes the procedure under such an operation. Before the procedure starts there are a lot of preparations made. They are however irrelevant to this study and are therefore left out. This walkthrough begins with the making of the incision.

The first cut is made with a scalpel and is very thin, but is quickly deepened with the monopolar electrosurgery. It cuts through layers of fat and muscles. The length of the cut was estimated to approximately 30 cm during the attended operations. When reaching the liver, the incision is widened and the retractors are strapped in place to keep it opened. The size and number of retractors depend on the size of the incision.

Parts of the liver are removed by cutting with the monopolar electrosurgery. The argon beam electrosurgery is periodically used to coagulate the new liver wall, thus preventing it from bleeding.

Blood and other fluids accumulates in the incision and are continuously sucked up using a sucker, to keep it clean and accessible. The surgeons must always pay attention to ruptured blood vessels, which they stop from bleeding by using the bipolar electrosurgery. This is especially important before closing the incision, to make sure that no vessels are left bleeding internally.

The operation is finished by removal of the retractors and stitching together the incision. This may need to be done in layers, to keep the inner structure in place. This final stage of the operation includes no use of electrosurgery.

5 Prototype

This chapter is about the procedure behind developing a prototype. Aspects that have to be considered are discussed and the resulting prototype is presented. There are a few aspects that have to be considered when developing a local exhaust for an operating theatre. The major ones are distance and size.

The surgeons must be able to perform the surgery without any extra disturbances, see Chapter 4, Section 4.4. This limits the possibilities regarding shaping and placing of the local exhaust. Another important factor is the capture ability of the local exhaust and as described in Chapter 3 the distance to the source is therefore of great importance. By placing the local exhaust further away from the source, the flow needed to keep constant capture ability must be increased exponentially. This will also increase the sound level in the room.

Further the size of the prototype affects the capture ability; a bigger exhaust covers a larger area but does not generate the same capture velocity as a smaller one. Placing of the exhaust is also an important aspect when sizing the prototype, because the closer to the incision the smaller it has to be.

Regarding the hygiene aspect the discussion is based on whether to make a disposable product or a reusable product. This decision affects the composition of the product in terms of material but also in terms of shaping the product. All reusable products, like the retractors, at Sahlgrenska University Hospital need to undergo autoclaving after usage in order to be sterilised[2].

The sterilising of reusable products at Sahlgrenska starts when it is washed in a disinfecting washer. Here the product is heated several times up to 90˚C during a minute at a time. After that it is packed in plastic bags and put in the autoclave for 7 minutes with a temperature of 134 ˚C. When the autoclaving is finished the air is extracted from the plastic bags and the procedure is completed[3].

The developed prototype is based on the considered aspects mentioned in the previous section. The idea is to use the equipment that already exists nearby the incision. This minimises the added disturbances and at the same time allows the local exhaust to be placed as close as possible to the contaminant source.

[2] Christina Ekroth (Surgical nurse and technical manager, Sahlgrenska University Hospital) 2015-05-18
[3] Christina Ekroth (Surgical nurse and technical manager, Sahlgrenska University Hospital) 2015-05-18

As mentioned in Chapter 4, Section 4.3.2, retractors are placed to create a better working space during the incision. After a few observations made during surgery the idea came to integrate the local exhaust with the retractors.

The retractors are fixed during surgery and in place during most of the time when electrosurgery is used, especially argon beam electrosurgery. These facts make the integration of the extractor with the retractors advantageous. The exhaust will also end up really close to the source and allows for the use of multiple extractors, since at least two retractors are usually used during abdominal surgery.

The idea of integrating the exhaust into the retractor puts some restrictions regarding the size, since the size of the incision does not allow for larger devices. As mentioned in Chapter 4, Section 4.3.2, the retractors can vary in sizes from 90 mm up to 155 mm for an abdominal retractor. An extractor integrated with the retractors would therefore be in this range of size.

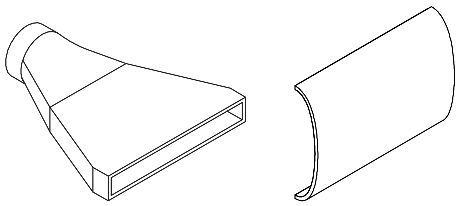

Figure 20 3D model of the separate exhaust and hook parts.

A 3D model based on the studies and observations was made in the software Inventor. It has a width of 90 mm and a length of approximately 100 mm. The front opening is 8.6 cm² and the outer diameter for the pipe connection is 28 cm. The entire prototype has a thickness of 2 mm. To visualise the idea a hook was made separately to be connected with the extractor as shown in Figure 20. The 3D model in its whole is shown in Figure 21.

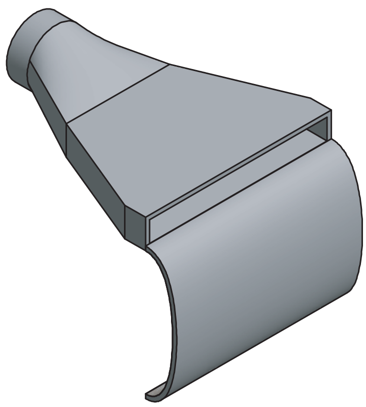

Figure 21 3D model of the prototype.

Using this 3D model a prototype was 3D printed in gypsum as shown in Figure 22. The printed prototype was used for tests and comparison with the minisquair.

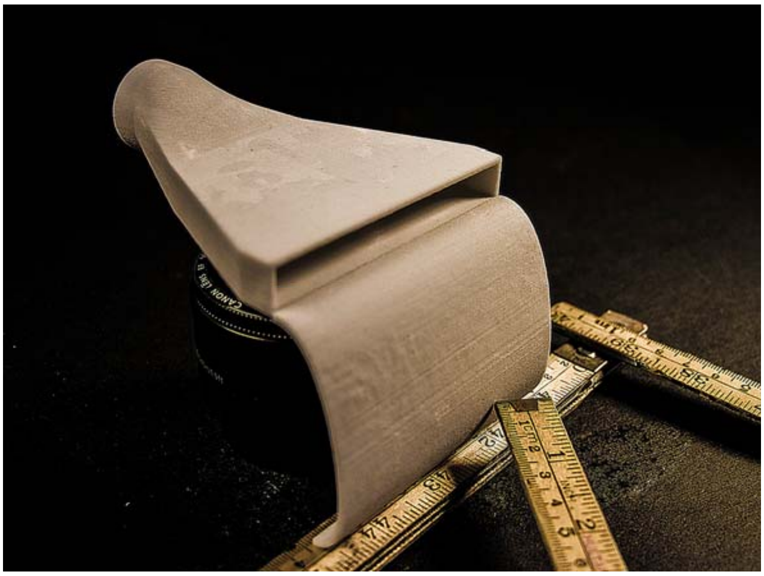

Figure 22 3D printed prototype of local extractor.

One idea was to have an extractor that could be clipped on the retractor instead of making them into one integrated unit. Using clips as a connection gives the possibility to make it disposable, which can be beneficial in a hygiene perspective. However making them into one unit in metal would allow them to be reused, by using autoclaving.

Making an integrated product in metal would allow it to be slim and result in a quicker installation process. It would also be more rigid resulting in less possible complications – when the combined product is fixated and fulfilling its retraction purpose, all that is needed is to attach the tube that is connected to an exhaust fan.

The idea of integration poses a problem, however, when considering other types of incision that uses other retractors. This might mean that there would be need of developing an extractor for each retractor, which would be expensive.

The prototype was made for visualising the idea and to make some first stage testing, why it is simplified in its appearance. The main idea is to adapt the exhaust more to the shape of the existing retractors where the performance of the retractor isn't compromised, but rather developed to fulfil another purpose as well.

6 Tests

The tests were carried out at two locations; in a test hall at Chalmers University and in the hybrid operating theatre at Sahlgrenska University Hospital. The tests were conducted for two local extractors; the minisquair, see Chapter 3, Section 3.3, and the prototype, see Chapter 5.

The test hall was used since it allowed for unrestricted access and did not strain the activities at the hospital, as the use of the real operating theatre would. Hence the test hall was primarily used for the tests and the operating theatre at the hospital was only used for later test where full equipment and higher precision was needed.

Smoke test was conducted to get an overview and visualise the airflow pattern, followed by capture velocity tests to more precisely determine the velocities. The particle measurement test aimed at measuring both the capture efficiency and the occupational hygiene efficiency. But due to the few and uncertain results that followed, no values were calculated and the result was analysed as it was.

6.1 Prerequisites of test hall

A replica of the operating theatre was designed and prepared in the test hall, see Figure 23. Only two people and no equipment were in the room during testing. This means that there were much fewer obstacles and thermal sources present than during a normal operation, which could change the velocity and flow pattern of the air drastically. Further, since the exhaust device was placed directly on the operating bed and no surgical or other activity were going on, the disturbances in the room were kept to a minimum. For a more detailed description of the room, see Appendix A.

The test room have LAF ventilation with adjustable flow supplied from the ceiling. The exhaust air outlets were placed at floor level and in each corner of the room to achieve a symmetrical air flow pattern.

The operating bed is located in the middle of the room. On top is a black paper to higher the contrast during the smoke tests. The paper is also used to mark distances from the exhaust device.

Figure 23 Overview of operating theatre in test hall.

The local exhausts were placed on the black paper on the operating bed, see Figure 24. A regular vacuum cleaner was used to power the exhaust device, which was connected by a tube. The vacuum cleaner was placed outside the room to reduce the noise and to not let in the exhausted smoke.

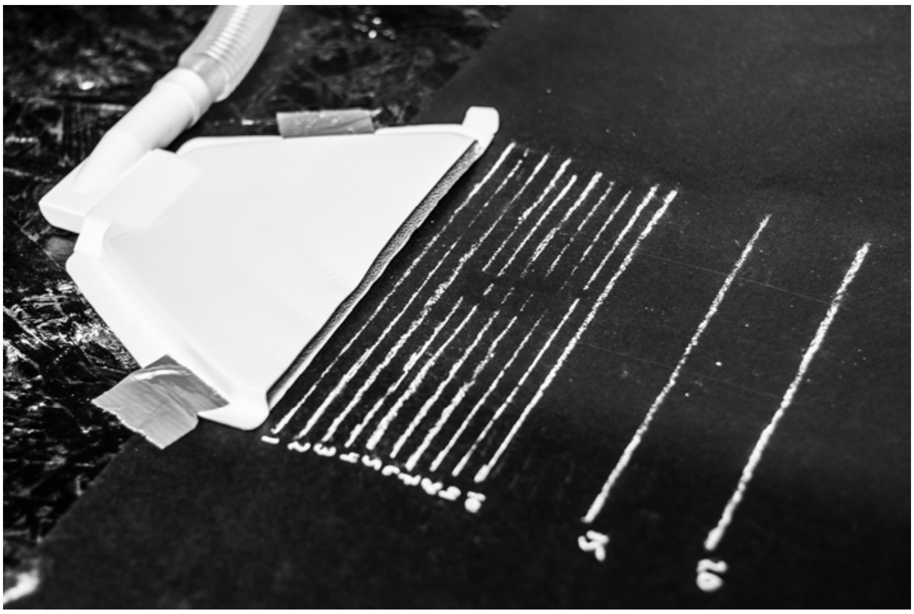

Figure 24 Minisquair and black paper placed on the operating bed in the test hall.

A hole was made in the tube to enable measurements to be taken of the air flow through the local exhaust. The power source was led through a variac to make the air flow adjustable, with an approximate maximum of 1300 l/m.

6.2 Smoke test

The smoke tests were conducted in order to get an overview and visualise the airflow pattern and the influence of the general ventilation on the capture ability. They were carried out on both devices and in the test hall described in Section 6.1. All measurements of velocities during the tests were done using a recently calibrated Swemaair 300.

Two tests were done with the minisquair, having the general ventilation either turned on or off. Having done this comparison, it was deemed unnecessary to conduct the test with no general ventilation on the prototype as well, and so only the test with general ventilation turned on was done.

The smoke machine generated smoke which was exhausted with a quite high velocity from a handle connected to the machine through a tube. The potentially bad effect of the smoke on the measuring device was unknown and so the velocity of the smoke was not measured.

The smoke was directed with an angle towards the table in order to slow it down. The surgical smoke is rising because of the thermal effect, thus it would have been more accurate to direct the smoke upwards. However no method to decelerate the smoke worked.

The LAF ceiling supplied air at a constant flow of 720 l/s when the general ventilation was turned on. This is equivalent to an output speed of 0.3 m/s. It was 1.55 m between the suspended ceiling and the operating bed, on which the local extractors were placed.

The airflow rate of the extractors were set to 250, 500, 750 and 1000 l/min in the tests. This was done by changing the settings of the variac while continuously measuring the velocity in the tube until the correct flow was obtained. The smoke was supplied parallel to the extractor 7.5 cm from its centreline (along the line C in Appendix B) and at a distance of 3, 6, 10, 15 and 20 cm from the extractor.

The camera filming the tests were put on a tripod and the pipe supplying the smoke was held by hand. After starting recording, the smoke machine was turned on and both person stood completely still to not create unwanted air movements. The smoke machine and the filming was turned off after the smoke distribution had reached steady state, under which one picture were extracted from the film to visualise the result in Chapter 7, Section 7.1

There were four factors being changed during the tests: extractor, general ventilation, airflow rate and distance from source to extractor. A total of 55 measurements were therefore taken, see overview in Table 1.

Table 1 Overview of smoke tests conducted.

	Minisquair		Prototype
	No LAF	LAF	LAF
Airflow rates [l/min]	1000, 500, 250	1000, 750, 500, 250	1000, 750, 500, 250
Distances [cm]	3, 6, 10, 15, 20	3, 6, 10, 15, 20	3, 6, 10, 15, 20

6.3 Capture velocity test

The capture velocity tests were conducted in order to more precisely determine the capture velocity in front of the local extractors. They were carried out on both the devices and in the test hall described in Section 6.1. All measurements of velocities during the tests were done using a recently calibrated Swemaair 300. The tests were done with no general ventilation and for both the minisquair and the prototype.

The airflow rates of the extractors were set to 250, 500, 750 and 1000 l/min in the tests. This was done by changing the settings of the variac while continuously measuring the velocity in the tube until the correct flow was obtained. The capture velocities were measured one centimetre above the operating bed, which was the same as the centre height of the extractors. They were measured on the centreline going out from the device at a distance of 3, 6, 10, 15 and 20 cm from the extractors.

The minisquair is quite long and therefore the capture velocity was instead measured in a grid. The centreline is called B and a parallel line was added 7.5 cm from the centreline on each side, A and C. The capture velocities were measured along line B and C while A was considered to be equal to C because of symmetry. For more details, see Appendix B.

Three factors were being changed during the tests: extractor, airflow rate and position in measuring grid. A total of 50 measurements were therefore taken, see overview in Table 2.

Table 2 Overview of capture velocity tests conducted.

	Minisquair	Prototype
Airflow rates [l/min]	1000, 500, 250	1000, 750, 500, 250
Lines	A, B	A
Distances [cm]	3, 6, 10, 15, 20	3, 6, 10, 15, 20

6.4 Sound test

The sound test was conducted in order to get a sense of how the sound level varies depending on the airflow through the extractor. The test was done using the minisquair. The vacuum cleaner was closed in by blocks of Styrofoam to minimise its background noise.

A decibel meter was placed 50 cm above the local extractor, which is an approximation of where the closest person working is located. The sound levels were measured when the extractor was both connected and disconnected. This was done so that all other noise could be excluded from the result. The vacuum cleaner was connected when the extractor was disconnected so that it wouldn't affect the sound level. The results were subtracted incoherently according to eq. (6) for each airflow rate measured.

$$L_p = 10 \cdot \log_{10}\left(10^{\frac{L_{p,1}}{10}} - 10^{\frac{L_{p,2}}{10}}\right) \quad (6)$$

L_p Calculated sound level of extractor [dB(A)]

$L_{p,1}$ Sound level, extractor on and vacuum cleaner on [dB(A)]

$L_{p,2}$ Sound level, extractor off and vacuum cleaner on [dB(A)]

The airflow rates for which the sound levels were measured are 250, 500, 750 and 1000 l/min.

6.5 Particle measurement test

The particle measurement tests were conducted in the hybrid operating theatre at Op. 2, Sahlgrenska University Hospital. The purpose was to test the extractors in a real environment and verify the results from the tests done in the test hall. Three cases were studied; one for each extractor and one without extractor to have as reference case.

The operation was carried out on two pieces of calf liver instead of a patient. The tests were done in conjunction with two health professionals from the hospital and in total nine people were present in the operating theatre. The health professionals prepared the operating bed, putting blankets that would act as body and placing the livers in between, with return electrode beneath. They also acted as surgeons during the tests and stood on either side of the operating bed, see Figure 25. Everyone else present kept outside the aseptic area.

The general ventilation with laminar airflow was turned on during all measurements. The local extractors were connected to the monopolar exhaust, for which the available airflow was 135 l/min.

The particle counter used were two P-Trak Ultrafine Particle Counter 8525 (P-trak) and one Climet CI-500 Innovation Portable Laser Particle Counter (Climet). The P-trak measures particles in size range 0.02-1 μm and manages concentrations of 0-500,000 particles/cm³. They were set to log data every five seconds. The Climet measures particles based on size, grading them 0.3, 0.5, 1, 5, 10, 25 mm.

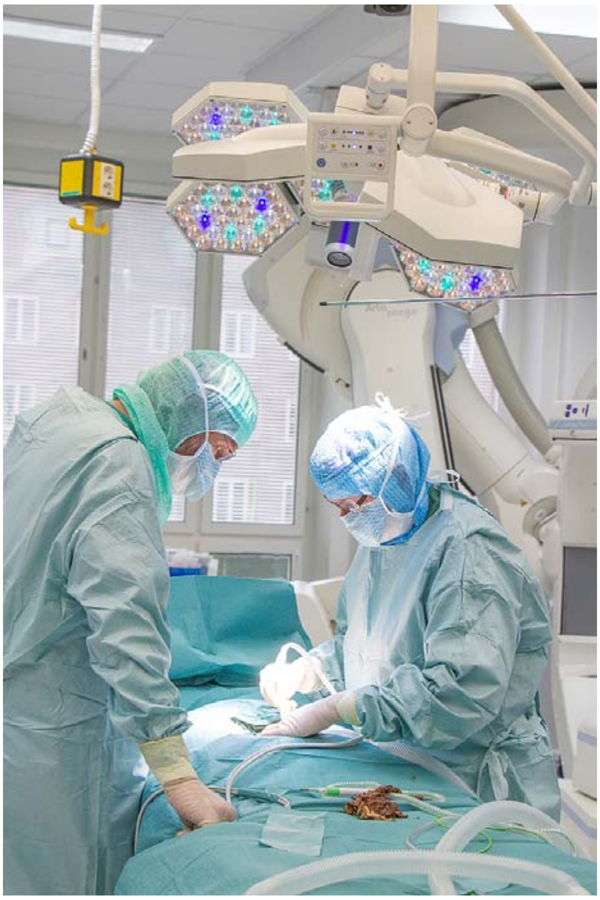

Figure 25 The position of the surgeons and equipment. To the left is Steven Muskantor, nurse anaesthetist and to the right Christina Ekroth, surgical nurse and technical manager.

Tripods were used to place the measuring tubes at their positions. One P-trak was placed 70 cm directly above the liver and the other just beneath the LAF ceiling to make sure that the supply air was clean, see Figure 26. The Climet was placed in front of one of the ventilation outlets.

Figure 26 Placing of particle counters in operating theatre. Red circle marks the counter at the exhaust ventilation, red horizontal oval marks the counter above operating bed and red vertical oval marks the counter measuring at the supply air.

The prototype extractor was placed on the head-side of the simulated incision, since it is meant to be placed on or integrated with the retractors (see Figure 27). The minisquair on the other hand must be placed where it doesn’t interfere with the retractors and was therefore placed along the side. The prototype was taped while the minisquair was fixed by its adhesive back. The hook part of the prototype was not mounted during the test because its effect on the capture ability was assumed to be negligible.

 

Figure 27 *The prototype (left) and the minisquair (right) in their respective position. Both pictures are taken from the foot-end of the operating bed.*

The tests had to be kept relatively short because of the limited amount of liver disposable. The test without extractor was conducted first and it was divided in three parts: argon beam electrosurgical instrument with and without argon beam function, and monopolar electrosurgical instrument. The monopolar electrosurgery has an integrated exhaust which was used during the test. The test lasted for 14 minutes. The argon beam electrosurgical instrument with and without the argon beam function were used exclusively during the tests of the prototype and the minisquair. The tests of the devices took approximately 7 minutes each. See Figure 28 for argon beam electrosurgery in action.

Figure 28 *Argon beam electrosurgery.*

The surgeons took turns using the electrosurgical instruments. They also had to make pauses for cleaning of the instruments and to cut the liver in order to free up more fresh area.

7 Results

7.1 Smoke tests

The results from the smoke tests are separated by flow and distance from the local exhaust, and also if the LAF ceiling is running or not. In each figure the different flows for a specific distance are shown.

7.1.1 Minisquair with no general ventilation

In this section the results are presented for the minisquair as the local exhaust without any general ventilation.

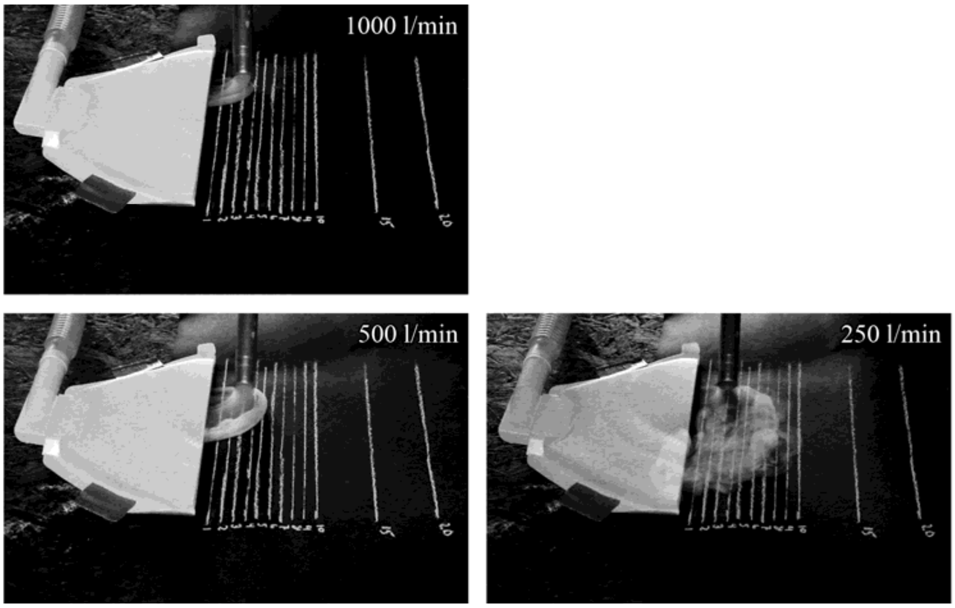

Figure 29 No general ventilation, distance of 3 cm from source to minisquair.

In Figure 29 the minisquair seems to capture all of the smoke for flows of 500 and 1000 l/min, at a distance of 3 cm from the source. At a flow of 250 l/min a small part of the smoke escapes.

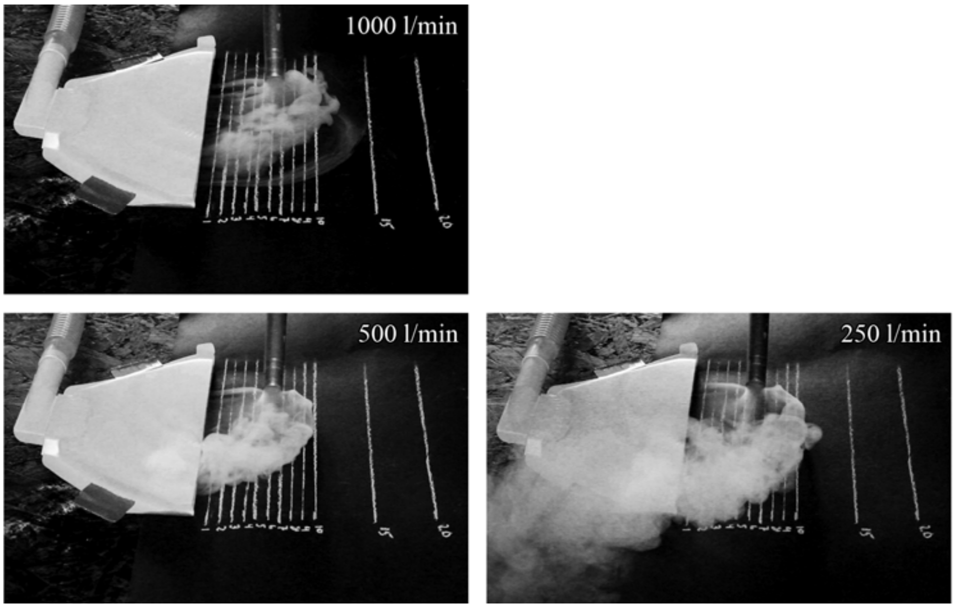

Figure 30 No general ventilation, distance of 6 cm from source to minisquair.

In Figure 30 the minisquair seems to capture all of the smoke for the flow 1000 l/min, at a distance of 6 cm from the source. At 500 l/min a small part of the smoke escapes and at 250 l/min a significant amount of smoke escapes.

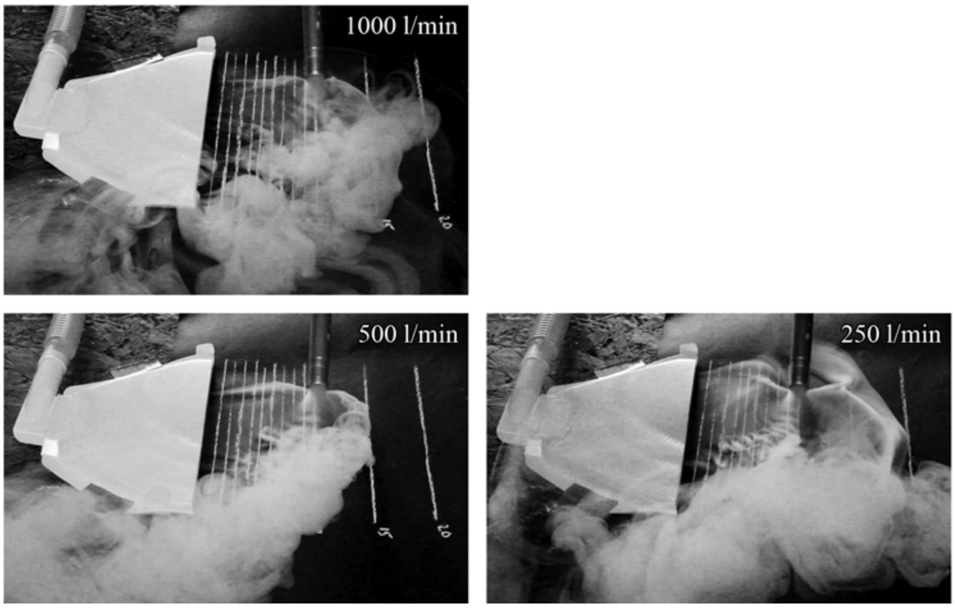

Figure 31 No general ventilation, distance of 10 cm from source to minisquair.

In Figure 31 it is clear that at a distance of 10 cm between source and exhaust the minisquair doesn’t capture all of the smoke. Even at a flow of 1000 l/min a lot of the smoke is spread in the room instead of being captured by the minisquair.

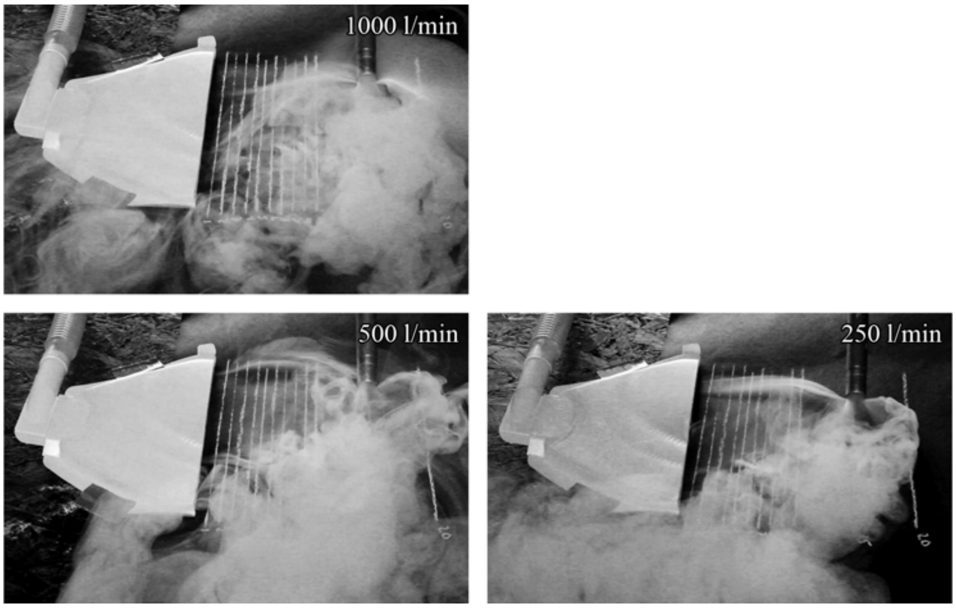

Figure 32 No general ventilation, distance of 15 cm from source to minisquair.

In Figure 32 it is clear that only a small amount of the smoke is captured by the minisquair, while the major part is spread out in the room for the tested flows.

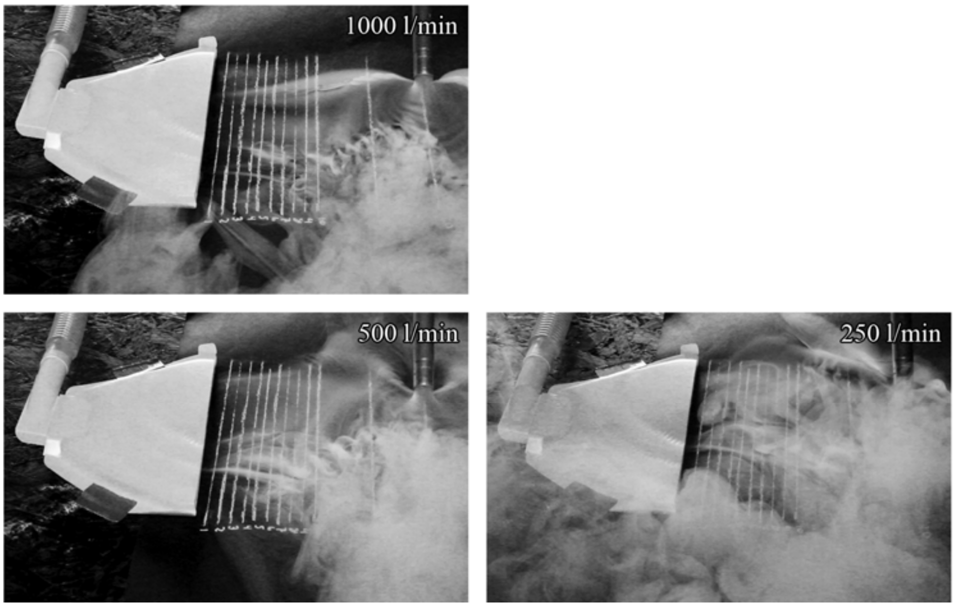

Figure 33 No general ventilation, distance of 20 cm from source to minisquair.

In Figure 33 it is clear that only a small amount of the smoke is captured by the minisquair, while the major part is spread out in the room for the tested flows.

7.1.2 Minisquair and laminar air flow

In this section the results are presented for the minisquair as the local exhaust together with the general ventilation of laminar air flow.

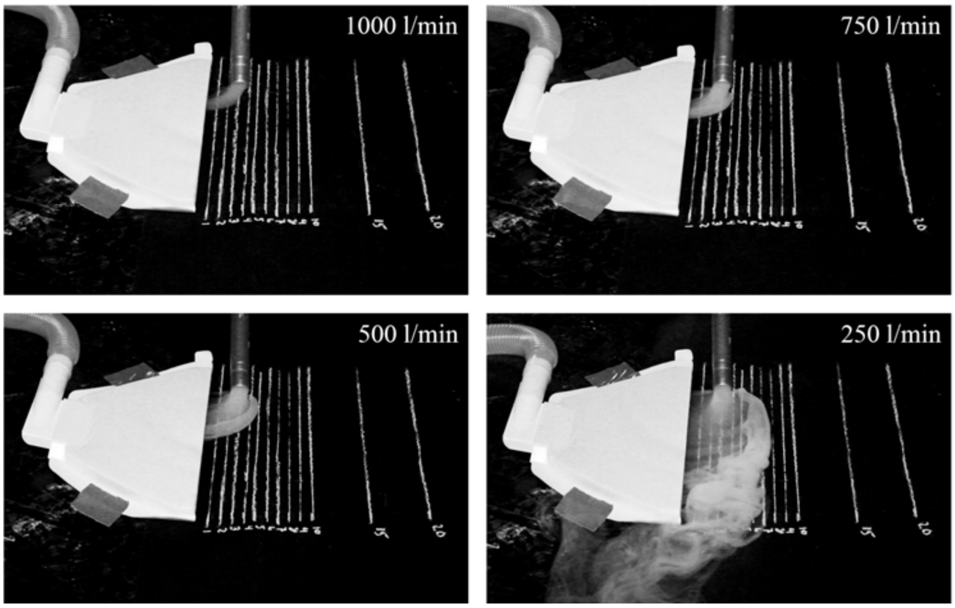

Figure 34 General ventilation, distance of 3 cm from source to minisquair.

In Figure 34 the minisquair seems to capture all of the smoke for flows of 500, 750 and 1000 l/min, at a distance of 3 cm from the source. At a flow of 250 l/min a notable part of the smoke escapes.

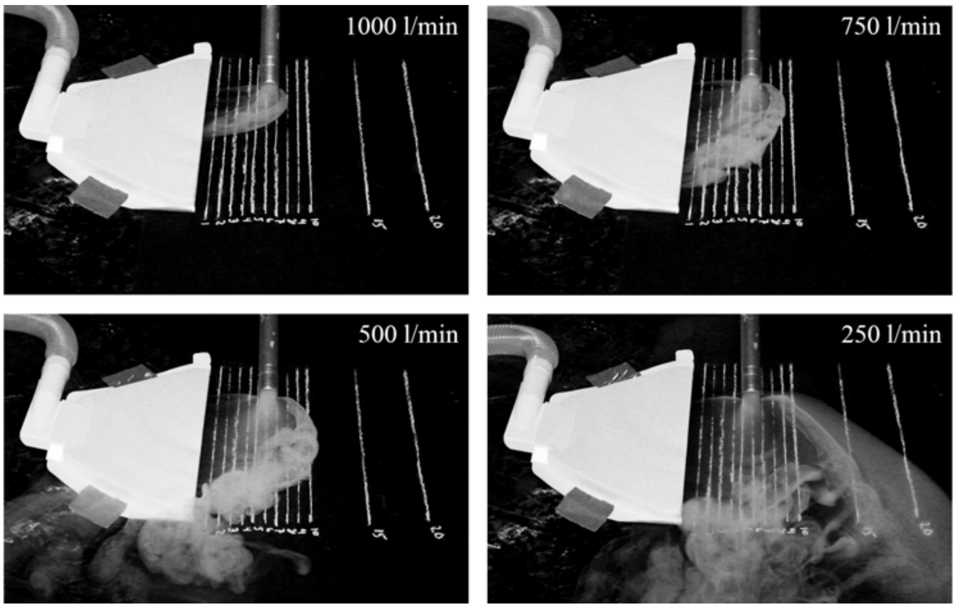

Figure 35 General ventilation, distance of 6 cm from source to minisquair.

In Figure 35 the minisquair seems to capture all of the smoke for flows of 750 and 1000 l/min, at a distance of 6 cm from the source. At a flow of 500 l/min a notable part of the smoke escapes whiles for 250 l/min a big part is spread in the room.

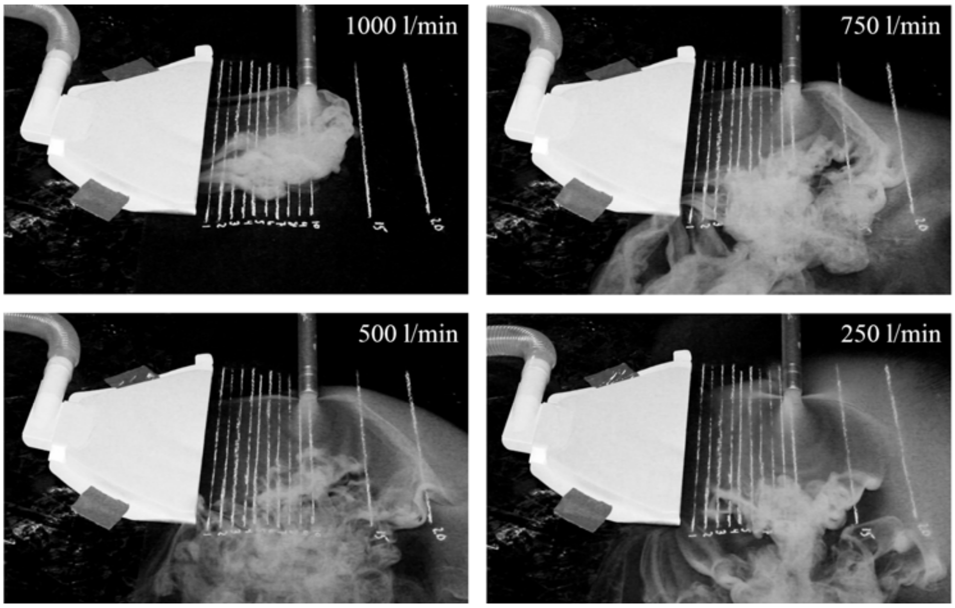

Figure 36 General ventilation, distance of 10 cm from source to minisquair.

In Figure 36 the minisquair seems to capture all of the smoke for the flow of 1000 l/min, at a distance of 10 cm between source and local exhaust. At the flows of 750, 500 and 250 l/min the most of the smoke is spread in the room.

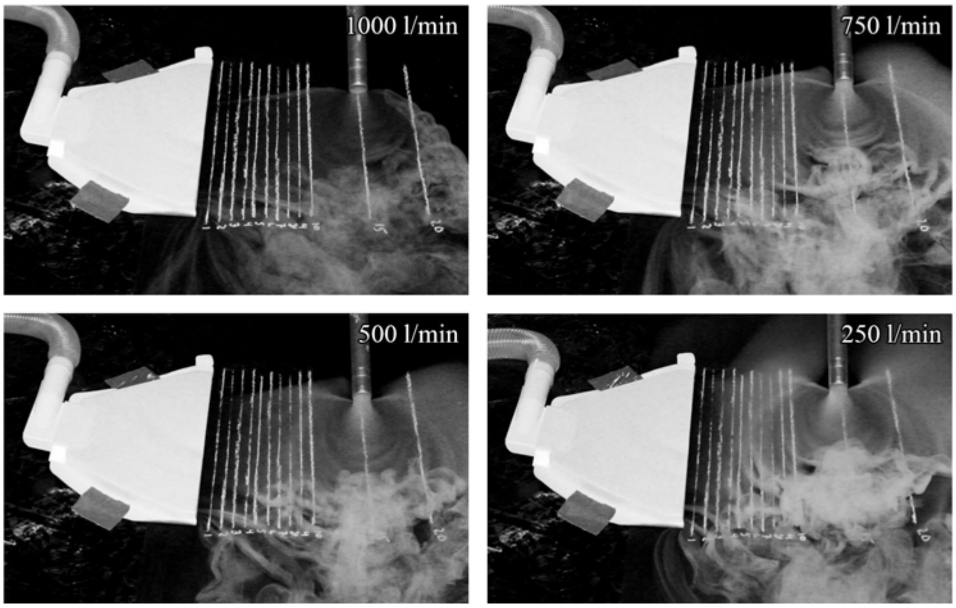

Figure 37 General ventilation, distance of 15 cm from source to minisquair.

In Figure 37 it is clear that only a small amount of the smoke is captured by the minisquair, while the major part is spread out in the room for the tested flows.

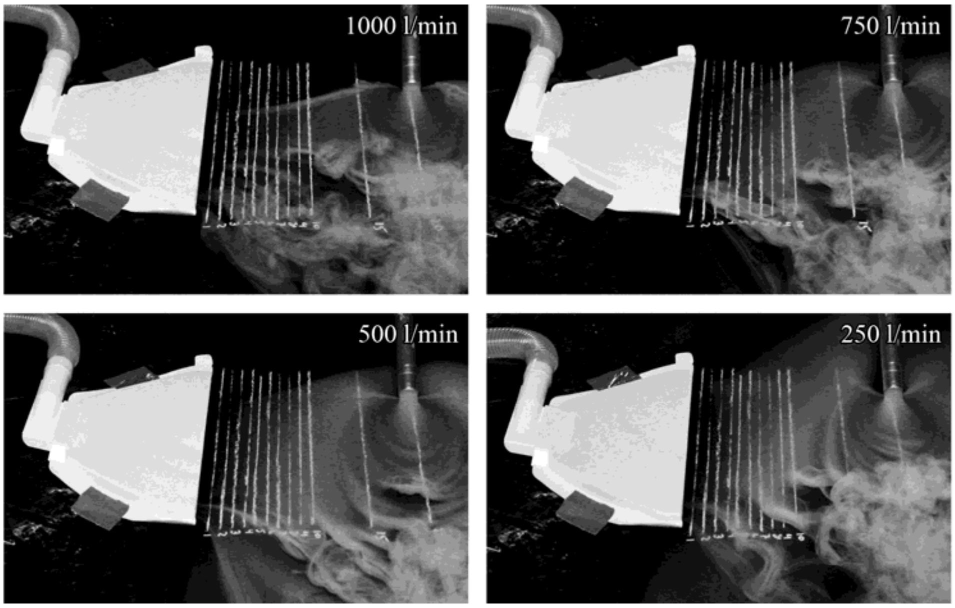

Figure 38 General ventilation, distance of 20 cm from source to minisquair.

In Figure 38 it is clear that only a small amount of the smoke is captured by the minisquair, while the major part is spread out in the room for the tested flows.

7.1.3 Prototype and laminar ventilation

In this section the results are presented for the prototype as the local exhaust together with the general ventilation of laminar air flow.

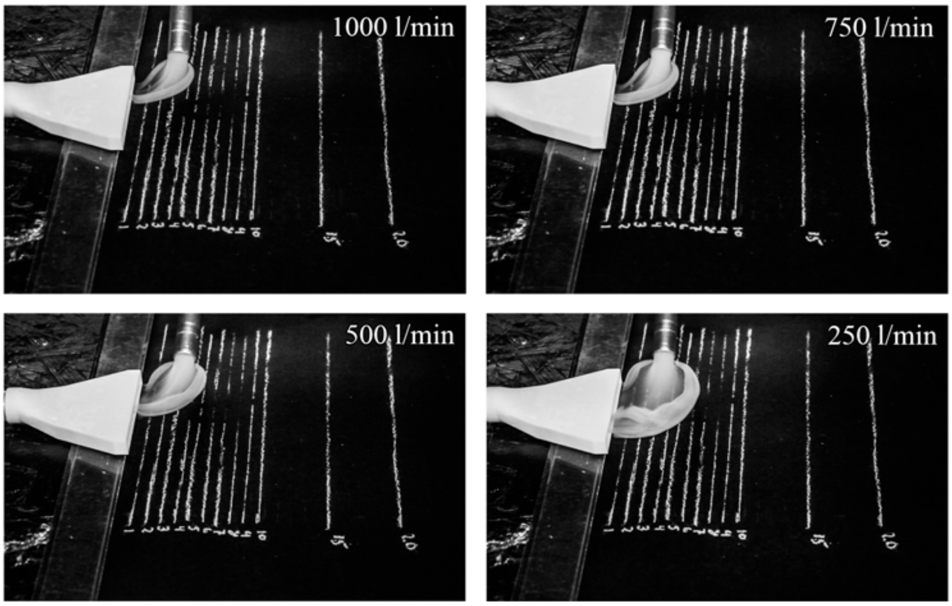

Figure 39   General ventilation, distance of 3 cm from source to prototype.

In Figure 39 the prototype seems to capture all of the smoke for the tested flows, when the distance to the source is 3 cm.

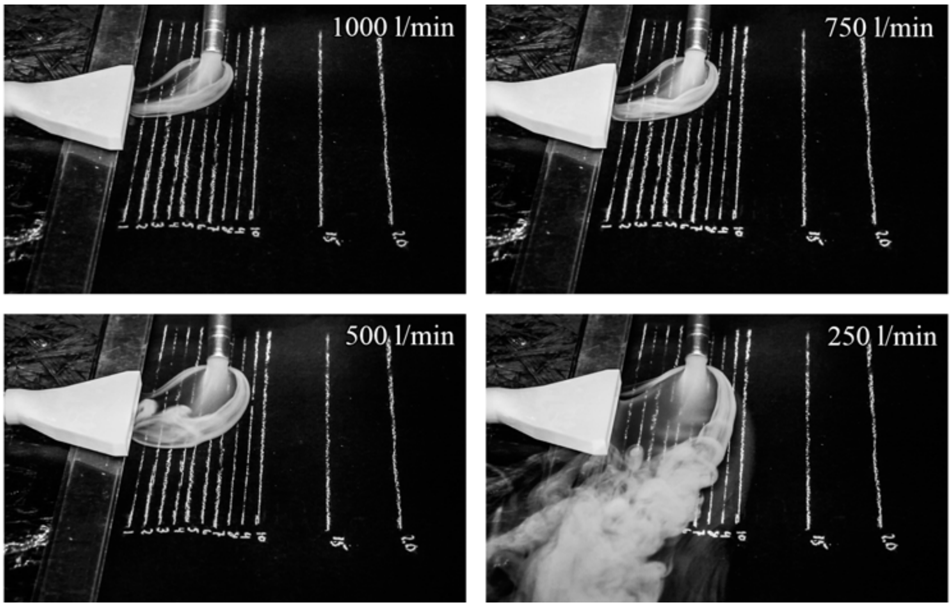

Figure 40   General ventilation, distance of 6 cm from source to prototype.

In Figure 40 the prototype seems to capture all of the smoke for the flows 1000, 750 and 500 l/min, when the distance to the source is 6 cm. When the flow is 250 l/min a significant part of the smoke is spread in the room.

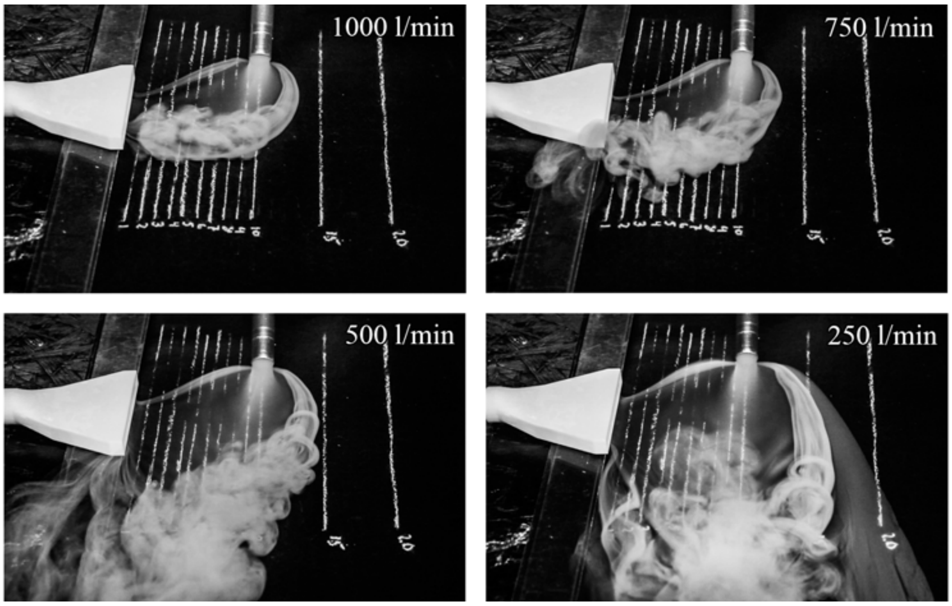

Figure 41 General ventilation, distance of 10 cm from source to prototype.

In Figure 41 the prototype seems to capture all of the smoke when the flow is 1000 l/min, when the distance to the source is 10 cm. When the flow is 750 l/min a notable part of the smoke is spread in the room, whiles for 500 and 250 l/min the major part escapes the prototype.

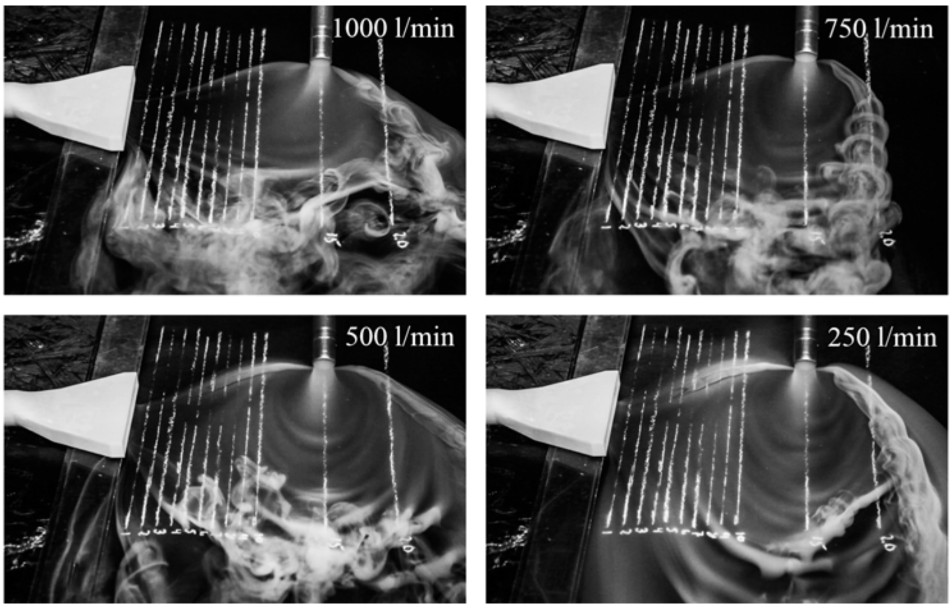

Figure 42 General ventilation, distance of 15 cm from source to prototype.

In Figure 42 it is clear that only a small amount of the smoke is captured by the prototype, while the major part is spread out in the room for the tested flows.

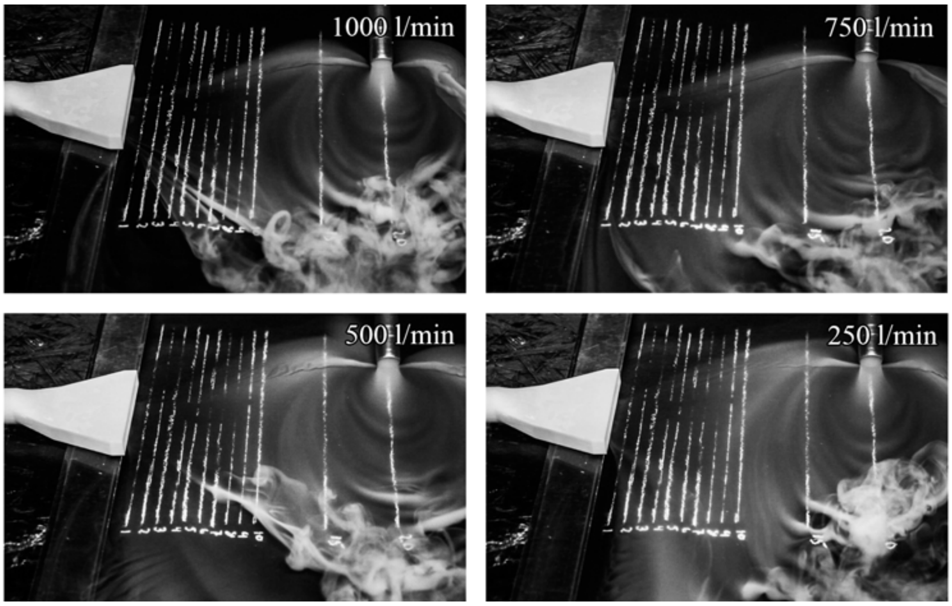

Figure 43 General ventilation, distance of 20 cm from source to prototype.

In Figure 43 it is clear that only a small amount of the smoke is captured by the prototype, while the major part is spread out in the room for the tested flows.

7.1.4 Analysis

The results from the smoke tests give a good indication of how the extractors work based on flow and distance from source. The effect of the LAF ceiling can also be interpreted based on the results.

By comparing the results of the tests of the minisquair with and without the general ventilation activated it becomes clear that the capture ability is affected by the LAF ceiling. A larger amount of smokes escapes the minisquair for the tests with general ventilation. This is because of the force created by the LAF ceiling, which pushes the smoke down at the table and over its edges before it is captured. This factor becomes even clearer with a lower flow or a larger distance because then the capture velocity of the minisquair is much lower than the velocity created by the LAF ceiling.

The prototype shows a little bit higher capture ability than the minisquair at shorter distances from the source because of the higher velocity closer to the opening. The difference between the two extractors diminishes when the distance to the source is increased.

7.2 Capture velocities

The results from the capture velocity tests are presented based on flow and positioning relative to the local exhaust. The results are separated based on which local extractor is used.

The measured velocities in the openings for each flow do not correspond exactly to the stated flow. This has to do with uncertainties in measurements of the velocities and the flows. However the indication of the results is still clear.

7.2.1 Minisquair

The results in Figure 44 below show how the capture velocity varies for different flows and at different positions from the minisquair. The plots are based on the results from the measurements in the test hall at Chalmers University, which are listed in Table 3.

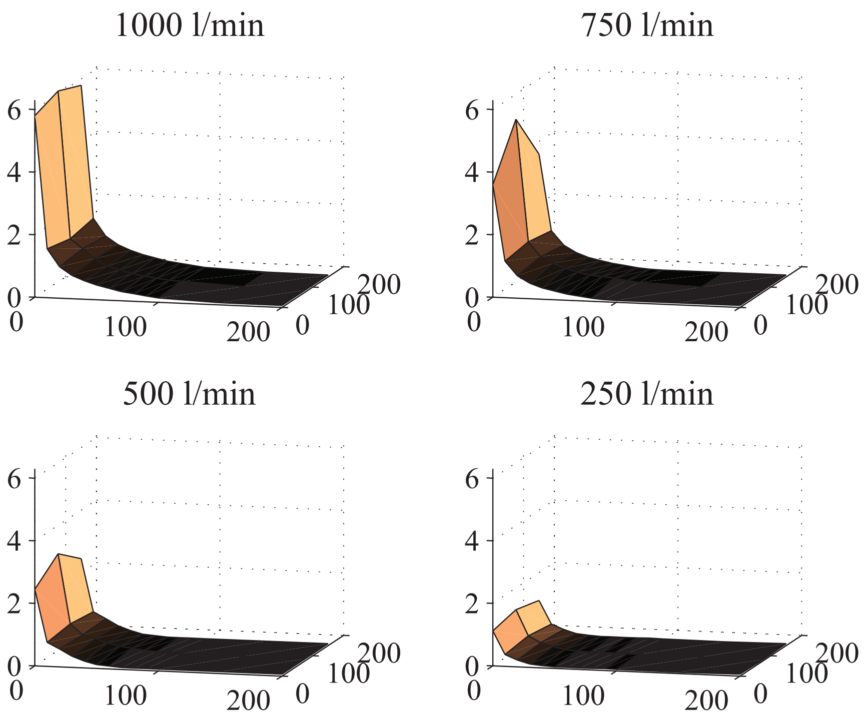

Figure 44 Capture velocities measured for the minisquair. Units are mm, mm and m/s for the x-, y- and z-axis respectively.

Table 3 Capture velocities measured for the minisquair. Units are in m/s.

Distance [cm]	1000 l/min		750 l/min		500 l/min		250 l/min	
	A	B	A	B	A	B	A	B
0	5.8	6.1	3.6	5.2	2.45	3.1	1.12	1.31
1	1.56	1.4	1.17	1.3	0.77	0.87	0.38	0.49
2	1.01	1.1	0.72	0.85	0.57	0.54	0.22	0.29
3	0.75	0.8	0.5	0.65	0.36	0.43	0.11	0.18
4	0.59	0.57	0.36	0.5	0.22	0.31	0.07	0.1
5	0.47	0.47	0.28	0.4	0.12	0.22	0.05	0.07
6	0.38	0.37	0.2	0.31	0.09	0.17	0.05	0.05
7	0.29	0.3	0.15	0.29	0.06	0.13	0.05	0.06
8	0.24	0.25	0.1	0.25	0.06	0.1	0.05	0.05
9	0.19	0.2	0.07	0.19	0.06	0.09	0.06	0.05
10	0.14	0.18	0.06	0.15	0.06	0.08	0.05	0.05
15	0.07	0.09	0.06	0.08	0.06	0.06	0.04	0.04
20	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.04

As can be seen from the results presented above a higher flow in the local exhaust means a higher capture velocity by the opening, like expected. Also the capture velocity decrease with increasing distance from the minisquair.

The decrease of velocity is exponential and at a distance of only 1 cm from the minisquair the velocity has decreased 75−80 %, compared to the opening. At 5 cm from the opening the capture velocity has decreased with up to 95 %. Since the decrease is exponential the influence of the flow at distances from 15 cm and over are very small and the local exhaust doesn't have the same effect.

7.2.2 **Prototype**

The results in Figure 45 below show how the capture velocities vary for different flows and at different distances from the prototype. The plots are based on the results from the measurements in the test hall at Chalmers University. The results are listed in Table 4.

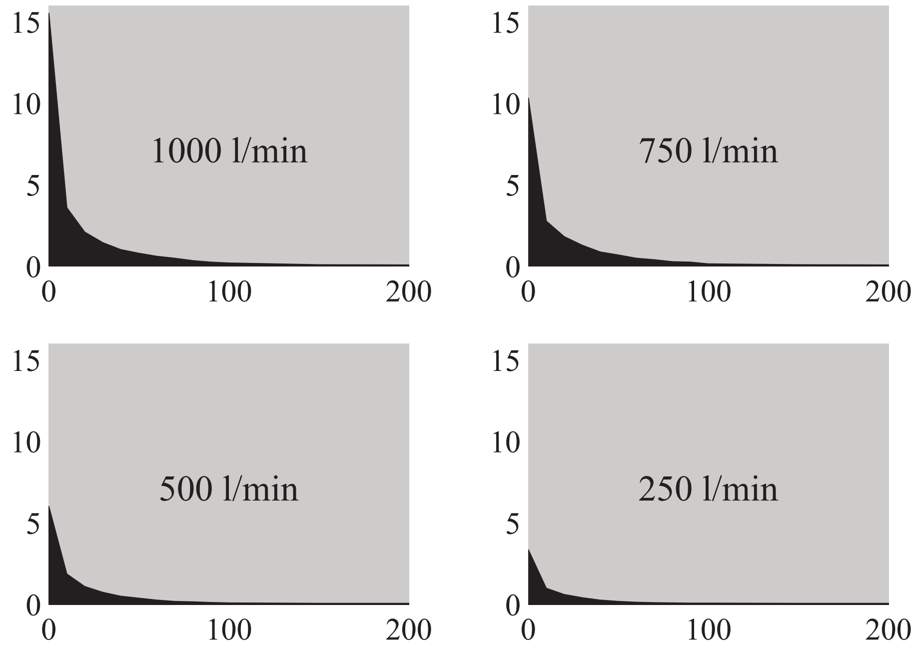

Figure 45 Capture velocities measured for the prototype. Units are mm and m/s for the x- and y-axis respectively.

As can be seen from the results presented in Figure 45 and Table 4 a higher flow in the local extractor means a higher capture velocity by the opening, like expected. Also the capture velocity decreases with increasing distance from the prototype.

The decrease of velocity is exponential and at a distance of only 1 cm from the minisquair the velocity has decreased 70-80 %, compared to the opening. At 5 cm from the opening the capture velocity has decreased with up to 95 %. Since the decrease is exponential the influence of the flow at distances from 15 cm and over are very small and the local exhaust doesn’t have the same effect.

Table 4 Capture velocities measured for the prototype. Units are in m/s.

Distance [cm]	1000 l/min	750 l/min	500 l/min	250 l/min
0	15,5	10,3	6,00	3,34
1	3,58	2,75	1,85	0,97
2	2,08	1,80	1,08	0,59
3	1,43	1,27	0,73	0,39
4	1,00	0,86	0,49	0,25
5	0,78	0,67	0,37	0,17
6	0,59	0,47	0,24	0,11
7	0,47	0,38	0,17	0,09
8	0,32	0,26	0,14	0,07
9	0,23	0,23	0,10	0,06
10	0,18	0,12	0,07	0,06
15	0,07	0,07	0,05	0,04
20	0,06	0,06	0,04	0,04

7.2.3 **Analysis**

The test of the capture velocities for the two local extractors shows similar results. Naturally they both have the highest capture velocity closest to the opening and the decrease in velocity is exponential with similar rate. Since the prototype has a smaller area at the opening it results in a higher capture velocity. Up to 10 cm from the opening the prototype keeps showing a higher velocity than the minisquair, however further from the extractors the result is not affected in any larger extends.

7.3 Sound test

Table 5 shows the results from the measurements of the sound level in the room caused by the minisquair.

Table 5 Result of sound test for minisquair.

Airflow [l/min]	Sound level, with extractor [dB(A)]	Sound level, no extractor [dB(A)]	Calculated sound level [dB(A)]
1000	61.7	47.2	61.5
750	56.7	41.4	56.6
500	47.0	37.0	46.5
250	38.2	35.0	35.4

The results show a decrease in sound level when the airflow decreases in the local extractor, which is reasonable. Also the sound level in the room when the extractor is connected differs from the case when it is disconnected. A greater difference is presented at higher airflows than at lower airflows. When the sound level from the disconnected case is incoherently subtracted it is clear that the extractor is causing most of the noise.

The measured sound levels when the extractor was disconnected varies from 35 to 47.2 dB(A), which shows that the noise from the vacuum cleaner affects the sound level in the room. Hence the adjustment was needed.

At the airflow of 250 l/min the sound level does not increase more than about 3 dB showing that local extractors at such low flows do not affect the sound level in the room in a large extent.

7.4 Particle measurements

In this section the results are presented from the particle measurements made at the hybrid operating theatre at Sahlgrenska University Hospital. The results also include some subjective comments from the personnel that performed the electrosurgery. Three measurements were made at three locations.

The particle counter placed just below the LAF ceiling registered zero particles throughout the tests, indicating a clean supply air. The data from the particle counter measuring in front of the outlet gave questionable results and has therefore been left out.

7.4.1 Electrosurgery with no local extractor

In this section the results from the particle measurements for the reference case are shown. No local extractor was used.

In Figure 46 it is clear that there are three periods during this test; the first five minutes when argon beam electrosurgery was used, between 5 and 9 minutes when the argon beam electrosurgical instrument without the argon beam function was used to cut and the last five minutes when the monopolar electrosurgery was used instead. During the first five minutes there are two peaks where the particle concentration reaches 300,000-350,000 particles/cm³ which corresponds to the activation of the handle. Between 5 and 9 minutes the concentration peaks 3 times, in other words reaching the maximum value of the particle counter of 500,000 particles/cm³. These peaks correspond to the activations of the handle. During the last 5 minutes only low particle concentrations were measured.

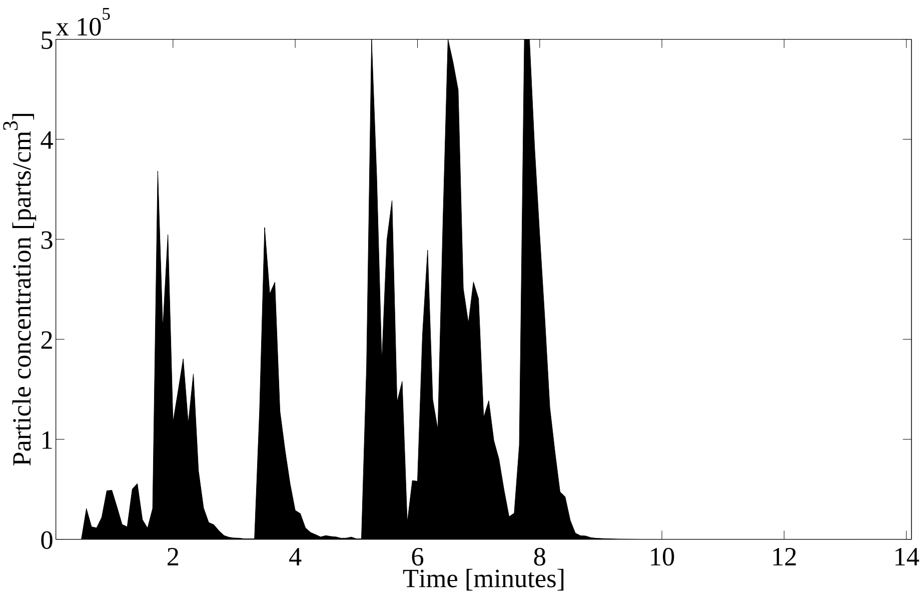

Figure 46 Result from particle measurement, no local extractor.

During the first 8 minutes of this test the medical staff experienced acrid smell and smoke generation caused by the electrosurgery, which correlate with the results presented in Figure 46. They could also see the smoke spread away from the simulated incision into the room.

When the method was switched to monopolar electrosurgery after just over eight minutes they experienced a much better environment by the operating bed. This corresponds very well with the measurement from the particle counter placed above the incision which indicates that the local exhaust integrated with the handle works very well.

7.4.2 Electrosurgery with prototype

In this section the results from the particle measurements are shown for the case where the prototype was used as the local extractor. In Figure 47 a peak can be seen after 1 minute and 45 seconds, where the measurement above the patient reaches a particle concentration of 200,000 particles/cm³. Between 3 and 4 minutes the particle concentration reaches 2 tops with concentrations of 300,000-400,000 particles/cm³. The last 3 minutes of the measurement show low levels of particle concentration with only two tops of approximately 50,000 particles/cm³ each.

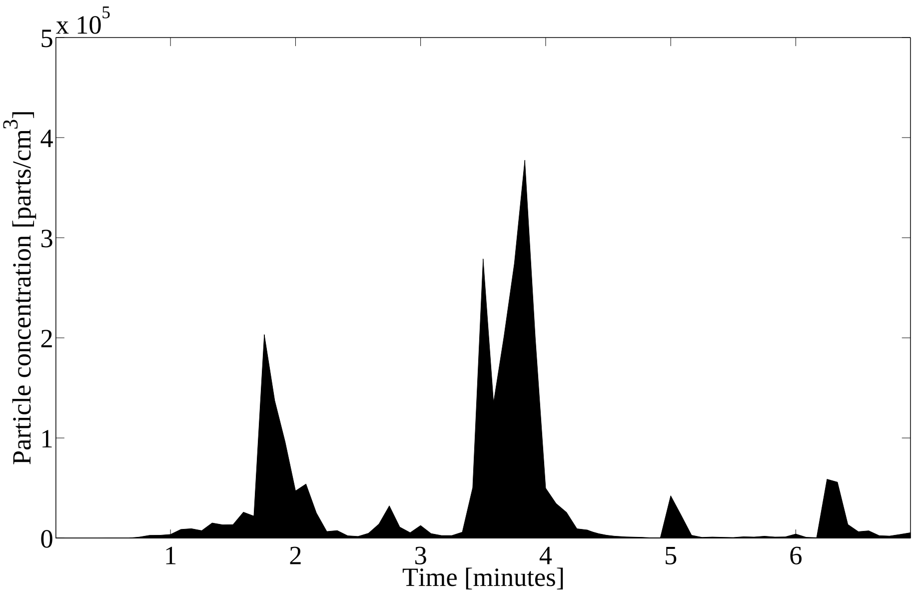

Figure 47 Result from particle measurement, prototype as local extractor.

The medical staff experienced a decrease of smoke spread from the simulated incision when the prototype was used as a local extractor. However in their experience still much surgical smoke spread to the room, especially when the distance between extractor and source increased.

7.4.3 Electrosurgery with minisquair

In this section the results from the particle measurements are shown for the case where the minisquair was used as the local extractor.

In Figure 48 a peak can be seen after 1 minute and 20 seconds, where the measurement above the patient reaches a particle concentration of almost 500,000 particles/cm³. Between minute 2 and 3 the particle concentration reach levels of almost 100,000 particles/cm³ 2 times. The last 4 minutes of the measurement show low levels of particle concentration.

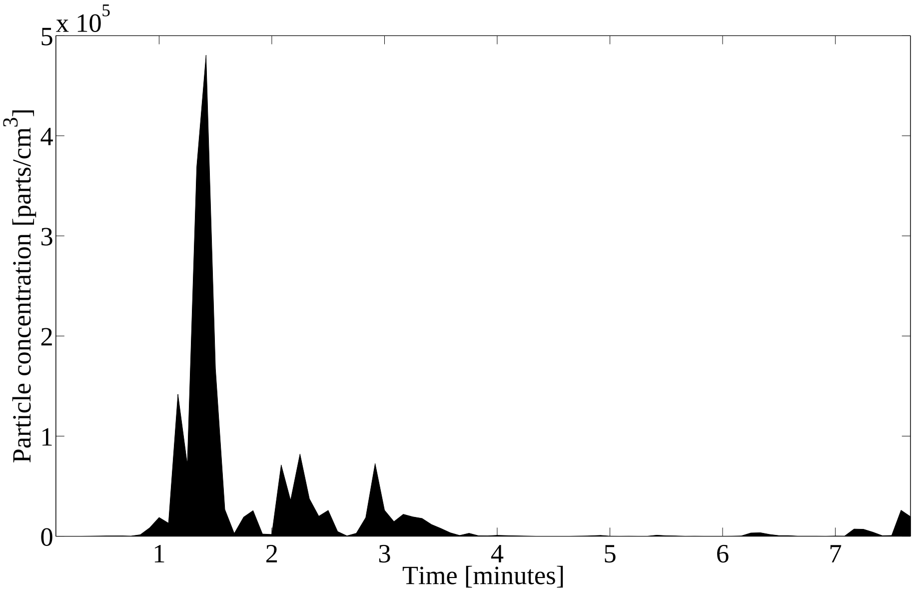

Figure 48 Result from particle measurement, minisquair as local extractor.

The medical staff experienced a decrease of smoke spread from the simulated incision when the minisquair was used as a local extractor. However in their experience still much surgical smoke spread to the room especially when the distance between extractor and source increased. Compared to the prototype they felt that the minisquair had slightly higher capture ability.

7.4.4 Analysis

Based on the results presented above it is clear that the extractors do improve the room environment during electrosurgery. However the effect of the extractors are minor and there are still a few peaks reaching really high concentration levels. The major reason for this is most probably the low airflow rate available in the extractor. Having airflow rates in the order of magnitude used in the smoke tests would result in much higher capture ability and lower particle concentrations.

Three factors that affect the capture ability of the extractor are the distance between source and extractor, hands covering the extractor and hand movements creating disturbances in the air. These might be the cause of the high peaks registered by the particle counter.

8 Discussion and Conclusions

The exhaust integrated with the monopolar electrosurgery has good capture ability, but placing the exhaust this close to the argon beam electrosurgery is no option, see Chapter 4, Section 4.3.1.3. The focus has instead been on placing the extractor in the immediate proximity of the incision. However the activities during surgery (Chapter 4, Section 4.4) significantly limit the size and shape of an extractor at this position. Further the result from the smoke test in the test hall (Chapter 7, Section 7.1) indicated that an exhaust at this distance would need an airflow rate of at least 750 l/min to have any significant effect.

Such high airflow rates through such a small device will result in very high velocities, which could generate disturbing noise levels. The sound test in the test hall also indicated that this could be the case, see Chapter 7, Section 7.3. However the noise level could not be tested in the operating theatre where airflow rates of this size was not available. The maximum airflow rate available from the equipment is only 135 l/min.

One of the reasons to the particle measurements in the hybrid operating theatre was to confirm the other tests made in the test hall. However these tests were conducted with airflow rates between 250-1000 l/min and since the maximum airflow rate in the operating theatre was much lower, no clear comparison could be made. An exhaust with capacity to airflow rates up to 1000 l/min should therefore be used in future studies.

Further the final test conducted in the hybrid operating theatre seemed to indicate that both the extractors had a notable effect on the particle concentration in the room (Chapter 7, Section 7.4). There are however a large number of factors (of which several are unknown) that can affect the result, e.g. hand movements, location of electrosurgical instrument, time periods and frequency of activation, placing of retractors, etc. To more accurately state if and how much the extractor helps, future tests will need to last for longer periods of time. This would reduce the influence of individual errors and temporary deviations.

The option of placing the device at a much greater distance than in the immediate proximity of the incision is not realistic since the required airflow rate increases exponentially and quickly become absurd (Chapter 3, Section 3.1). The indicated magnitude of the airflow rates at this distance is already much bigger than that of the extractor on the monopolar instrument and might affect the ventilation in the room.

The pressure difference between the operating theatre and its ambience could be affected, creating a negative pressure in the room (Chapter 4, Section 4.2). This would have to be counteracted by increasing the supply air or decreasing the exhaust air, however one important consequence is that this must be considered during the planning of the operating theatre.

Further the effect on the general airflow pattern that the addition of a local extractor will have is unknown and ought to be studied. It could lead to unwanted airstreams that either must be counteracted through changes in the layout of the operating theatre. But the conclusion could also be that airflow rates of this size are too high, which would entail that a local extractor is not an acceptable solution to the problem. This is however only speculations and it could very well be that a local extractor is a suitable solution.

All things that are in the ambience of the incision interfere with the surgical activity and it is of utmost importance that the surgeons can do their work and that the extractor does not increase the risk of mistakes. However one part of the problem is to make the surgeons give themselves a chance to get used to it instead of being too quick to dismiss it. One way of doing this is by integrating the extractor with the retractor, so that it is not experienced as a new gadget and thus easing the transition period. The prototype was design with this in mind.

The idea of integration poses a problem, however, when considering other types of incision that use other retractors. This means that there would be need of developing an extractor for each retractor, which is expensive and time consuming. In addition, all retractors would need to be replaced which would result in great costs. It is not an ideal solution and it might be a better idea to have an external local extractor that is fixed on of the retractor. This would however increase the size of the product and lose the advantage that having one integrated product entails.

Regarding the minisquair the product is a more flexible solution than the prototype considering that it can be reshaped and positioned independent of the retractors so that it works with many kinds of surgery. However the space close to the incision doesn't allow for much more equipment as discussed earlier.

Neither the prototype nor the minisquair managed very well in the test in the hybrid operating theatre. On the other hand, because of the insufficient airflow rate the test was inconclusive and both ideas are interesting and worthy to study further.

References

Blom, H. (2008). *Modern surgery environment and ventilation: A work environment study with concentration on argon diathermy*, Chalmers tekniska högskola, Göteborg.

Dallavalle, J.M. (1952). *Exhaust Hoods*. 2nd ed. New York: The Industrial Press.

Davison, J. & Zamah, N. (2008). *Electrosurgery: Principles, Biologic Effects and Results in Female Reproductive Surgery*. http://www.glowm.com/section_view/item/21 [2015-05-04]

Emed. (2014). *Argon in electrosurgery.* http://www.emed.pl/pdf/argon_in_electrosurgery.pdf [2015-02-05]

Fumex a. *R Rosrfti Atex*. [Online image] http://fumex.se/wp/wp-content/uploads/R-EXHP.png [2015-05-05]

Fumex b. *Terfu*. [Online image] http://fumex.se/wp/wp-content/uploads/TERFU_MBO50_MK350-1000.jpg [2015-05-05]

Gallagher, K., Dhinsa, B. & Miles, J. (2011). *Electrosurgery*. Surgery (Oxford), vol. 29, no. 2, pp. 70-72.

Jansson, A (1982). Utsugs infångning av föroreningar. *Arbete och hälsa*, 1982:11, pp. 1-23.

Jansson, A. (1990). Local exhaust ventilation and aerosol behaviour in industrial workplace air. *Arbete och hälsa*, 1990:43, pp.1-32.

Lundblad, S. & Nilsson L. (2013). *Diathermy and airborne particles in operating rooms: An investigational measurement study about dispersion of airborne particles and the variation of particle levels during operation*, Chalmers tekniska högskola, Göteborg.

Meda, D. (2014). *Air Contamination Control in Hybrid Operating Theatres: Particle content during different types of surgery with focus on diathermy*, Chalmers tekniska högskola.

Medtronic a. *Electrosurgical pencils*. [Online image] http://www.covidien.com/surgical/products/electrosurgical-instruments/pencils [2015-05-04]

Medtronic b. *Argon Handset*. [Online image] http://products.covidien.com/imageServer.aspx/doc64227.jpg?contentID=3023&contenttype=image/jpeg [2015-05-28]

Micromed. *Bipolar Forceps Angled*. [Online image] http://www.micromed.com/media/bilder/Bipolar-forceps_angled.jpg [2015-04-29]

Nascent Surgical. (2015a). *From First Sketch to Finished Product*. http://nascentsurgical.com/first-sketch-finished-product/ [2015-04-22]

Nascent Surgical. (2015b). *Distrubution Agreement Brings miniSQUAIR to European Union*. http://nascentsurgical.com/distrubution-agreement-brings-minisquair-european-union/ [2015-04-22]

Olander, L., Conroy, L., Kulmala, I., Garrison, R.P., Ellenbecker, M., Biegert, B., Fletcher, B., Goodfellow, H.D., Rosén, G., Ljungqvist, B., Reinmüller, B., Dumas, A., Robinson, M., Ingham, D.B., Lommel, A., Tsuji, K., Welling, I. & Wen, X. (2001). Local ventilation. In: Goodfellow, H. & Tähti, E. ed. *Industrial Ventilation Design Guidebook*. Academic Press, pp. 807-1023.

Safeair. *Safeair Smoke Pencil*. [Online image] http://safeair.ch/wp-content/uploads/smoke_pencil_page1.jpg [2015-05-04]

A Drawing of test room

The area of the test room was 11.7 m² (3x3.9m) and a ceiling height of 2.7 m. The LAF ceiling had an area of 2.4 m² and a suspension of 0.3 m. Each exhaust opening had an area of 0.07 m². See figure for more details of the test room.

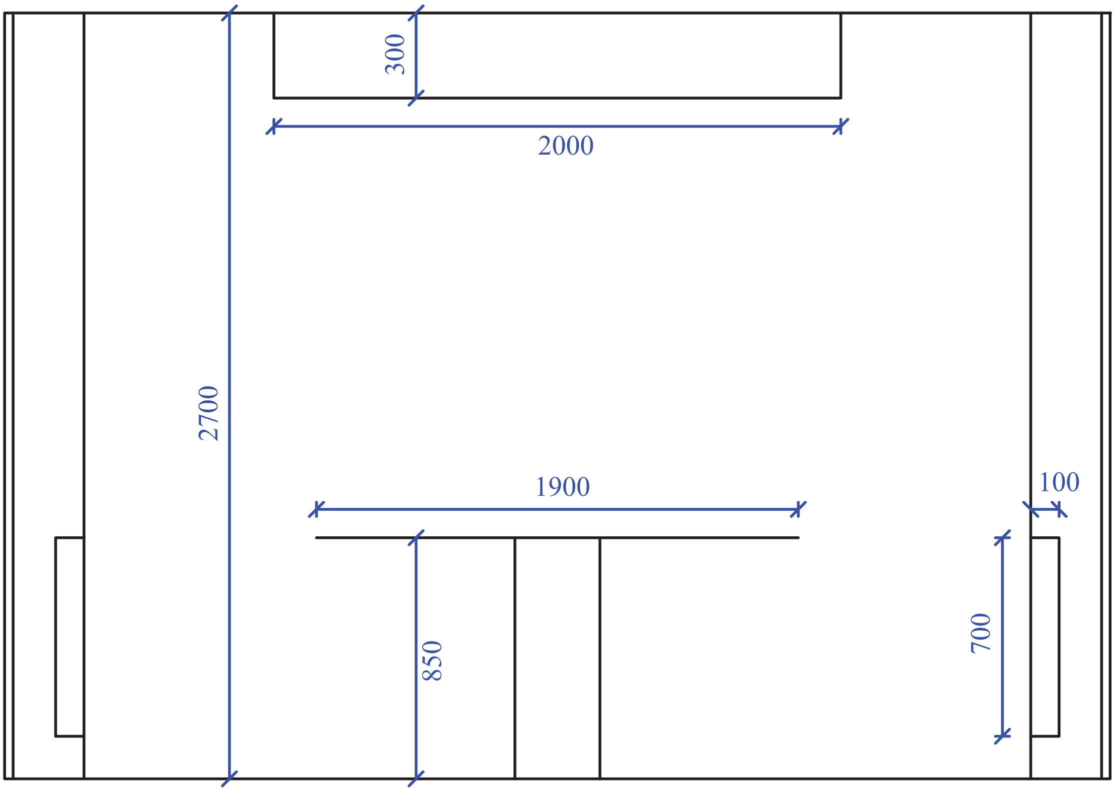

Figure 49 Drawing of test room seen from side. Units in millimetre.

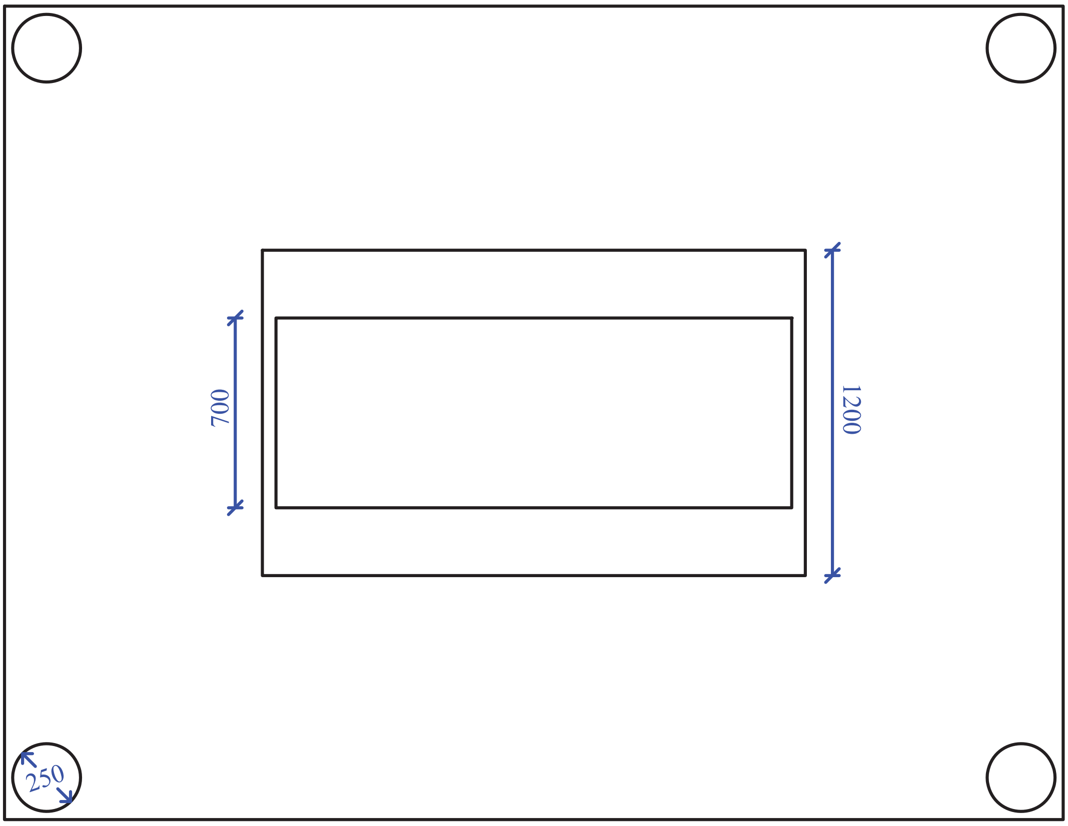

Figure 50 Drawing of test room seen from above. Units in millimetre.

B Sketch of measuring grid for capture velocities