BACHELOR

Plasma plaster
beginnings of something great

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Bachelor End Project

Plasma Plaster

Beginnings of something great

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Abstract

Infection of newborn babies during IV treatment is a common problem in hospitals, possibly with serious or even deadly consequences. The treatment of infections with medical plasmas is a field of study that has experienced increased interest for the last years and might provide a solution. The objective of this research is to design an early version of a device called a 'plasma plaster', that can disinfect wounds caused by IV treatment on newborn babies and to research the characteristics of plasma produced by such a device. A prototype setup was designed after a literature research on several different geometries that were deemed appropriate for the set objectives. A parallel plate electrode configuration separated by a dielectric, capable of producing dielectric barrier discharges was made in the laboratory. Chemical composition within the plasma, power dissipation, voltage and current characteristics and UV intensity were determined by measuring the output of the plasma: emitted radiation and electric characteristics like voltage over the electrodes and the current passing through.

The research brought the following results. Intensity of the plasma is much higher when the electrodes are attached very tightly to the dielectric. The surface distribution of the plasma is also much more homogenous. Using meshes with smaller diameter wire as ground electrode in the setup makes for plasma forming at lower voltage input and higher plasma intensity. An inverse relation was found between the wire diameter and the ratio of plasma intensity and input voltage. This was also seen when comparing the breakdown voltage to the wire thickness. Using meshes made of different materials makes for plasma with different intensities. Breakdown voltages varied between 4,9 kV and 6,5 kV. An ITO plate wasn't suitable due to the thick glass, the high dielectric constant and thickness caused no plasma production. Flexible printed circuit boards were tested and also produced plasma. Overall plasma was easily produced using this plasma generator. UV radiation emission of one treatment session is too low to cause damage to the skin. The UV-index was lower than the standard set up by the WHO, one order lower than the lowest standard. The early plasma plaster can maintain operative for 18 minutes in one continuous session.

In order to produce well working plasma when using the plasma plaster, future research should minimize distance between electrodes and dielectric and ensure a tight attachment between electrodes and dielectric. If future designs of the plasma plaster are to use meshes as ground electrodes, they should be comprised of wires with a small diameter to make for a higher intensity and a lower, and thus safer operating voltage. The optimal wire diameter is yet to be researched though. Making use of iron meshes doesn't seem to be more favorable than using aluminum or brass. Other, possibly even more favorable materials are to be investigating by future researchers. Although UV radiation levels are not high enough to damage human skin during one treatment, caution is advised when using the plasma plaster multiple times in succession on the same patient, especially on the thin skin of newborns as UV radiation may damage the skin in the long run. This is to be researched in the future. The durability of the plasma plaster is such that it can survive one treatment easily. Effects of multiple sessions are to be investigated. Plasma plaster has shown signs of potential viability for medical use: Lifetime is longer than most disinfection times, the electrodes and dielectric can be made flexible and some important radicals are present.

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1. Introduction

In the world of medicine, an infection is never good and a lot is done to prevent it. When an infection is not prevented bigger issues arise. Patients with already weak immune systems can have deadly effect from these infections.

An example of an especially weak patient is a newborn. Such babies have weak immune systems and can possibly die from infections. Prematurely born babies always need IV therapy (inserting fluids directly into veins trough tubes) in order to stay alive. The needle used to enter a vein creates an opening in the skin. Bacteria exploit this to enter and infect the newborn. Disinfecting once is not enough, over the period of time of the IV therapy bacteria can return. To counter this, the skin has to be disinfected regularly as to counter the return of bacteria and making sure none can enter the body. By preventing infections newborns will have a higher chance of survival.

A relatively new method to disinfect skin is with the use of plasmas. Plasmas are already used to cleanse and disinfect. Using plasmas on human skin can be dangerous: Plasmas can have temperatures of over 100 °C, can emit radiation of every wavelength and can create radicals and chemicals. All these products and properties are potentially dangerous for patients and have to be eliminated if this method will ever be viable. Cold atmospheric plasmas (CAPs) eliminate some of these arguments; as the name suggests, they are relatively cold and can be used close to the skin.

To accomplish this, a device has to be designed that meets all criteria. This device, the plasma plaster, will be a sort of patch that will be applied to the skin. In the space between the patch and the skin plasma will be made by using high voltages hereby creating a dielectric barrier discharge. This plasma should disinfect the skin when needed.

This work focuses on investigating the viability of the plasma plaster and characterizing the plasma made. The design phase will initiate with research on other similar devices and the contemporary use of CAPs in medicine. Especially works that focused on plasma sterilization were addressed.

Firstly, we will make a literature research about related subjects. The biological effects, mainly bactericidal, of cold atmospheric plasmas will be addressed. The effects of this on human skin will also be discussed. For this we need a better understanding of plasmas and especially its production of chemicals, this will also be addressed. Air is used as ionizing agent due to practical reasons and its bactericidal effects.

This report will be used to help design the plasma plaster. The literary research is done to design a first concept. Design boundaries and the final result will be presented. By using this concept design and advice from other professors an early model of a device was made to experiment with. More on this model can be read in the section 'Experimental Setup'. To explore the aspects of the plasma plaster different sizes, flexibility and transparency will be experimented with. These experiments will give birth to a better understanding of the mechanisms of the plasma at hand. To fully exploit these, the results of these experiments will be discussed. This will lead to recommendations for future research in this field.

1.1 The problem

As stated above newborns are very fragile in the first phase of their lives. To sustain these children IV's are inserted to supply them with necessary supplements to enhance their chances of survival. Unconditionally IV's create an opening in the human skin to the outside world. This is done with utmost care in respect to bacteria. The opening is standard carefully sealed by Tegaderm, a transparent dressing that will adhere to skin and protect the wound from the outside world. This dressing is necessary and is widely used and regarded standard for IV related openings of the skin [1].

Sometimes bacteria still creep through these safeties and make their way inside the newborn baby's body. The babies are extra susceptible for diseases and will have a higher chance of dying from this. This is an inevitable effect that contributes to the mortality numbers among newborn babies. If the bacteria can be denied passage or destroyed many babies can be saved.

Today a lot less mortalities occur under newborn babies due to higher hygiene standards in hospitals [2]. So in order to contribute to this already growing prospect in reducing newborn mortality the Plasma plaster has to be cheap in production and easy in use.

A plasma that is approved by medical standards has to be created that can be integrated in the currently used methods and is able to destroy enough bacteria to prevent infection. Our idea is to create a patch that can enclose the catheter entry site and create plasma close to the surface. This will ensure the destruction of pathogens and a comfortable fit. Currently used methods like the use of Tegaderm have to be taken in the consideration of the design to make sure it fits perfectly in the current process. The numerous other devices used to monitor and help the newborn baby around a Neonatal Intensive Care Unit (NICU) should also be taken into account. Low frequency signals (especially radio frequencies) tend to disrupt the surrounding devices; producing plasma in air is usually done with these frequencies. Disruption of other devices is a challenge that has to be dealt with once the concept has matured more.

2. Background

2.1 Bactericidal effects

The use of plasma for disinfection is a relatively new field of science [3]. There is still a lot unknown and not yet confirmed. However the bactericidal effects are confirmed [3]. To give an indication of time, a wound can be disinfected in 1-2 min [4]. A lot of factors determine the plasma's capability of decimating bacteria. These effects of plasmas are derived from its products: Chemicals (radicals and other molecules; the plasma cocktail), electric fields, heat and radiation. The mixed effects of all these products make it hard to single out effects of one. These products are also traditionally used to inactivate bacteria:

One of the properties of plasma is its heat. Heat can be used to destroy bacteria. By increasing the temperature most bacteria are destroyed. Contemporary medicine uses heat to disinfect, but only instruments not skin.

In contrast, products similar to the plasma cocktail are still used extensively today in the form of medicines. The plasma cocktail of chemicals produced by plasmas are a lot different from contemporary medicines but can be equally potent. These reactive species (RS) have various effects in the cell's regulatory systems. Positive as well as negative effects have been observed. The major problem is the applied dose; to create plasma that can produce controlled doses of its chemical cocktail is a big challenge [3].

Eto *et alia* [5] showed that different mixtures of airlike gasses (N_2 and O_2 mixtures) give different results. While changing little, the disinfection time can be doubled. They also showed that air is a good gas mixture for disinfection, especially humid air. This is due to the RS created in this gas. The N_2 and O_2 in the air can create radicals like O, O_3 and NO. By adding water (humid air) other RS like OH, H_2O_2 and HNO_3 can be created. These all participate in different aspects of the cell's regulatory systems, the precise effects heavily depend on the concentrations of the individual and combination of radicals. For example, low concentrations of NO have inflammatory effects while high concentrations contribute to cell destruction [3].

Last, radiation can also be used to disinfect. It is usually too dangerous to use radiation to kill bacteria. A high dose is needed that can also cause cancer and other side effects. UV-light is used to disinfect non-living objects like water, the light attacks cell walls and DNA [3]. Xinpei Lu *et al.* [6] showed that UV radiation and heat usually don't contribute much to the bactericidal effect of plasmas in comparison to the chemical contribution. This is due to the low amount of power used: there is usually not enough heat production and radiation production to create damage in one treatment. Damage done by multiple sessions can produce problems.

Creating plasma and using high voltages creates electric fields. Electric fields with short pulses (ns) can cause cell apoptosis (self-destruction) in bacterial cells. This shows that short pulsed electric fields can also disinfect. [3]

From the previous we can conclude that the main bactericidal agent is the plasma cocktail of radicals produced by the plasma. This will be taken into account for the design for the plasma plaster. If the chemicals are the most important bactericidal agent then the used gas for the plasma is highly important. Air will be used as an agent to create plasma. This way no external gas flow is needed and as stated above, air is an excellent agent to create disinfectant plasma.

2.2 Effects on human skin

By using plasmas that are full of radiation, the plasma cocktail, electric fields, heat and high voltages damage to the skin seems imminent. These factors should be carefully investigated and measured for this kind of treatment to reduce damage. To avoid this damage, cold atmospheric plasmas have been a subject of research in recent years. This is a non-equilibrium plasma; the electrons carry more energy than the ions and therefore the bulk temperature is relatively cold (30°C). This leaves little damage to the skin. Numerous experiments have been performed to measure the effects of these factors on the human skin [3], this was all done with low power plasmas. Finding the balance in disinfecting and not damaging the skin is very important here.

As an indication: It is shown by Fridman *et alia* [7] that exposure to a certain CAP for 5 minutes shows no short term visible damage to the skin, it even contributes to tissue regeneration. This is not representable for all plasmas but shows the possibilities. Another study on using a plasma source to disinfect hands before an operation also concluded the disinfectant effects (Morfill *et alia* [8]). One of the biggest challenges is the needed dose: it needs to be high enough to destroy the pathogens but not damage the skin. In general bacteria are more susceptible to the effects of CAPs than the skin thus are destroyed before permanent damage is done. However the quest for this equilibrium and the optimal plasma has to be found again for every setup of plasma and bacteria.

The plasma cocktail produced by the plasma differ when using different gasses. It is hard to determine the effects of a single chemical product. So overall measurements are done and as shown by Eto *et alia* [5] humid air has different effects on certain bacteria than dry air. Ozone and H_2O_2 are also produced in humid air and are highly reactive. Because of this these radicals are important. H_2O_2 can stimulate wound healing and can destroy bacteria. Too high concentrations and it will damage the skin [3]. By interacting with the cell wall and DNA of the bacteria the plasma cocktail can destroy bacteria and disinfect wounds [3].

Ozone can disinfect but it is also a toxic to humans when the inhaled dose is high enough. Only low ozone concentration can be accepted, otherwise damage to the patient can be done. One advantage is that ozone degenerates rather quickly. The exact time varies from 40 minutes to 40 hours. It depends on several factors; presence of H_2O and good ventilation (spread of ozone) seem to speed up ozone degeneration [9]. When the ozone is kept away from the newborn it can degenerate while posing no threat to the newborn. Another unwanted effect is that ozone reacts with more than the wound; this gives unwanted side effects. It can deteriorate some plastic by reacting with its surface.

Besides chemicals and heat also a high voltage is used. By creating a high voltage near skin a discharge could occur between the electrode and the skin. This would destroy cells and leave a burn wound. Especially in the case of newborn babies this should be avoided at all cost.

Electric fields have different effects on living cells: It seems to govern the direction in which cells grow and improve cell regeneration. Also the transport processes of ions in the cells are altered due to the electric force. If the electric field produced by the plasma plaster has any of these effects isn't known

2.3 Dielectric barrier discharges and gasses produced

2.3.1 Dielectric barrier discharges

Dielectric barrier discharges, or DBD's for short, is a discharge that is made by creating a high voltage between two electrodes where one or both of the electrodes is shielded by a dielectric barrier, which is an insulator. A DBD is a low-temperature non-equilibrium discharge. This means the gas temperature and electron temperature inside the plasma aren't the same. These temperatures can differ almost a factor 10^3 in K. The gas temperature dictates the heat content whereas the electron temperature dictates disassociation and the amount of radicals (reactivity). As a result the plasma is relatively cold, near room temperature. DBD's can be produced at atmospheric pressures. This way no pressure chambers have to be used in the experimental set-up and make it easy to use on humans.

There are many different arrangements possible and used as shown in figure 1. One of the key aspects is that DBD's can be made quite simply by creating a high enough AC voltage (3-25 kV) and ensuring no direct current can run between the electrodes. The discharges will eventually produce a net current. DC current will destroy the setup simply because the charge buildup will be too great and a discharge will break the dielectric. The frequency and waveform of the signal is also important; this is usually 50 Hz to 10 kHz [10].

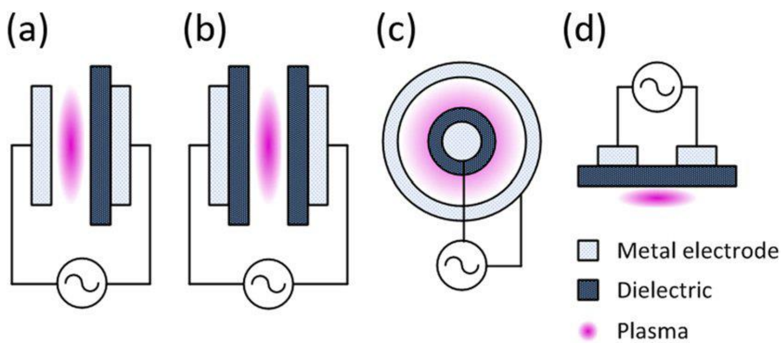

Figure 1: Various DBD configurations such as (a), (b) parallel plate (c) coaxial and (d) coplanar. [11]

A DBD can manifest in a spectrum of discharges. A general dissection of this spectrum is made in two: diffuse discharges and filamentary discharges. When plasma discharges diffuse a cloud of plasma is created, this is also called glow discharge. This creates more homogenous plasma and a uniform discharge. In practice it is hard to achieve this at atmospheric pressure and most DBD's run in filamentary mode. There are however examples of atmospheric diffuse discharges [10]. In filamentary mode many ultra-short (ns) discharges are produced [12]. The filamentary discharge is initiated by high electric fields. This leads to rapid collision ionization (ripping electrodes from nuclei) and thus high electron densities at the high fields. These electrons will ionize its surroundings fast in the direction of the other electrode. Streamers will travel from one side to the other, ionizing molecules and atoms in its path. Immediately afterwards the remaining charge in the dielectric will negate the high electric fields locally and hereby stopping the streamer. When the polarity reverses and the electric fields are high enough for breakdown new streamers will be generated. These are affected by the charge depositions of the streamers created in the previous cycle.

2.3.2 Gasses produced

Air is a complicated mixture of gasses. Air consists of 78% of N_2, 21% O_2 and 1% noble gasses, H_2O vapor, CO_2 and more. When the air is humid, other radicals can be formed due to the presence of H. Radicals like H_2O_2 and HNO_3 can form in this humid air and have their unique effects. By creating plasma in the air, energy is put into the air. This causes molecule bonds to break and new gasses are formed and have their effect on their surroundings. Typically, plasma created in the open air mostly produces O, O_3 and NO. This is as expected from the high concentrations of N_2 and O_2 in the open air [13]. Most of these products are not stable i.e. they are very reactive.

When the air is humid even more reactions can take place. The most common is the production of OH^-, which is a very reactive radical. It seems this also contributes to the disinfection rate as shown by Eto *et alia* [5] and Hähnel *et alia* [14].

2.4 Flexible Geometries and Materials

The need for flexible geometries comes from the human being. The human skin is curved and everybody's skin is curved differently. The flexible geometry will make sure the distance of the plasma to the human skin can remain roughly the same. By doing this the treatment can be applied homogenously over the skin. This is very important because the balance between destroying bacteria and destroying the skin is very delicate; if on one point the plasma intensity is much higher the risk of damaging the patient becomes higher.

Flexible geometries bring with it various challenges. The materials that we use have to be flexible and still have their normal attributes. A flexible design has to produce similar results as a rigid design. Flexible electronics are a challenge, making HV contact points and creating a safe device is a top priority. There are companies specialized in printing electronics on flexible surfaces, like Würth Elektronik. By using their expertise a working model can be achieved more quickly.

The total of materials also needs to be transparent. This is a design boundary that came forth from interviews with doctors. Doctors need to have clear vision of the entry point as to see the first signs of infection on the entry wound to take precautions. This means the plasma plaster needs to be transparent for visibility. This can be done by using meshes, clear plastics and a layer of ITO that can conduct electricity.

3. Design

3.1 Concepts

Two concepts were made for this experiment considering the problem and with regard to the research. A coplanar design was made: this is a design where the two electrodes are in the same plane on the dielectric. The high electrical field lines created that also run to the mesh can create plasma at the mesh. Second, a parallel plate design was made: this is a design where the mesh itself is part of the circuit and grounded. The mesh is one of the plates and the HV electrode is the other, both of them will be parallel; thus a parallel plate design. We will focus our research on the parallel plate design. We chose this concept due to the time available and the simplicity and reliability of this concept. The coplanar design is certainly worth investigating: in one of our talks with dr. ir. A.J.M. (Guus) Pemen the potency of this design was discussed and Guus was excited over its possibilities.

3.1.1 Coplanar design

The design shown in ***Figure 2*** is one of the two concepts. This concept is somewhat more complicated in terms of electric field. Both are in the same plane on top of the dielectric. The electric field lines will mainly run between these electrodes but the presence of the metal mesh will certainly have its effects. Under the patch a closed bubble is created, here the created plasma cocktail will be directed at the entry and interaction with other parts will be minimized. This way the dangerous radicals of the plasma cocktail can safely decay so nothing can be inhaled or damage other parts. The ionization will be primarily formed at the mesh wires. Here the electric field lines created by the electrodes will curve greatly (field lines have to be perpendicular to a conductor). The curvature and strength of the electric field ensures ionization of the air. When the air is ionized and plasma created in between the mesh wires, deposition of radicals can start.

An advantage of this design is a physically built in failsafe. When you approach the gaps as capacitors and take a look at the electrical circuits something happens: the voltage over the mesh and the skin is inversely proportional to the distance between them ($C = \frac{\epsilon_r \epsilon_0 A}{d}$ capacitance gets lower, so does the voltage difference). This way if the mesh comes too close to the skin no discharge can be made, which is a failsafe for discharges.

One of the downsides is the indirect creation of plasma, the field lines don't run directly to the mesh. It may take more electrical power before plasma is created. Also there is a possibility of creating plasma on the outside of the plasma plaster. These two effects create a higher risk for the patient. The indirect creation of plasma can also lead to lower plasma production. This can extend exposure time, this leads to higher health risks. Another risk is a discharge between the electrodes; this can damage the system and the patient. The distance "d" can be created by using a hard plastic of some sort to ensure space for the plasma to be created. Also the IV that is inserted under the patch will create some space for the plasma.

Not much is needed to make this design flexible. When the right materials are chosen the plasma plaster can have enough flexibility. Electronics aren't a problem when using the techniques of Würth. The electrodes and dielectric can be made from flexible metals (meshes, aluminum tape and plastics).

3.1.2 Parallel plate design

The other design made is shown in ***Figure 3*** it differs slightly from the former. Here the mesh is grounded and not an outside electrode. This ensures that charge buildups on the HV electrode are discharged on the mesh and not the skin. The electric field lines will mainly run between the HV electrode and the grounded mesh. Under the patch a closed bubble is created, here the created plasma cocktail will be directed at the entry and interaction with other parts will be minimized. This way the dangerous radicals of the plasma cocktail can safely decay so nothing can be inhaled or damage other parts. The ionization will be primarily formed at the mesh wires. Here the electric field lines will curve greatly (field lines have to be perpendicular to a conductor). The curvature and strength of the electric field ensures ionization of the air. When the air is ionized and plasma created in between the mesh wires, deposition of radicals can start.

In this design the patch also needs to be a distance "d" from the skin; this is to ensure the skin is a safe distance from the plasma and also to give the plasma space to be created. The electronics of this design are relatively simple and almost all electric field lines will be directed to the mesh. This ensures plasma creation at lower voltages than the first design. This geometry also ensures that discharges are primarily created between the electrode and the mesh inside the dielectric. This is to ensure the safety of the patient.

A downside of this design is that the top electrode totally covers the top: when a not transparent material is used visibility for doctors will be zero. Doctors won't be able to see the first signs of infections if they do not have vision of the entry wound. The coplanar design could be made as to give visual on the entry wound. This is a challenge but certainly not unsolvable. This design also has a failsafe, the grounded mesh. Still if the mesh comes close to skin and a discharge occurs, the heat and charge produced could still affect the skin.

Not much is needed to make this design flexible. When the right materials are chosen the plasma plaster can have enough flexibility. Electronics aren't a problem when using the techniques of Würth. The electrodes and dielectric can be made from flexible metals (meshes, aluminum tape and plastics).

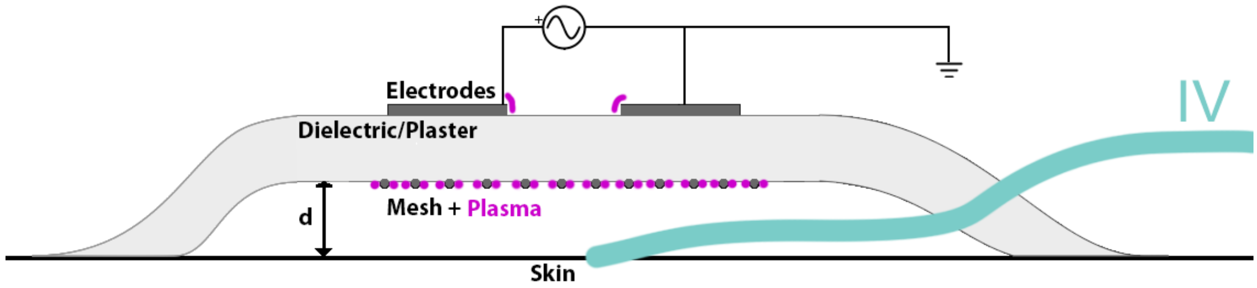

Figure 2: schematic view of the coplanar design and its electrical circuit. The pins on the side illustrate that there must be a finite distance "d" between plasma and skin. The plasma on the top side is only hypothetically, tests should be made to confirm this.

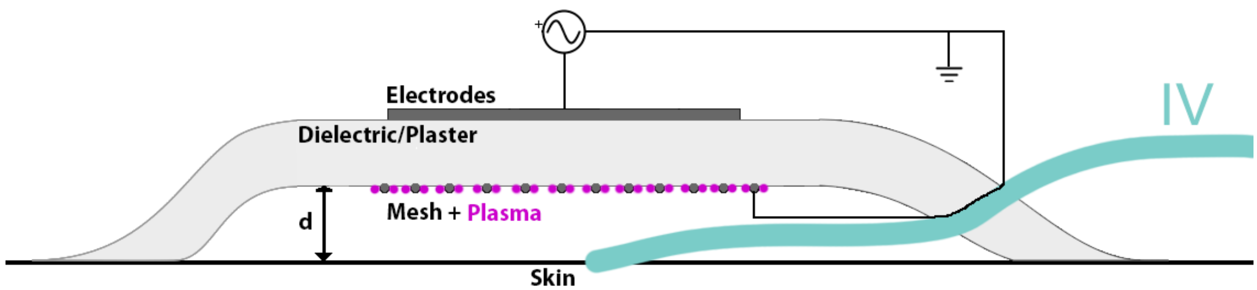

Figure 3 : Schematic view of the parallel plate design and its electrical circuit. The pins on the side illustrate that there must be a finite distance "d" between plasma and skin.

4. Experimental Setup/Method

4.1 Main setup

The purpose of these experiments is to determine the characteristics of different kinds of electrodes and dielectrics that can possibly be used in a plasma plaster and of the plasmas that are formed using these electrodes. Characteristics like breakdown voltage, chemical content (the plasma cocktail's contents), intensity, power usage, voltage and current characteristics and UV intensity. These characteristics are determined by measuring the output of the plasma: emitted radiation and electric characteristics like voltage over the electrodes and the current passing through. Using these characteristics, the plasma can be generally characterized.

The setup consists of a power supply, two electrodes, a dielectric barrier, a voltage probe, a current transformer, an oscilloscope, a spectrometer and a laptop. This is schematically shown in *Figure 4*.

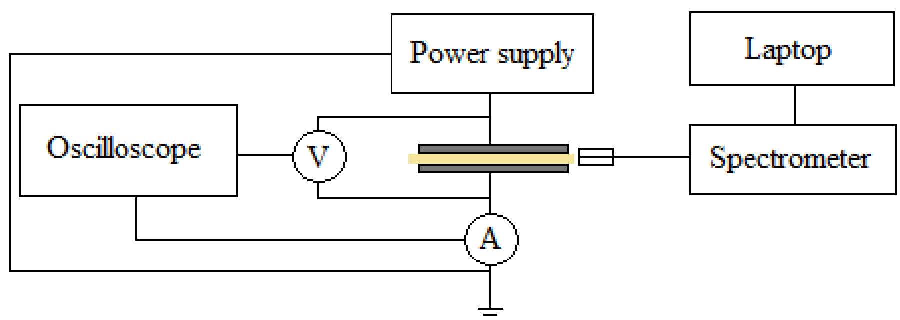

Figure 4: Schematic overview of the experimental setup.

With this setup two aspects of the produced plasma could be investigated: The emitted spectrum and the electrical properties. The plasma source itself was setup as simple as possible. With this main setup several experiments were performed while only changing minor aspects. Primarily the plasma source was altered. The Voltage meter was applied directly to the plasma to measure the voltage over the electrodes. The current meter was placed directly behind the electrodes; this is to minimize measuring leak currents that occur at the top side. Here these currents dissipate into heat and charge buildup.

The power supply used was a PVM500 plasma driver from www.amazing1.com. This is a power supply designed for plasma display/to experiment with plasma. The electrical power/voltage output was hard to control; turning one knob had effect on all of them. Frequency, voltage and electrical power were hard to keep constant. Frequencies of the applied voltage were kept constant as far as the power supply could.

The oscilloscope used was a DSOX2024A oscilloscope by Agilent Technologies. This oscilloscope could cope with the high frequencies. A voltage probe and current probe were used to measure the voltage and current with this oscilloscope.

The spectrometer used was an AvaSpec-ULS2048LTEC by Avantes. Its range was 200nm to 750nm. The Sensitivity was 470.000 counts/(µW*ms). An optic fiber was connected to its opening for measuring. The opening of the fiber was directed at the underside of the plasma, the distance between fiber and plasma was kept constant: the fiber was always inserted fully in a hole in the underside. Any deviation due to stretch and small vibration were not accounted for.

The whole setup is schematically shown in *Figure **5***.

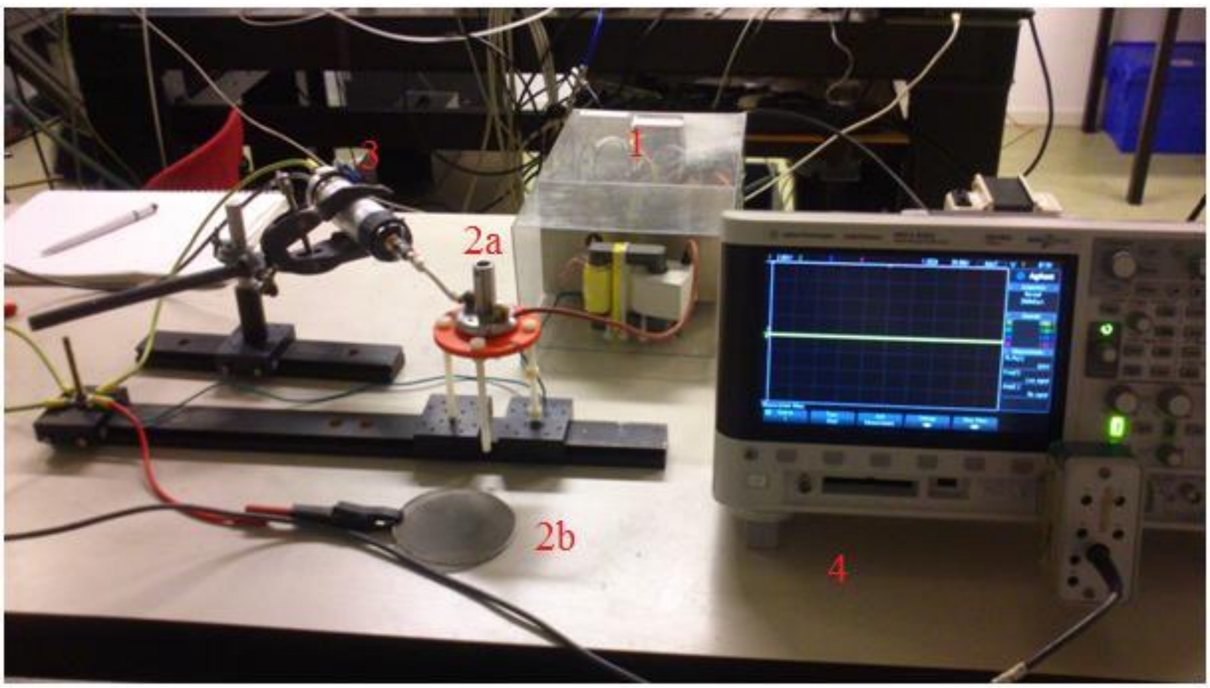

Figure 5: Experimental setup; 1: Power supply, 2a: High voltage electrode, 2b: Grounded electrode, 3: Voltage probe, 4: Oscilloscope.

4.2 Ionization or not?

To explore if our setup was viable and worked for different meshes ionization was tested. Different meshes were used as ground electrodes. Different materials and wire thicknesses (ranging <0.1 mm to 0.3 mm wire thickness) were used to research differences between meshes. First a round of testing the parallel plate design for feasibility. This to test if this is a feasible design to produce plasma at the voltage and power we were able to create. This while not producing discharges or other dangerous effects. The meshes can be seen in *Figure **6*** sorted on mesh width. These meshes were inserted in the setup as seen in *Figure **7***.

Figure 6: Used meshes of different gap widths and wire thicknesses. From left to right will be numbered mesh 1 to mesh 5

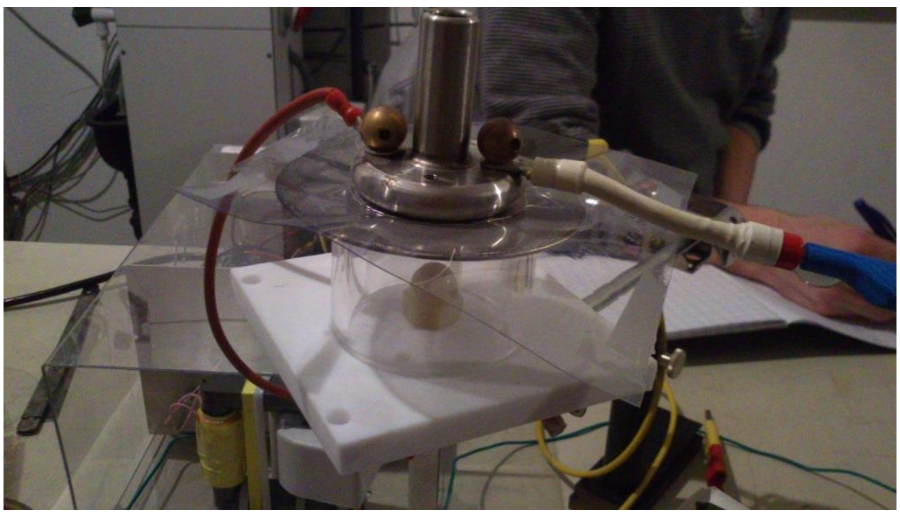

Figure 7: Dielectric barrier setup: On top a high voltage electrode (with HV connection and voltage probe), below that a dielectric and at the bottom the grounded electrode.

This setup consisted of clear PVC as dielectric, a mesh as bottom electrode (grounded) and a big HV electrode. The big electrode should be flat in further experiments but for the sake of practicality this was used. But to still maintain the same effect aluminum tape was stuck on the up side of the plastic as seen in *Figure **8***. This way the electrode only served as a conductor. Aluminum tape is aluminum in a roll with a special adhesive that also has conductive properties. Using the aluminum under the big electrode affects the setup less; One potential over the surface is maintained as well as the same shape as top electrode. The big electrode only serves as a medium to interconnect all the wires. The top electrode as a whole has little sharp edges; no discharges on the top side are produced this way. A downside is that the top electrode is able to absorb heat, which decreases the temperature at the aluminum tape. We also experimented with using the aluminum tape as the only connector as seen in *Figure **11***. The whole was connected into the main setup as seen in *Figure 4*.

Figure 8: Aluminium tape stuck to a plastic sheet. The tape is the high voltage electrode and the sheet is the dielectric barrier.

With this setup different meshes were connected to HV. This to test if this is a feasible design for the reasons mentioned at the beginning of this section. Also different plastics were used and even an ITO (clear conducting material) plate (as seen in *Figure **9***) to test their feasibility of the same aspects (see *Table **2***).

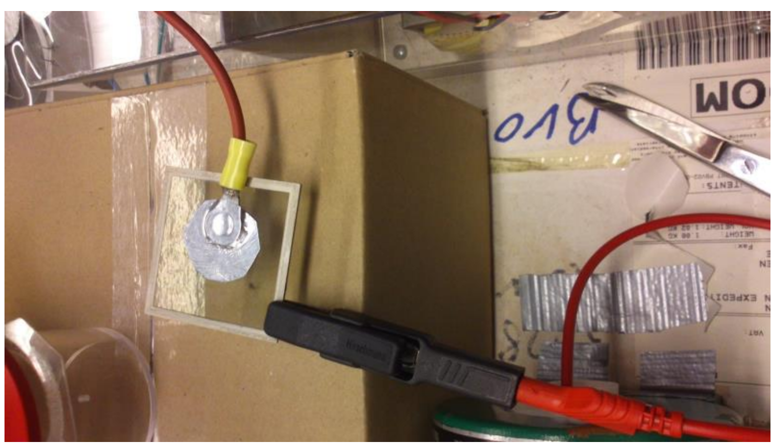

Figure 9: Connecting the ITO to the main setup using aluminum tape.

Also experiments were conducted with a strip of a Twinflex circuit board made by Würth Elektronik. This flexible circuit board was printed on a thin (>0.075 mm) dielectric (polymide with coverlay). One side was aluminum tape serving as the HV electrode and the underside was the flexible electronics. It was connected as seen in *Figure **10***.

Figure 10: Connection of the flexible electronics strip to the main setup.

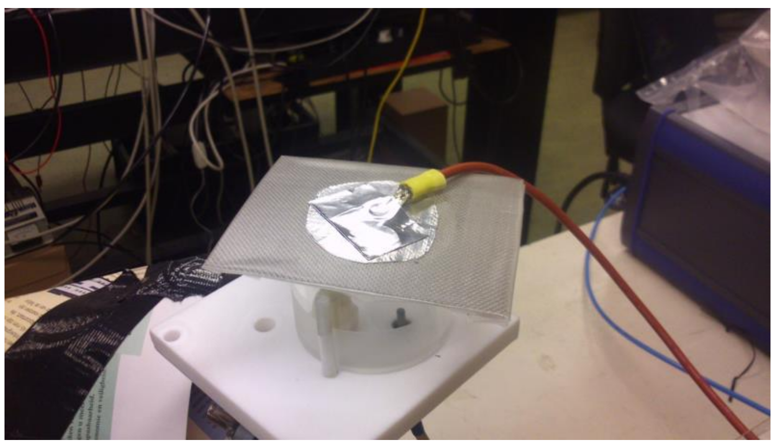

Figure 11: Example of a high voltage electrode - dielectric barrier - ground electrode combination with a flat electrode.

4.3 Calculating the power dissipated in the plasma output

For these measurements a set of standardized meshes different from those in the previous section has to be used. A set of stainless steel meshes (same material and fabricator) with one type of plastic dielectric (laminate plastic) was used for this experiment so that the conditions for all meshes were the same. Only the wire thicknesses (and gap distances) differed. These were produced by cutting the meshes the same size and then laminating them; this ensured that all layers stuck on each other, the aluminum tape, dielectric and mesh. This mesh dielectric combination was incorporated in the main setup. The frequency of the input voltage sine was kept constant for these meshes. The behavior of the voltage over the electrodes, produced current behavior and produced radiation were carefully measured for these 5 meshes. Note that the 0.34 mm mesh had a different weaving and a bigger gap width.

Table 1: Specification of the set of standardized meshes as mentioned in Figure 6

Mesh wire thickness (mm)	Gap width (mm)
0.40	1
0.34	2.2
0.22	1
0.15	0.56
0.14	0.45

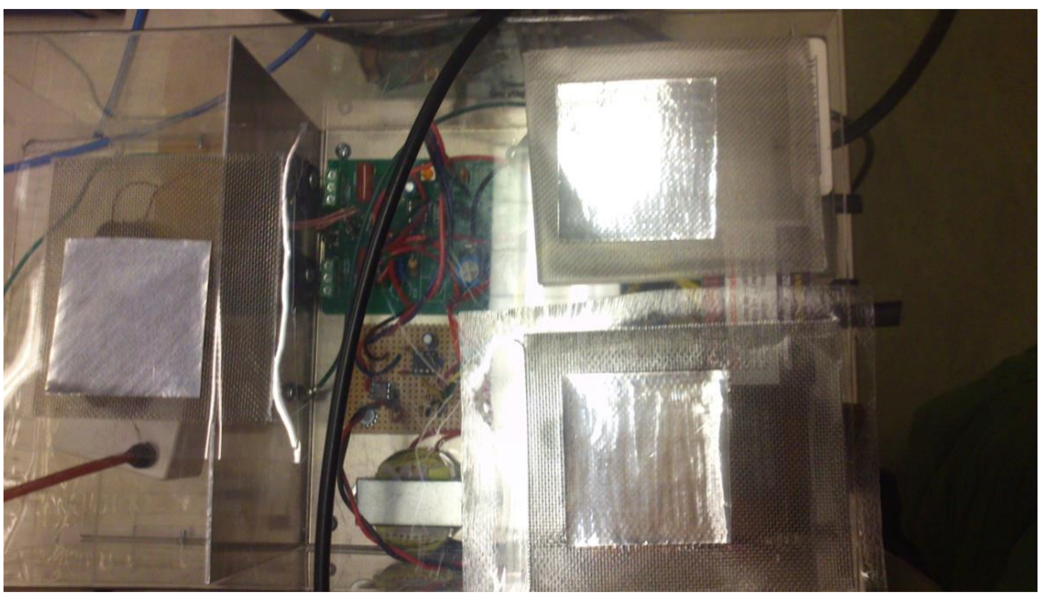

Figure 12 Laminated meshes with aluminum tape as high voltage electrode.

5. Results

Firstly we tested the feasibility of different combinations of materials as stated in the method. The produced plasma was observed and measured. Next the set of standardized meshes (*Table 1)* were used to produce plasma. Voltage characteristic diagrams were measured and other diagrams were made to visualize the electrical characteristics. Here we will put extra focus on calculating the power dissipated by the plasma. After that the measured frequencies of the radiation produced by the plasmas will be shown. After that the intensity and different wavelengths of the radiation produced by the plasma will be presented. Finally the maximum time the plasma is on before the plasma plaster breaks will be measured. The temperature of the plasma plaster will also be noted to check if the temperature is safe and not too hot for application on the human skin.

5.1 Ionization or not?

When using the first combination of materials, plasma was produced immediately. This was a great result; the simple design produced plasma quickly. We used different types of materials and geometries to test if this combination was able to produce plasma. Frequencies of the applied voltage were kept constant as far as the power supply could.

All setups produce plasma, the effectiveness however changes with different meshes and shapes. Also the flexibility of meshes plays a roll: If the whole of components aren't fastened together the plasma produced on the underside reduces. When a mesh is more flexible these effects occur more easily.

It is also seen that coarse meshes (wire thickness ≥0.34 mm) have an "on-off" behavior: Coarse meshes tend to show no variation in radiation intensity within the plasma itself. Fine meshes have variation in radiation intensity within the plasma. Fine meshes also create plasma easier but the intensity is usually lower, see *Table **4***. All feasibility tests are collected in ***Table 2*** and *Table **3***.

Table 2: The different meshes that were used and their potency of becoming the plasma plaster.

Mesh Number	Mesh description	Dielectric description	Plasma description	Comments
Mesh combination 1	Mesh 1: Square (wire thickness ±0.4 mm, gap width 1,9 mm) made of brass	1.5 mm thick flexible PVC that is highly cleaned	Plasma is produced at the surface of the wires in the gaps between the wires. It is randomly distributed over all the gaps in the whole mesh. No significant difference in plasma intensity is seen across the surface.	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and loose from the plastic.
Mesh combination 2	Mesh 2: Square mesh (wire thickness ±0.2 mm, gap width 1,0 mm) made of aluminum	1.5 mm thick flexible PVC that is highly cleaned	Plasma is produced at the surface of the wires in the gaps between the wires. Plasma is higher in the gaps in the middle. Fewer gaps are lit towards the edges.	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and loose from the plastic.
Mesh combination 3	Mesh 3: Square mesh (wire thickness ±0.1 mm, gap width 0,4 mm) made of iron	1.5 mm thick flexible PVC that is highly cleaned	Plasma is produced further from the surface of the wires and occurs in the middle of the gaps. Plasma formation in the middle of the mesh is not present. This due to the electrode being placed in the middle and thereby changing the underling attachment of the layers.	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and loose from the plastic.
Mesh combination 4	Mesh 4: Square mesh (wire thickness under 0.1 mm) made of iron	1.5 mm thick flexible PVC that is highly cleaned	Plasma is further from the surface of the wires and occurs in the middle of the gaps. Areas of different plasma intensity can be seen. Plasma production occurs throughout the whole mesh.	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and loose from the plastic.
Mesh combination 5	Mesh 5: Round mesh (wire thickness under 0.1 mm) made of iron encircled by a thick border.	1.5 mm thick flexible PVC that is highly cleaned	Plasma is produced in the middle of the gaps between the wires. Areas of different plasma intensity can be seen following the curvature of the mesh. Layers aren't attached well to each other.	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and loose from the plastic.
Mesh combination 6, fastening dielectric with pressure	Mesh 3	1.5 mm thick flexible PVC that is highly cleaned	Visible plasma radiation is more intense and plasma surface is bigger than at mesh combination 3. Plastic tends to loosen from the mesh. The underling attachment is broken; this decreases visible plasma intensity	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and fastened to the plastic by pressing it in the plastic with high force
Mesh combination 7, fastening dielectric with pressure and heat	Mesh 3	1.5 mm thick flexible PVC that is highly cleaned	It is seen that visible radiation intensity and breakdown distribution of plasma increases when the layers are better attached underling. A discharge occurred when this method was used. The thickness of the plastic was decreased in the heating process	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and fastened to the plastic by pressing it in the plastic with high force and heating to ensure fastening.
Mesh combination 8	Mesh 3	0.2 mm flexible wrapping plastic with sticky side.	The sticky wrapping plastic connects badly to the mesh. The visible radiation intensity and breakdown distribution of the plasma is decreased in comparison to all other combinations	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and fastened to the plastic by glue
Mesh combination 9	Ultra-fine metal mesh. Gap width and wire thickness around 0,02 mm wire thickness and gap width	0.2 mm flexible wrapping plastic with sticky side. The PVC is too difficult to attach to the mesh.	Visible plasma radiation intensity is low in comparison to others but distribution of breakdowns is evenly over the mesh	On the plastic conducting aluminum tape is taped. This ensures no air gaps. Mesh is grounded and fastened to the plastic by glue

Table 3 : The different meshes that were used and their feasibility for use as the plasma plaster.

Mesh Number	Mesh description	Dielectric description	Plasma description	Comments
ITO	Glass plate with a conducting layer on one side.	Square glass plate of ±5 mm thickness	Originates from the edges at the end of the aluminum tape outwards. Only visible on the top side of the glass plate (where HV is applied). Large (1 cm) lightning like discharges were observed at the top side.	Aluminum tape is used to connect the HV connection to the ITO glass, a conducting strip on the bottom is used as ground
Flexible circuit board	Strip of brown plastic with conducting strips on one side of the strip.	Thin (<1 mm) brown plastic designed to protect the circuit board and prevent discharges.	Plasma is observed in between the conducting strips. Discharges occur from copper strip to copper strip. No variation in plasma intensity throughout the plasma is observed.	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. The mesh is connected to earth and highly fastened to the plastic.
Mesh combination 10 with flat electrode (only aluminum tape)	Same mesh as mesh combination 3	1.5 mm thick flexible PVC that is highly cleaned	Plasma is formed away from the surface of the wires. The distribution of plasma breakdown shifts more to the edges and is not visible in the center of the mesh. This due to the electrode being attached with aluminum tape and thereby changing the shape of the layers.	On the plastic conducting aluminum tape is taped. This ensures fewer air gaps in between the layers. Mesh is grounded and loose from the plastic. Little difference was seen with mesh 3. More heat buildup on the electrode (39°C).

For the standardized meshes the breakdown voltage was also measured. Other meshes were often too dependent on shape and how well all layers were fit together to measure one breakdown voltage.

Table 4: The breakdown voltages, the voltage were plasma starts to form, for the steel meshes are shown together with a description of the plasma and further development of the plasma.

Mesh wire thickness (mm)	Breakdown voltage (kV)	Plasma location	Plasma behavior at 10 kV
0.40	6.5	Mostly directly around the wires.	Plasma is visibly more intense and larger.
0.34	5.9	Mostly directly around the wires.	A little plasma appears in between wires.
0.22	5.2	Mostly directly around the wires.	Plasma appears directly around, in between and under wires.
0.15	5.1	Around and in between wires.	Plasma appears directly around, in between and under wires, although weaker now.
0.14	4.9	Around and in between wires.	Plasma mostly in between wires. Very weak plasma.

By plotting these measurements a relation between mesh wire thickness and breakdown voltage can be seen. This behavior seems quadratic, but can also be linear or exponential. More measurement points should be taken to determine this.

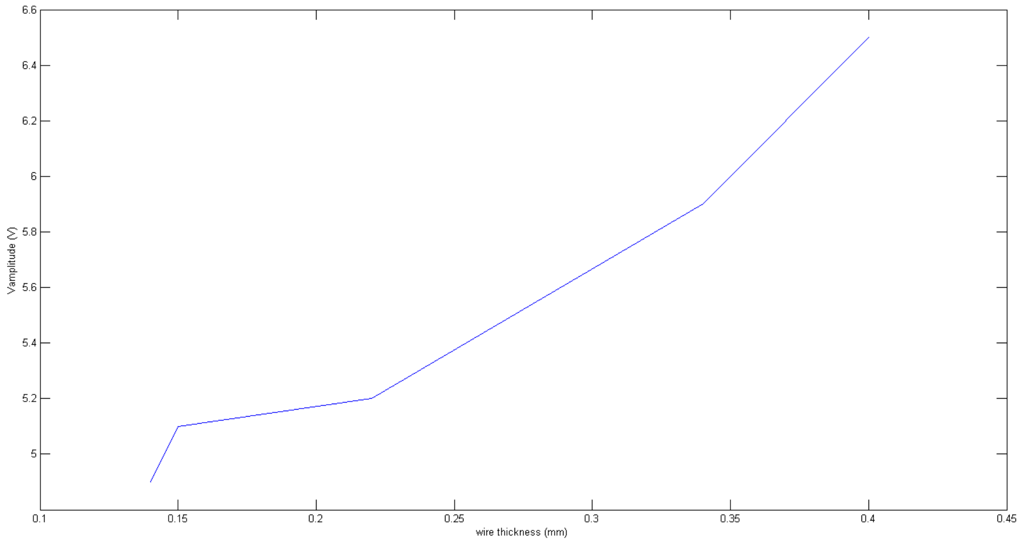

Figure 13: Graph of the breakdown voltage vs. the mesh wire thickness. Only a few measurements were taken. It can be approximated with $V = 23{,}17*W^2 - 7{,}14*W + 5{,}65$ where V is the voltage in kV and W the wire thickness in mm.

The reason for this quadratic behavior can be the relation between the electric field and the wire thickness. More research can point out the actual cause of this behavior.

5.2 Calculating the power dissipated in the plasma output

First the amount of losses dissipated in the system around the plasma has to be estimated. This can be done by calculating the power dissipated in the plasma output when there is no breakdown i.e., no plasma. The power dissipated in the plasma output is calculated by using the following formula:

$$P = f \oint Q * dU$$

Where *P* is the power dissipated in the plasma, *f* the frequency of the applied voltage, Q the charge on one electrode and *U* the applied voltage. This can be used to calculate the surface enclosed by a Lissajous curve (a system of parametric equations representing harmonic motion, in this case electric characteristics). This can be used to calculate the power dissipated in the plasma. The power dissipated in the plasma output while no plasma is on changes when different voltages and frequencies are used. With the current setup these couldn't be kept constant so only estimations could be made. It was determined that when no breakdown was observed the setup consumed 1 W of power. This will be used as a correction for further measurements.

The following graphs include figures to calculate power; charge buildup development versus voltage development and a current development versus voltage development. A good view of the evolution through time of different characteristics is also shown. The discharges (seen as spikes) are also important to consider. These were made for all the standardized meshes.

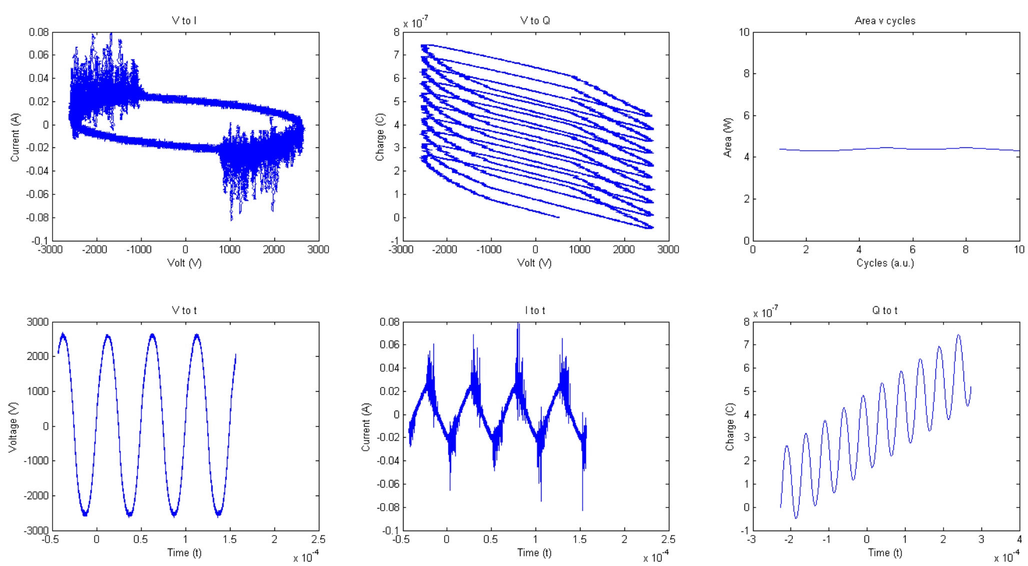

Figure 14: Electrical characteristics of a mesh with 0.40 mm thick wires. The area is the area inside the Lissajous figure, this is equivalent to the power dissipated in the plasma. The charge seems to build up; the equilibrium of the wave function rises

The discharges can clearly be seen in the current characteristic. The discharges are recognizable by sudden fast currents of charge, seen as high spikes in the current characteristic. The height is unknown; the changes are far too fast to be sampled correctly by the used oscilloscope (so >2 GSa/s).

There seems to be a rising charge on one of the electrodes. This is seen by a rising charge over the course of multiple cycles in *Figure **14***. This behavior over time is something that should be covered in future research.

It is important to check if the power dissipated in the plasma is constant over multiple cycles. This is to make sure that taking an average is allowed. It was already shown in *Figure* 6 but a clearer figure can be made. The following diagrams indicate the power dissipated in the plasma that is calculated by taking the area of the Lissajous figures and correcting for the estimated losses. The power dissipated in the plasma is constant over multiple cycles within 0.3 W.

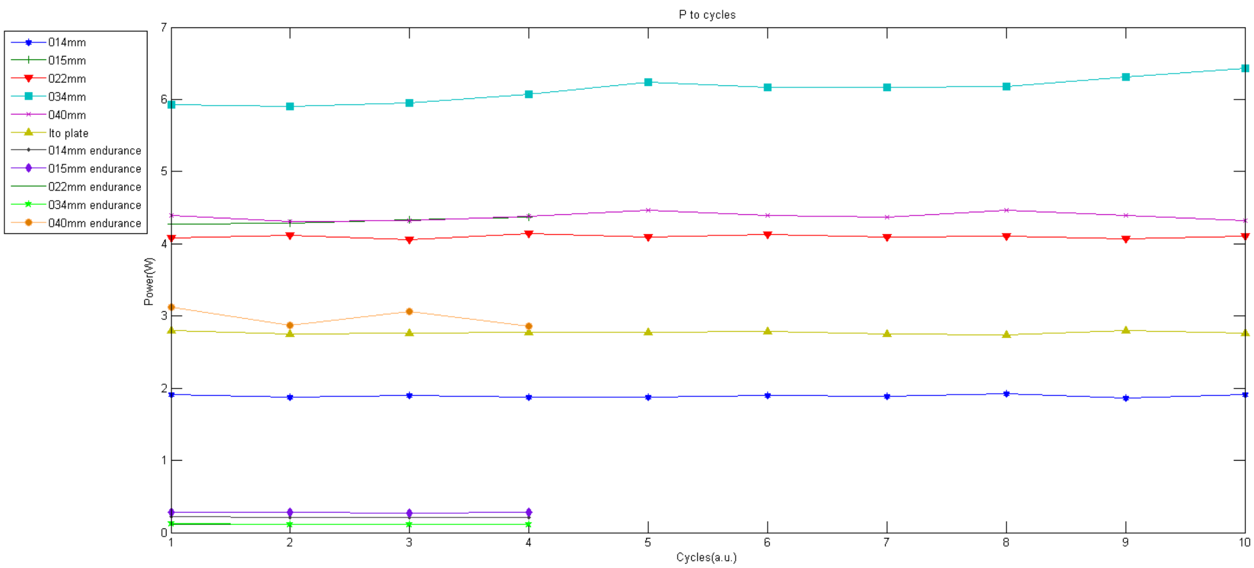

Figure 15: Calculated the power dissipated in the plasma of meshes with a different mesh wire thickness. There is difference in power produced by the plasma. This is the effect of using different meshes and voltages. The mesh wire thicknesses are named in the legend, voltage are as seen in Figure 16

As seen in ***Figure 15***, the calculated the power dissipated in the plasma is constant over its cycles between a 10% margin. Some of the measurements are shorter as fewer cycles were measured. To demonstrate the effect of different mesh widths and wire thickness on the power dissipation, while considering the applied voltage, the following figure was made:

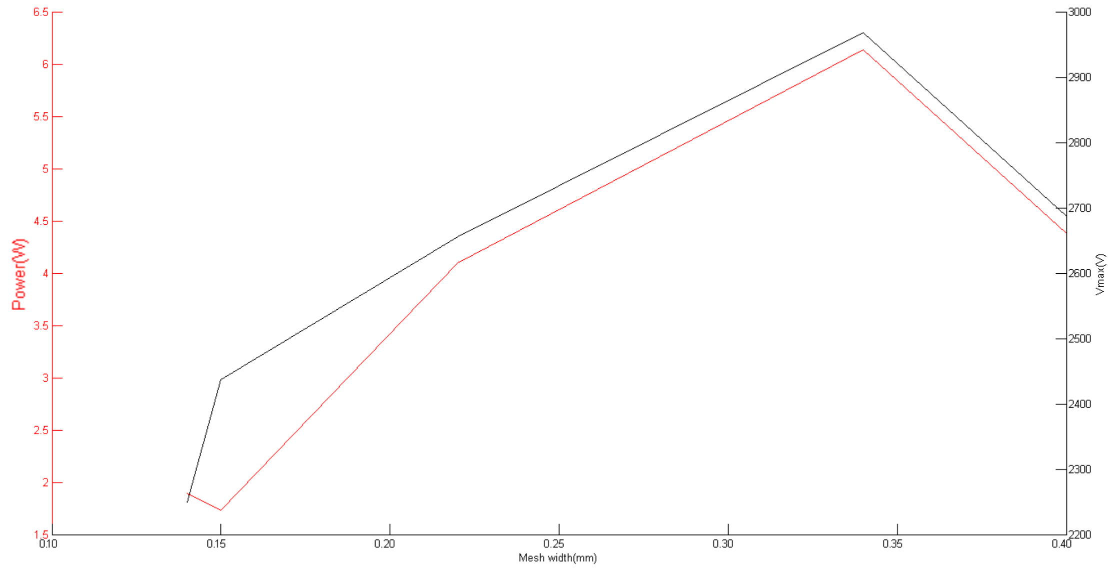

Figure 16: Calculated the power dissipated in the plasma vs the mesh wire thickness. The voltage is also shown because this couldn't be kept constant with the setup. The power dissipated in the plasma has to be corrected for this.

The voltage over the electrodes couldn't be kept constant with the used power supply. The power dissipated in the plasma can be corrected for the voltage by taking a ration between these. When we calculate this ratio *Figure* ***17*** can be made.

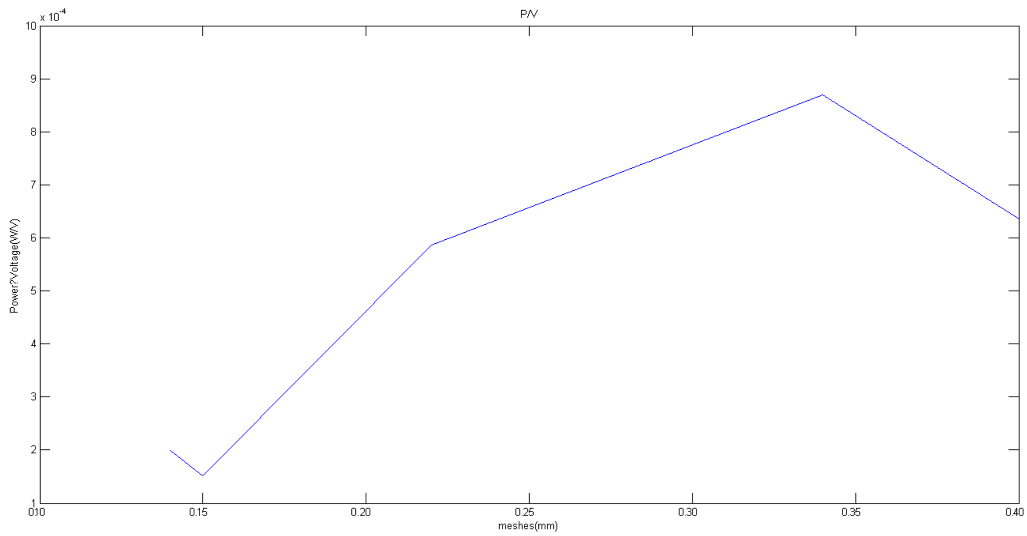

Figure 17: Calculated the power dissipated in the plasma over the voltage vs the mesh wire thickness. After the correction the line flattens somewhat indicating there is little difference between the meshes.

By comparing ***Figure 16 &*** *Figure* ***17*** it is shown that correcting for the voltage makes little difference in the shape of the graph. The power dissipated in the plasma seems to be less dependent on the applied voltage. These figures also show that the power dissipated in the plasma is different for different meshes; especially the gap at 15 mm is interesting. Also the peak at 0.34 mm wire thickness is interesting; the peak could be an effect of the different weaving used for this mesh.

5.3 Spectra

5.3.1 Spectral intensity

These spectra show what kinds of molecules and radicals are produced within the plasma using different kinds of meshes. The intensity differs and is therefore a measure for the effectiveness of the different setups.

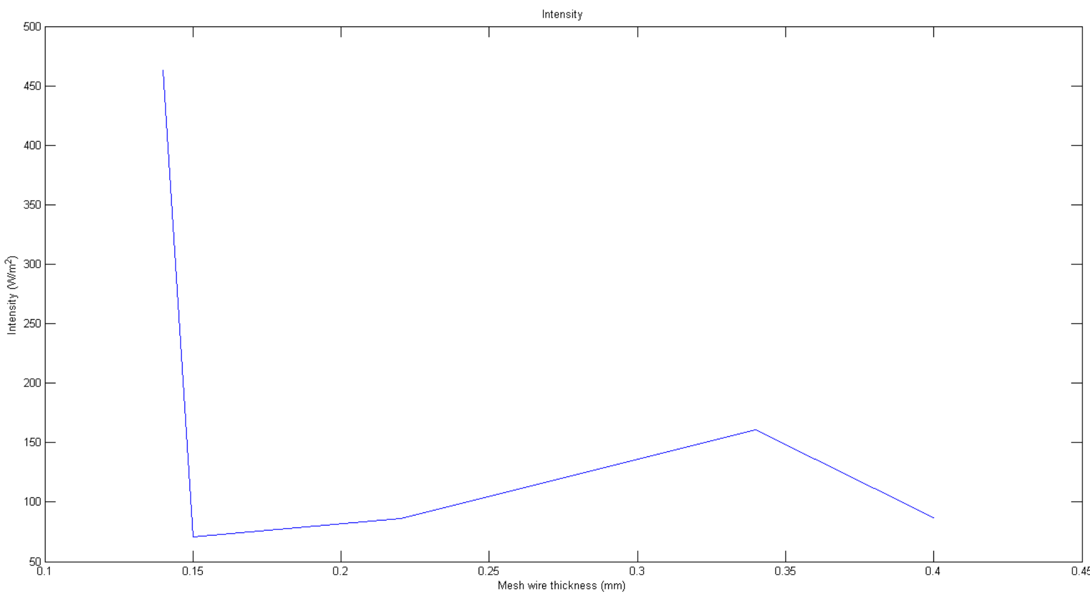

Figure 18: Intensity measured through the fiber. Intensity was calculated by integrating the spectrum and dividing over the cross-section. The figure is only for the behavior of the line; the amount of photons measured by the spectrometer that produces one count is not constant.

This may seem like seem like the 34mm is the most effective at radiating but we used different powers. To make a comparison between them we should take a look at the ratio of intensity and power.

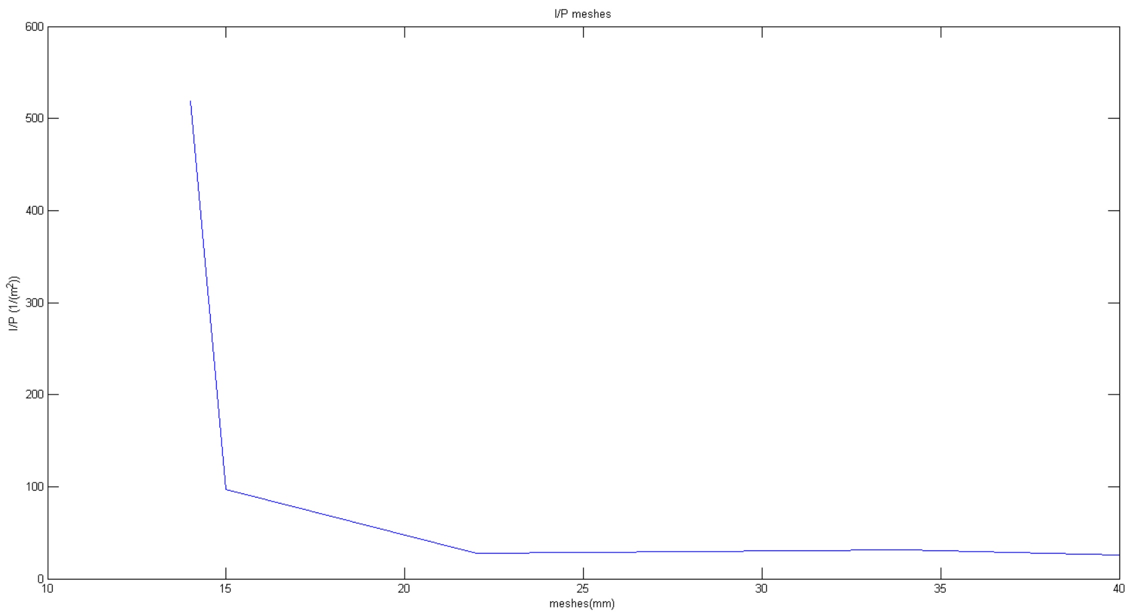

Figure 19: Intensity corrected for the measured voltage plotted against the mesh wire thickness.

This shows that the bigger the wire the less the plasma radiation intensity is. This means plasma forms at a lower power, at a small wire thickness (a higher electric field at a lower voltage) and so radiates more.

5.3.2 Spectral lines

By measuring the spectrum of an ionized gas the contents can be partly discovered. The following spectrum was made of the plasma. A lot of spectra were made but all had the same spectral lines, the ambient air was used every time. Temperature and humidity were kept relatively constant (temperature and humidity were not measured) by measuring the spectra on the same day.

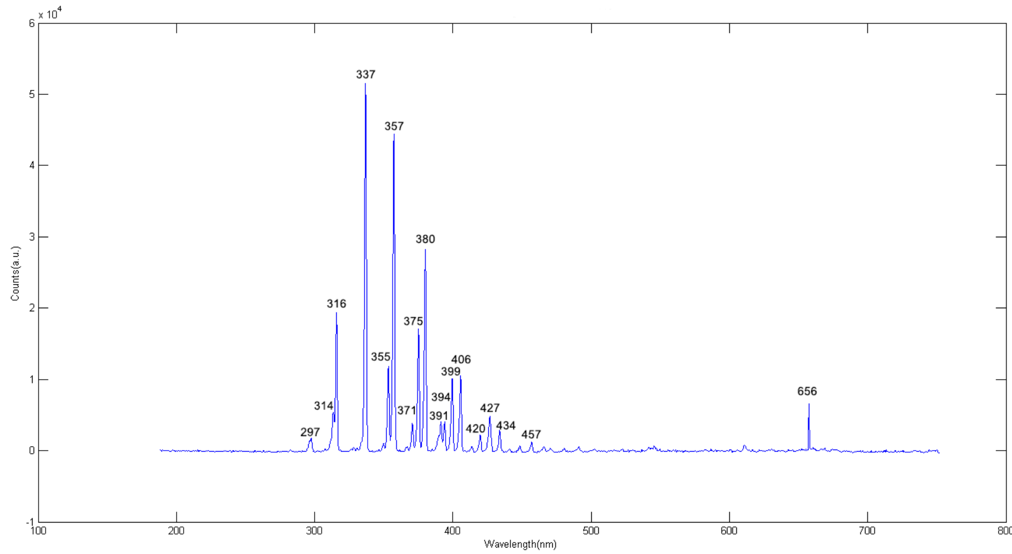

Figure 20: Spectrum of the plasma produced, note the spikes on the left indicating N and the line on the right indicating H.

Figure 20 shows several spectral lines. The hydrogen alpha line (656 nm) on the right side of the spectrum wasn't observed in all measurements, it seems hydrogen isn't always present. There is no evidence of OH radicals; these spectral lines should be at 306-310 nm and aren't found. By zooming in on the left side of the spectrum (N_2 lines) we can discern the first negative and second positive vibrational systems of N_2 and N_2^+, in accordance with [15]. Spectral lines of O (for example 777 nm) are not visible, they were not in the range of the spectrometer (<750 nm). This concludes the presence of N_2 and H in the plasma.

5.3.3 UV index and danger for humans

From ***Figure 20*** the UVI can be calculated [16]. The UVI is an index made to assess the amount of possible damage UV radiation could cause.

$$UVI = \frac{1}{25}\int_{286.5\ nm}^{400\ nm} I(\lambda) * w(\lambda)d\lambda$$

$$w(\lambda)\begin{cases} 1 & 250 < \lambda \leq 298 \\ 10^{0.094(298-\lambda)} & 298 < \lambda \leq 328 \\ 10^{0.015(139-\lambda)} & 328 < \lambda \leq 400 \\ 0 & 400 < \lambda \end{cases}$$

Where *I* is the measured spectrum, *w* is a weight function (lower wavelength UV is more damaging so needs to be weighted more) and *λ* is the wavelength of the radiation. The measured spectra are low in counts so will probably give a low UVI. Calculation show typical UVI values around 10^{-1} as seen in *Figure **21***. These values are not damaging to adults according to [16]. Exposing neonates to the same dose could be potentially dangerous. The skin of babies is thinner and more vulnerable, so caution is still advised especially when using multiple treatments. This could harm the baby and have effect on its further development. The spectrometer wasn't calibrated, only an indication provided by the manufacturer was used. Because of this the measurement isn't totally reliable to use as a strong argument. But it gives an indication.

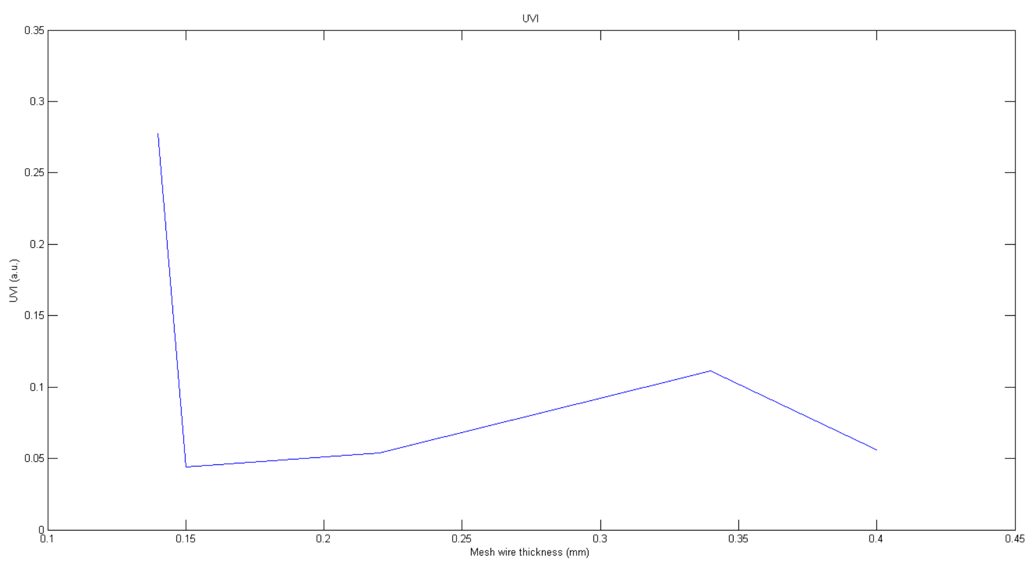

Figure 21: UVI of the plasma plaster using different mesh wire thicknesses.

5.4 Lifetime

When the dielectric breaks a short circuit is created that prevents surface plasma production and produces more heat. By keeping the prototype plasma plasteres operational until a discharge broke the dielectric, and thus stopping operations, an estimate of the lifetime can be obtained. If you compare this to the power dissipated in the plasma it seems there is an optimum around 4 W of plasma on a mesh of 25 cm^2. But still all the meshes worked longer than typical disinfection times of plasmas and were constantly lower than the average body temperature of 37°C. This is very promising; skin damage due to heat will be prevented this way. The temperature was measured with an infrared meter. Private communication [17] within our faculty indicates this approaches the temperature around the plasma well. The results are shown in *Table **5***.

Table 5: Results of the lifetime measurement on the standardized meshes coated with laminating plastic using only aluminum tape as HV electrode.

Wire thickness	Power	Time until breakdown of the dielectric	Temperature at breakdown of the dielectric (plasma temperature)
0.14 mm	1.9 W	25 m 26 s	31 °C
0.15 mm	1.7 W	25 m 55 s	30 °C
0.22 mm	4.1 W	27 m 49 s	31 °C
0.34 mm	5.9 W	18 m 45 s	30 °C
0.40 mm	4.2 W	34 m 48 s	29 °C

6. Discussion/recommendations

The purpose of this research was to determine the characteristics of the plasma made by using different materials for the plasma plaster. Meshes of different materials and sizes as bottom electrode, different metal top electrodes and dielectrics were used as seen in the results. Using these characteristics, an educated advice can be given for making a plasma plaster designed to disinfect the skin around the entry site of the IV on prematurely born babies.

There are several side effects (see Background) of plasmas that can disinfect skin and thereby destroy bacteria. These effects are potentially dangerous to an early born baby, all these need to be taken into consideration while designing the plasma plaster. Using any setup that was used in the experiments, it was determined that heat poses little danger, as the hightest temperature of the plasma measured was 31°C when the setup was running for more than 30 minutes. This is lower than the human body temperature thus poses no direct threat for humans. The heat can possibly affect the dielectric and hereby increasing the chance of a discharge, this can be determined in future research

No real research about the effects of the radicals and chemicals could be done on living samples. A subject of caution is the high O_3 production by the creation of radicals by the plasma. The ozone could be smelled; this is an indication of too high a concentration (>50ppb) of ozone in the air. The spectrum showed spectral lines of the vibrational spectrum of N_2, the main ingredient of air. With spectrometers that have a better resolution the plasma temperature can be approached by using the measured spectrum, this to be able to create a good model of the plasma. The temperatures were already low enough to avoid damage. Also the concentration of ozone can be a subject of research.

As calculated and measured the UV radiation dose within the exposure time is not harmful to humans according to the World Health Organization [16]. This means it poses little threat within such a timeframe to the patient. Using multiple treatment session on the patient the chances of damaging the skin increases. Also the effects of neonatal exposure to UV are present and potentially dangerous [17]. The measurement techniques used were rough, better tests should be performed to truly dismiss the effects of UV radiation

The power dissipated in the plasma was between 0 W and 10 W. This is not a lot of power, as expected from such a small device. This amount of power also doesn't significantly alter the temperature as shown in one of the previous sections. Durability test all showed the plasma plaster could produce plasma for more than 18 minutes. Other sources [3] show that this is well beyond other typical bacteria decimation times. No actual disinfection measurements were done but this is an indication that this design can produce plasma long enough to destroy the bacteria population in one session. How long it will last when used multiple sessions is not clear

The design was tested to curve around human skin. However the efficiency of the plasma was highly dependent on the underling attachment of the layers; plasma breakdown distribution and radiation intensity differed when the materials were deformed. When maintaining full underling attachment of the layers a good distribution of plasma and higher radiation intensity was achieved. Higher quality plasma plasters, e.g. made by using the technology of Würth Elektroniks, to pack the layers of materials should be devised and used.

The materials should be chosen to make sure all layers can be fitted perfectly together. All plastics functioned as dielectric, plasma intensity differed between materials. The laminate had a lifetime of more than 18 minutes, this is sufficient for treatment. Using aluminum tape as the top HV electrode was a success, plasma was produced and no discharge occurred.

It was seen that plasma forms more easily (less power) at a small wire thickness (a higher electric field at a lower voltage) and radiates more. The breakdown voltages and power production of meshes with different wire thicknesses both agreed on this.

Future research should test the coplanar design for a plasma plaster. This design incorporates other safety methods and different plasma characteristics. Having different options can help in future designs. Also a lot of health related issues have to be addressed before this treatment is publicly accessible.

All in all, a plasma device that can disinfect the skin around the entry site of an IV seems possible after this early research.

7. Citations

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