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Application of nanofiltration in a nasal filter

Industrial Engineering and Management

Integration Project

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Disclaimer

Abstract

A nasal filter using nanofiltration was designed to filter out pollen particles from the air, placed in a 3D printable customized housing.

First, the design requirements for the filter were specified by determining the size of allergen, allergy causing particles, and studying the nasal airflow and nasal airway resistance. Electrospinning parameters were set to produce a nanofilter which adheres to the design requirements for the nanofilter.

Second, the design requirements for the housing were specified. The material of the housing had to be 3D printable, biocompatible, flexible, and transparent. With the requirements, elastic resin from Formlabs was chosen as material. Furthermore, five prototypes for the housing were developed. The housing should not hinder breathing through the nose and therefore the prototype with the highest emerging airflow was chosen.

Finally, the value of a reusable housing was estimated to be €10.04. The filter, which needs to be changed after 140 minutes, is estimated to cost €0.14. The nasal filter costs in total €12.00, with the initial purchase of the housing and assuming the user goes outside each day for four hours and thus needs two new filters each day.

Keywords: Nasal filter; Electrospinning; Nanofiltration

Contents

1 Research design

1.1 Introduction

According to the World Health Organization, 10 to 30% of the entire world population has hay fever (Pawankar et al. [2011]). I am one of the people of this crowd. People have created many products to battle against the symptoms of hay fever. In a normal drug store, a person can buy pills, nasal spray or nasal filters. For each person the effect of the products is subjective: for some the nasal spray helps, for others the pills work.

Research has shown that nasal filters improve hay fever symptoms significantly compared with a placebo group (Kenney et al. [2015]) (Kenney et al. [2016]). However, the Allergic Rhinitis and its Impact on Asthma (ARIA) report of 2010 does not state anything about nasal filters (Schünemann et al. [n.d.]). Allergic Rhinitis is the collective term for an allergy. The ARIA guideline is used by doctors in the field. More research on nasal filters could expand the ARIA guidelines to treat allergic rhinitis, and more specifically hay fever.

Current nasal filter producers do not use nanofilters. Nanofiltration could be the next step for nasal filters as Han et al. [2018] show with their design for a nasal filter using nanofiltration. Nanofiltration is a membrane technology in which particles can only pass through the filter if their size is in the order of magnitude of nanometers (nanometer = meter $\cdot 10^{-9}$). Nanofiltration is currently used mostly for its production capabilities such as water purification, carbon dioxide removal, and desalination. (Yacubowicz and Yacubowicz [2005]). This research shows the design of a nasal filter comprised out of an electrospun nanofilter in a personally customized 3D printable housing. The novel design of the nasal filter in this research improves nasal filter knowledge and aims to help hay fever patients by showing a solution for their hay fever symptoms.

Before designing the nasal filter some preliminaries were investigated. The preliminaries include the size of pollen and the nasal anatomy. The preliminaries gave design requirements for both the nanofilter and the housing. The parameters for electrospinning the nanofilter were determined and both the material and form of the housing were worked out. Electrospinning is a nanofiber production technique. Implementing the nanofilter into the housing results in a personally customized nasal filter to filter out pollen particles from the air.

1.2 Problem Analysis

A problem analysis is executed in order to understand the problem. First, the context of the problem is determined. Second, the stakeholders and the problem-owner are analyzed. Third, a system description is created for overview purposes. Next, from the problem context and the stakeholder analysis a problem statement is formulated. Finally, a quick overview of current literature on the subject is presented and briefly discussed.

Problem context

An estimated 10 to 30% of the world population suffer from hay fever, making it the largest allergy in the world (Pawankar et al. [2011]). People who suffer from hay fever experience symptoms in and around their nose or in their throat. The symptoms range from nasal congestion to an irritated throat resulting in coughing (Small et al. [2018]). There are two ways to treat the symptoms: reduce exposure to allergens (prevention) or treat the symptoms regularly with nasal spray or pills. In terms of prevention, nasal filters are an uncommon phenomenon but have proven to be useful for people suffering from hay fever (Kenney et al. [2015]) (Kenney et al. [2016]). However, in the Allergic Rhinitis and its Impact on Asthma (ARIA) report of 2010 nasal filter do not make an appearance (Schünemann et al. [n.d.]). The ARIA guideline is used by doctors to help patients with allergic rhinitis.

At the University of Groningen, an electrospinning machine can be used to create ultra thin nanofiber which can be used for nanofiltration. An electrospinning machine uses electric force to create charged submicrometer fiber. Nanofiltration is a membrane technology which filters out particles larger than the pore size of the filter. The pore size of nanofilters are in the order of nanometer where nanometer = meter $\cdot 10^{-9}$. Currently nanofiltration is mostly used for its production capabilities such as water purification, carbon dioxide removal, and desalination. (Yacubowicz and Yacubowicz [2005]) (Verma [2010]).

At first glance, the subjects of the two paragraphs above do not seem to have an relation between them. However, nanofiltration could be the membrane technology used for nasal filters to prevent allergens from entering the system of the patient.

System description

In Figure 3 in Appendix A, a clear overview of the systems can be seen. There are two systems at play in this research (the circles in Figure 3). The first is the system of allergies and the second is the allergy remedy system to treat symptoms of allergies. The text boxes where the letters are bold and cursive are the scope of the research. Other parts of the system will not be taken into account.

Allergic Rhinitis is the medical term used by doctors to describe an allergy. An allergy is an overreaction of the human immune system against harmless particles from outside (M. van den Berge (TNE-medical in training), interview, March 11, 2020). The particles can be lactose, gluten, certain pet hairs or pollen. If the particles do enter the human system, the overreaction of the immune system can happen in certain ways and areas. The most prominent areas are the nose and the throat. As the nose and/or throat start to show certain symptoms, patients start to look for remedies to stop the symptoms. There is a wide range of symptoms in case of an allergic reaction, for example an itchy throat, nasal congestion, and sneezing. There are two ways to stop the symptoms of an allergic reaction. The first is preventing the allergen from reaching the system of the human. The second is treating the symptoms. Treating symptoms can be done by using a nasal spray, pills, or other treatments. Reducing allergen exposure can also be done in two ways. The first is physically avoiding allergen. For people with a pet allergy this is easy: they avoid the pet they are allergic to. For hay fever patients this is more difficult, pollen are hard to avoid in the spring as they are everywhere outside. The second way to prevent allergen from reaching inside the human system are facial filters. The filter will filter out pollen particles while the user can still breath. There are two options to choose from facial filters, namely nasal filters and facials masks which cover both the nose and the mouth.

Stakeholder analysis

The problem dissecting tool of a stakeholder analysis is applied. A stakeholder analysis will present the needs of the stakeholders clearly. The product (nasal filter) should consider these needs to create a product optimized to customer demand. The stakeholders for the project are:

People suffering from hay fever. People with a pollen allergy have low interest in the project as there are already several nasal filters on the market but these products are highly subjective. For some people the nasal filters work and for others pills seem to help them with hay fever symptoms. Furthermore people suffering from hay fever have high power in the project. They create the customer requirements the product should adhere to.

Another stakeholder and also the problem-owner is prof. dr. ir. Jayawardhana. Prof. Jayawardhana is the initiator of the project. As prof. Jayawardhana suffers from hay fever himself, he wanted to look into nasal filters as a feasible option. A lot of attention is put into eyes and the mouth but according to prof. Jayawardhana more regard for the nose area could be applied. Prof. Jayawardhana has high power, because he is the supervisor of the project and tracks progress. Prof. Jayawardhana also has high interest as this project could possibly help him with his hay fever.

Throat, Nose-, & Ear doctors (TNE-doctors) in the Netherlands (KNO-artsen) are also stakeholders. They want the best for their patients and a nasal filter could be what their patients want. Therefore, TNE-doctors have high interest in the project but low power as they do not control the inputs of the research.

Finally, the Discrete Technology & Production Automation (DTPA) are a stakeholder. DTPA is a section of the University of Groningen and they own the electrospinning machine and the 3D printer which will be used to house the nasal filter. DTPA has a low interest in the project as they have several researches being conducted and therefore do not have a high interest in one specific project. DTPA does however, have high power over the project as they own and control the machines needed to make the nasal filter. DTPA control schedules and output of the machines and are needed to assist in the project.

Problem statement

From the problem context and the stakeholder analysis a problem statement can be devised. The problem context clearly shows there is a problem in the application of nanofiltration in nasal filters as this has not been done before. Therefore, the problem statement reads as follows:

Current guidelines for the treatment of allergic rhinitis do not mention nasal filters. Current research shows effectivity of nasal filter and nasal filters therefore need more research. Nanofiltration could have potential to be the new membrane technology for nasal filters and improve nasal filter technology.

Literature review

Designing a nasal filter with nanofiltration requires knowledge of several distinctive subjects which are: current nasal filters, allergies, nose anatomy, nanofiltration.

Search for literature was done based on search terms of the four subjects above. At the end of every paragraph of current literature on the subject a knowledge question is presented of what still needs to be investigated.

Current nasal filters: Rhinix is the established competitor in the market for nasal filters. Rhinix conducted the research already mentioned in the Problem Context (Section 1.2) which determined nasal filters work to enlighten hay fever symptoms (Kenney et al. [2015]) (Kenney et al. [2016]). A document of Rhinix to the department of health and human services USA indicates the material of Rhinix their nasal filter to be a planar filter made of polypropylene non-woven fibers (Rhinix [2014]). The characteristics of this filter can be set against the characteristics of nanofiltration. Knowledge question: how do current nasal filters work and what kind of filters and pore size is used.

Hay fever: Hay fever is caused by pollen. Most patients therefore, suffer from hay fever only when it is pollen season. Some symptoms of hay fever are sneezing, nasal itching, and nasal congestion (Small et al. [2018]). An effective hay fever filter should deny the access to pollen as these cause the symptoms. The review article D'Amato et al. [2007] states the most common size of pollen in Europe and is therefore vital to the research. Knowledge question: what is the size of the allergy particles (pollen) and how can these particles be filtered from the air.

Nasal anatomy: Eccles [2000] presents a review of the current knowledge on nasal airflow. Although the article is from 2000 it will assist understanding the nasal respiratory system. After a brief first interview with a TNE-doctor the Allergic Rhinitis and its Impact on Asthma (ARIA) guideline was introduced (Schünemann et al. [n.d.]). The ARIA guidelines is used by TNE-doctors for treatment of allergies and asthma. Furthermore some pictures were shown to help understand the nasal anatomy and nasal airflow. Knowledge question: how does the nasal respiratory system work and what can be done to not hinder breathing.

Nanofiltration: Literature shows no current knowledge of nanofiltration or any form of membrane technology used for nose filters. From Baker [2012], Li et al. [2011],Yacubowicz and Yacubowicz [2005], and Verma [2010] it can be seen that nanofiltration is used for its production capabilities for example, desalination, water purification or carbon dioxide removal. Knowledge question: can nanofiltration be implemented in a nasal filter to stop allergy particles from entering a human's system.

1.3 Research goal

From the problem analysis and problem statement, a clear problem was defined. The goal of the research is to solve this problem. The knowledge of hay fever and nanofiltration will increase by conducting literature research. Interviews with Throat, Nose, and Ear medicals will help to understand the nose anatomy and nasal respiratory system. With this information and taking into account customer needs and demands, an iterative process of design will be put into motion. The research goal is:

Design a nasal filter using nanofiltration to filter out pollen particles from the air within two months. The nasal filter will be housed in a customized 3D printed housing. The nanofilter and the 3D housing should adhere to certain design requirements.

1.4 Research questions

Research questions are drawn up to achieve the research goal. The answer to the research questions should result in specifying the design requirements for the nasal filter. Furthermore, the research questions should be elaborate and clear enough to immediately understand the research activities which should be conducted.

Central question

With the above in mind, the following central question is formulated:

1. What are the design characteristics for a nasal filter with a nanofilter as membrane?

Sub-questions

The central question in itself is too broad. The answer for the central question consists of multiple parts which are elaborated in sub-questions. In order to answer the central question the following sub-questions are defined:

1. What are the parameters of pollen particles?
2. What are the characteristics of nasal anatomy and nasal airflow?
3. What are the specifications of an electrospun nanofilter which can be successfully implemented in a nasal filter?
4. What is the best composition of materials and form for a nasal filter housing which can be 3D printed and is safe to use?

Sub-question 1 will further develop the understanding of pollen and try to learn filter requirements needed to filter out pollen. The answer to sub-question 2 will give more requirements which a filter in a nasal filter should meet as the nasal filter should not hinder breathing. Sub-question 3 investigates what the best combination of materials is to create an electrospun nanofilter which adheres to the requirements of sub-questions 1 & 2. Lastly, sub-question 4 determines the materials and the shape of a nasal filter which can be 3D printed and does not damage or irritate the inside of the nose.

The answers to the sub-questions result in a nasal filter which has a nanofilter to filter out pollen particles and does not hinder breathing. Furthermore it results delivers a housing for the nanofilter which can be 3D printed and does not hurt the user.

1.5 Design cycle

The goal of the research is to design a nasal filter to improve current living conditions for hay fever patients.

The design cycle used for the research is the design cycle of Wieringa [2014]. In Figure 1 the steps of the design cycle can be seen. The Research and Design Proposal (RDP) is the first step of problem investigation. Here it is made clear what the problem is, why it is a problem, and whose problem it is. For the research the problem is the pollen particles, these are a problem as they cause hay fever symptoms. Pollen are the problem for people suffering from hay fever. Next, the requirements for the nasal filter should adhere to are specified, which is the treatment design. The treatment validation step will not be fully applied. Validating the nasal filter will be difficult as the nasal filter cannot be actually produced. Therefore, Solidworks simulations and the theoretical validity of literature research are the validation tools.

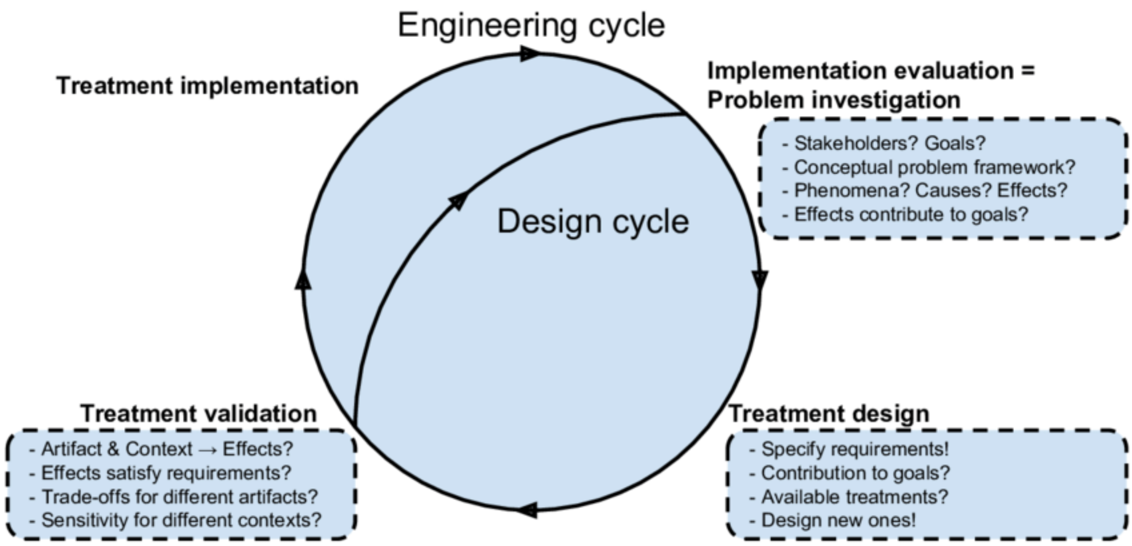

Figure 1: Engineering cycle by Wieringa [2014]

1.6 Research planning

A research plan has been made to track the progress of the research. The Gantt chart (Figure 4) can be seen in Appendix A.

1.7 Methods

First, to answer sub-questions 1 & 2 literature research is conducted using the desk research strategy from Verschuren et al. [2010]. Desk research is using material produced by other researchers instead of utilizing your own research. The answers to sub-questions 1 & 2 generate design requirements for the filter itself and the housing of the filter. The design requirements are taken into account to answer sub-questions 3 & 4.

To achieve the goal of the research and design a nasal filter inside a 3D printed housing, the research strategy experiment is used. There are two methods utilized to make the nasal filter. First, Solidworks is used to design the housing of the filter. Solidworks is a 3D designing software from which designs can be, after some manipulations, 3D printed. Second, an electrospinning machine can create the nanofiber. An electrospinning machine uses electric force to create charged submicrometer fiber such as nanofiber. Different parameters in the electrospinning process can be manipulated to produce a filter in compliance with design criteria. With the form of the housing and the parameters of electrospinning, the design for a nasal filter is complete and the goal is reached.

1.8 Validation

If the research sub-questions, which use literature research, are answered satisfactory than the method is validated. Satisfactory in this case means the size of pollen particles, the pressure of breathing through the nose, and the flow of breathing through the nose, among others, are known.

With the produced nasal filter in hand, the filter needs to be tested. The requirements of the nasal filter need to be taken into account. First, the nasal filter should filter out pollen particles. The filtration efficiency of the filter can be determined with an experimental set-up similar to Han et al. [2018]. The experimental set-up is comprised of a flow control system, a particle generation system, an air-particle mixing system, and a particle monitoring system. Particles of different sizes will be released into a stream which meets the filter. The amount of particles behind the filter are compared to the particles generated in front of the filter, giving the filtration efficiency. A satisfactory result of the filtration requirement is to find no particles of the size pollen, or bigger, behind the filter.

The next important requirement is: breathing through the nose should not be hindered. Testing this requirement can be done in two ways, either by measuring the total nasal airway resistance or by determining the pressure drop from the filter and relating this to the airway resistance. Nasal airway resistance is a measure used to determine breathability. A regular nasal airway resistance, without any masks or hindrance, is $230Pa/(L \cdot s^{-1})$. A satisfactory nasal airway resistance from the nasal filter should not be much higher than the regular airway resistance. By using, for example, a NR6 Rhinomanometer which measures the total nasal airway resistance, a value can be given to the breathability of the nasal filter. However physical testing is crucial as the subjective breathability can differ from the measured nasal airway resistance (Jones et al. [1989]). A pressure gauge can be added to the experimental set-up of Han et al. [2018] to determine the pressure drop of the filter. The pressure drop can be linked to the filter resistance which can be related to the airway resistance. With this method an indication of breathability can be given similar to measuring the total nasal airway resistance.

For the physical testing the Sino-Nasal Outcome Test (SNOT-22) is used. The SNOT-22 is a test of 22 self evaluating questions for the user of the nasal filter. The 22 questions are statements of physical, functional, and emotional consequences of the medical procedure, in this case using the nasal filter. The user gives a score between 0 (no problem) and 5 (problem as bad as it can be) for all the statements. Statements include, among others: Nasal blockage, Decreased Sense of Smell/Taste, Reduced concentration.

2 Preliminaries

2.1 Pollen

Allergens, the particles that cause an allergic reaction, of hay fever are found in pollen grains. Pollen are light powders which can travel through the air and contain pollen grains. The ability to be swept by air currents cause pollen to be widely spread. In Europe specifically, grass pollen are the primary source of hay fever symptoms (D'Amato et al. [2007]).

Fortunately, grass pollen are only harmful for hay fever patients during pollen season. For example, in the Netherlands, the grass pollen season, when grass pollen are produced, starts around mid May to June and ends in July. During these months, hay fever patients experience symptoms such as nasal congestion and sneezing Small et al. [2018].

In order to design a functional nasal filter it must be known what the nasal filter should filter from the air, and specifically how large these particles are. Pollen grains have a diameter between 15 and 40 micrometer (μm) (D'Amato et al. [2007]). One micrometer is equal to one meter $\cdot 10^{-6}$. However, according to Spieksma et al. [1990] smaller fractions of pollen grains are also present in the air. These smaller fractions range from 0.6 to 10 micrometer and the resulting allergic reaction is equal to the allergic reaction to normal sized pollen grains (15 - 40 μm).

Therefore it can be concluded that a nasal filter needs to filter out particles bigger than 0.6 micrometer (or 600 nanometer) to clean the air entirely from allergens.

2.2 Nasal anatomy

Two elements of the nose are important to take into consideration for designing a nasal filter. First, safety: a nasal filter should never harm the user. Therefore, it is important to understand the nasal anatomy and the dangers of putting a product inside the nose. Second, nasal airflow: the airflow of breathing should not be hindered by the nasal filter. This requirement is defined as critical by the initiator of the project, prof. dr. ir. Jayawardhana.

2.2.1 Safety

The separation between the left and right nostrils is called the septum. The veins inside the nose come together in the septum and therefore the septum is very fragile and susceptible for nosebleeds (Munir and Clarke [2012]). The medical term for a nosebleed is epistaxis. For a nasal filter the material of the housing should be closely watched. The housing must never damage the septum of the user.

Furthermore, all noses have different sizes and different nostrils. A nasal filter should be comfortable to wear but the air sucked in through the nose should all be filtered, there cannot be any gaps between the filter and the inside of the nose. Therefore, a requirement is set to produce a customized housing which can fit perfectly inside the nose.

2.2.2 Nasal airflow

Pressure

Breathing through the nose should not be hindered by the nasal filter. Therefore, the force with which a human breathes is examined. According to Hall [2016] the force is a result of the lungs expending in volume and thus decreasing the pressure according to Boyle's law. The outside air (ambient air) has a higher pressure and moves into the area with the lower pressure (the lungs). The difference in pressure between the ambient air and the lungs is the force generated to suck air into the lungs through the nose or mouth. This force is equal to one cmH_2O and one cmH_2O is equal to $98.0665Pa$.

Airflow

According to Takeuchi et al. [2000] the nasal airflow of a hay fever patient does not decrease during the pollen season. Although patients suffer from nasal congestion there is no difference in total nasal airflow ($\approx 325cm^3/s$ or $19.5L/min$). The results were gathered using a reference inspiratory pressure of $75Pa$.

Nasal airway resistance

The airflow going into the nose is subject to resistance because of different shapes inside the respiratory tract. The nasal airway resistance can be determined and is used commonly in research to determine the breathability of a subject. The nasal airway resistance R_{aw} can be determined using the following formula (Gupta et al. [2012]):

$$R_{aw} = \frac{\Delta P}{Q} \tag{1}$$

Where ΔP is the pressure difference between the ambient air and the alveolar pressure, also noted as the pressure inside the lungs. Q is the airflow. For example, filling in the results of Takeuchi et al. [2000], an airflow Q of $325cm^3/s$ and a pressure difference ΔP of $75Pa$, results in a nasal airway resistance of $0.230Pa/(cm^3 \cdot s^{-1})$ or $230Pa/(L \cdot s^{-1})$. Literature seems divided on choosing a normal nasal airway resistance (Morris et al. [1992]) (Syabbalo et al. [1986]) (Havas et al. [1994]) (Cole [1997]). The normal nasal airway resistance is the nasal resistance people experience at all times. For this research a normal nasal airway resistance of $230Pa/(L \cdot s^{-1})$ is employed based on literature and the calculated nasal airway resistance of Takeuchi et al. [2000].

3 Nanofilter

The resistance to airflow by a filter determines the breathability and is therefore crucial to know for a nasal filter The resistance to airflow by a filter R_{filter} can be determined by (Vanangamudi et al. [2015]):

$$R_{filter} = \frac{\Delta P}{v} \tag{2}$$

where ΔP is the pressure drop created by the filter and v is the velocity of the air flowing through the filter. Kim et al. [2015], however, tested facepiece respirators and the filter resistance by using the same formula (2) but replacing the velocity v by the flow rate Q:

$$R_{filter} = \frac{\Delta P}{Q} \tag{3}$$

With equation (3) the resistance of a filter can be related to regular nasal airway resistance. Lee and Wang [2011] reported a nasal airway resistance of $320 Pa/(L \cdot s^{-1})$ of the N95 (3M 8210) respirator on top of the regular nasal airway resistance. The N95 respirator is face mask which can be used during several dusty operations such as sawing. N95 stands for the collection efficiency of 95%. 3M and 8210 are product information. The N95 (3M 8210) respirator is approved by the federal institute NIOSH (National Institute for Occupational Safety and Health). The increase in nasal airway resistance is more than double of the normal nasal airway resistance. Although workers, who use the N95 respirator, report breathing difficulty (Bryce et al. [2008])(Baig et al. [2010]), an increased nasal airway resistance of $320 Pa/(L \cdot s^{-1})$ is deemed acceptable for the nasal filter.

Researches evaluating filters use the pressure drop as a reference of breathability. To calculate the pressure drop of the N95 (M3 8210) respirator the airflow Q is assumed to be $19.5 L/min$ (section 2.2.2) and the resistance of the N95 respirator R_{filter} is $320 Pa/(L \cdot s^{-1})$. The pressure drop of the filter ΔP is then equal to $107 Pa$. Therefore a pressure drop of $107 Pa$ is deemed acceptable for the nasal filter.

The Quality Factor (QF) is the measure to compare the overall performance of filters. The Quality Factor (QF) of a filter can be determined with the pressure drop ΔP and the collection efficiency η (Ding and Yu [2014]) as follows

$$QF = -\frac{ln(1-\eta)}{\Delta P}. \tag{4}$$

The collection efficiency of a filter (η) can be calculated by (Park and Park [2005]):

$$\eta = (1 - \frac{C_{downstream}}{C_{upstream}}) \cdot 100\% \tag{5}$$

where C_i is the concentration of particles downstream or upstream from the filter. A high Quality factor is desirable so it is essential to have a high collection efficiency while maintaining a low pressure drop (Zhu et al. [2017]).

4 Nanofilter design

4.1 Electrospinning

As mentioned in the problem context (1.2) the filter is constructed with an electrospinning machine. Other nanofiber producing techniques include: melt fibration, island-in-sea, nanolithography. Electrospinning holds the advantage of low cost and high production rate over the other techniques (Ramakrishna et al. [2006]).

The electrospinning process will be explained on the basis of figure 2. The electrospinning equipment consists of three major parts: a high voltage power supply (1), a needle containing a polymer solution (2), and a grounded collector (3). The solution is pumped into the needle with a specified feed rate. The solution is charged by the high voltage supply. At the tip of the needle the surface tension of the solution tries to hold the solution at the tip. The voltage difference between the tip of the needle and the collector needs to overcome the threshold force of the surface tension. When the threshold force is reached, the droplets at the tip form a Taylor cone and the solution ejects to the grounded collector in a thin, liquid form. The liquid solidifies onto the collector to create the fiber (Zhu et al. [2017]).

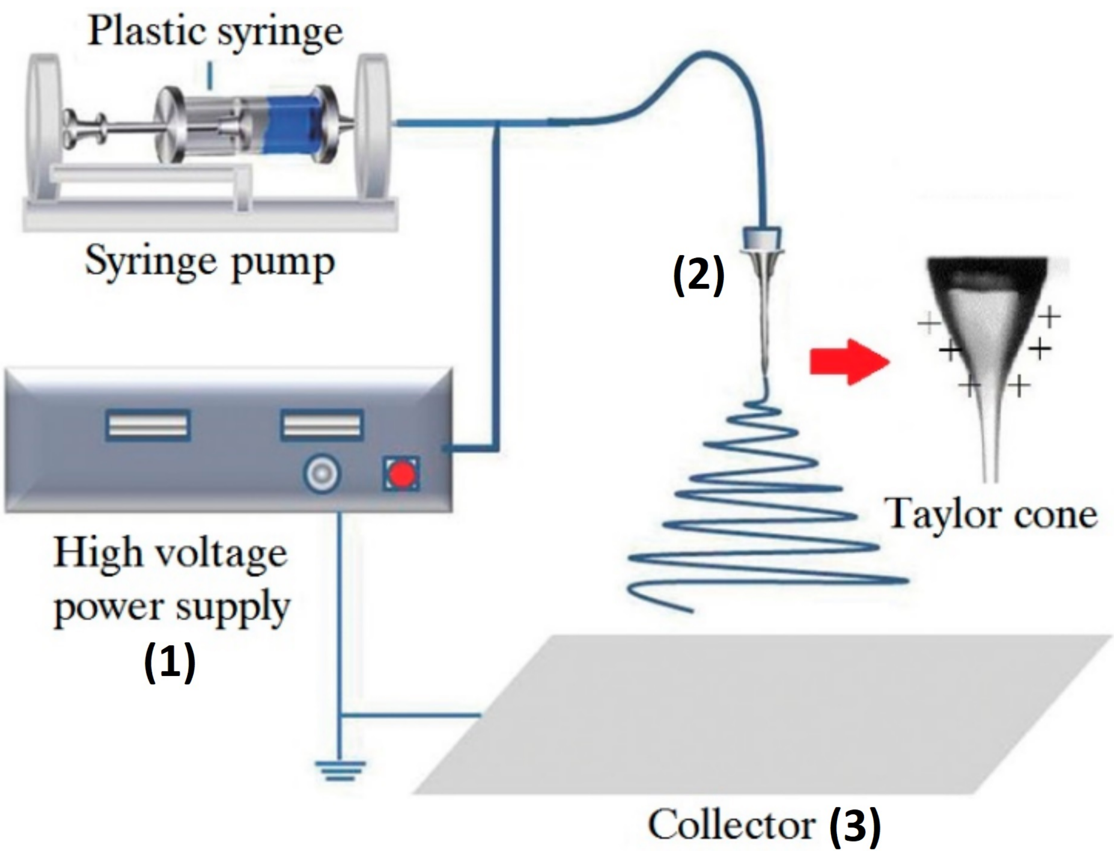

Figure 2: The electrospinning process consisting of a high voltage power supply (1), a needle containing a polymer solution (2), and a grounded collector (3) (Chen et al. [2019]).

4.2 Parameters

The nanofiber created by the electrospinning process is influenced by a lot of parameters. These parameters can be divided into three categories: solution, processing, and environment parameters (Zhu et al. [2017]). Solution parameters involve: polymer concentration and solution viscosity, polymer molecular weight, solvent volatile, electric conductivity of the electrospinning solution, surface tension of electrospinning solution. Processing parameters include: electric field strength, tip-to-collector distance, flow rate (feed rate). Environment parameters comprises two parameters: humidity and temperature. An overview of the parameters and the factors they affect can be seen in Table 1 in Appendix A.

The parameters determine the morphology and fiber diameter. The morphology is the structure of the fiber which can be, among others, smooth, with beads, or porous. For the nanofilter a smooth morphology is chosen. According to Agarwal et al. [2016] the mean fiber diameter is generally three or four times smaller than the pore size. The pore size for the filter is known from Section 2.1: 0.6 micrometer (μm). Therefore, the fiber diameter of the filter should be 0.15 micrometer (μm) or 150 nanometer (nm).

With the set parameters the filter can be produced and tested on its collection efficiency η, pressure drop ΔP, and resulting quality factor (QF). Furthermore, the parameters are argued to fulfil the filter requirements set in Section 2.1 and Section 2.2.2. Namely: the filter should filter out particles larger than 0.6 micrometer and a pressure drop of $107 Pa$ is acceptable.

Solution parameters

Similar to Han et al. [2018], the electrospun nanofiber will coat a regular filter. The nanofiber will increase the filtration efficiency of smaller particles ($< 0.3 \mu m$). First, the polymer and the regular filter must be determined. According to Agarwal et al. [2016] and Zhu et al. [2017] Nylon-6 and Nylon-6,6 polymers are typical examples used for filtration applications. Furthermore, Han et al. [2018] also used Nylon-6,6 in their design of a nasal filter. Therefore, for the electrospinning process of this research, Nylon-6,6 is chosen as well.

The regular filter, on which the nanofiber is deposited, is chosen to be polypropylene based on Bailar et al. [2006] noting the use of the same material for other respirators and Rhinix, a nasal filter producing company, also using polypropylene as their filter.

Next, the solution parameters can be determined. First, the polymer concentration and solution viscosity: The polymer concentration directly affects the solution viscosity. A low fiber diameter of 0.15 micrometer (μm) or 150 nanometer (nm) is required thus the polymer concentration, or weight percentage (wt%), should be low. Based on the research of Kim et al. [2008], Li et al. [2006], and Han et al. [2018] a weight percentage of 20wt% is the best for Nylon-6,6. For the current requirements a polymer concentration of 20wt% seems to be most favourable, but to compare performance, 15wt% and 25wt% should also be taken into account. The solution viscosity, electric conductivity, and surface tension has been measured for

15wt%, 20wt%, and 25wt% nylon-6,6 by Li et al. [2006] and can be seen in Table 2 in appendix A. The solution was made by gently stirring 88% formic acid and the weight percentage of homogeneous nylon-6 for 8 hours at room temperature.

Processing parameters

Processing parameters are the settings for the electrospinning machine. The first parameter is the strength of the electric field which coincides with the tip-to-collector distance. The strength of the electric field is expressed in kilo volts per centimeter (kV/cm) and is therefore dependent on the distance.

Heikkilä et al. [2008] determined that a nylon-6,6 coating performed best with an electric field strength of $80kV/400mm$ or $2kV/cm$. An electric field strength of $2kV/cm$ is also in line with Agarwal et al. [2016] where a normal tip-to-collector distance of 15 to $20cm$ is mentioned. Taking the shortest tip-to-collector distance of $15cm$ results in a voltage of $30kV$.

Li et al. [2006] used an tip-to-collector distance of $14cm$ and a voltage of $29kV$ and a feeding rate of $0.1mL/hour$. Because the tip-to-collector distance and voltage are almost the same, the feeding rate for this research is also chosen to be $0.1mL/hour$.

Environment parameters

For the temperature and the humidity the electrospinning circumstances of Kim et al. [2008] are followed with a temperature of 20 °C and a humidity of 40%.

With the parameters set to produce the desired nanofiber, the density of the coating on the regular air filter should be determined. Heikkilä et al. [2008] shows a coating density of $0.5g/m^2$ improves the filtration efficiency without increasing the pressure drop too much. Han et al. [2018] displays similar results with the same coating density but prefers a higher coating density to gain better filtration efficiency, at the cost of a higher pressure drop. For this research a coating density of $0.5g/m^2$ will be chosen to increase the filtration efficiency of the regular air filter. The volume of solution (V) needed for this coating density can be determined by (Li et al. [2006]):

$$V = \frac{CA \cdot CD}{C \cdot D} \tag{6}$$

where CA is the coverage area of the fiber which is equal to the area of the nostrils ($131.31mm^2$). CD is the coating density ($0.5g/m^2$). C is the concentration of the nylon-6,6 solution ($20wt\%$ or 0.20), and D is the density of the nylon-6,6 solution ($1.14g/cm^3$). The volume is a function of the time times the feed rate ($0.1mL/hour$). With these specifications the volume of the solution is determined to be $0.288mm^3$ to produce a coating density of $0.5g/m^2$. The time of electrospinning is therefore 10 seconds.

4.3 Resulting nanofilter

N95 respirators use polypropylene filters with a thickness of around $1mm$ (Bałazy et al. [2006]). For the nasal filter a polypropylene with a similar size will be used and the coating will not increase the thickness significantly making the thickness of the filter for the nasal filter $1mm$.

Han et al. [2018] shows a linear progression in pressure drop over time when their filter is exposed to air contaminated with small particles ($0.026\mu m$ and $3.1\mu m$) at an air velocity of $1L/s$. For the larger particles ($3.1\mu m$) the pressure drop starts at $10Pa$ after 10 minutes and increases to $182Pa$ after 240 minutes. The filter described in section 4 shows similarities to the hybrid filter of Han et al. [2018] but parameters were specifically chosen to have a lower pressure drop. A pressure drop of $107Pa$ was deemed acceptable (section 3). The hybrid filter of Han et al. [2018] reached a pressure drop of $107Pa$ after around 140 minutes. Then it must be taken into account that in the open air there are not solely particles of $3.1\mu m$. An estimation of the duration of the nasal filter until the pressure drop is too high can be made but can be tested better in similar fashion to the testing method of Han et al. [2018] as described in section 1.8. An estimation of the duration of the nasal filter can be set at the same number, around 140 minutes or 2 hours and 20 minutes. After this time the nasal filter will become hard to breath through and the filter needs to be changed.

5 Housing

The final step is to implement the filter in a housing. First, the material of the housing is selected. Next, the design of the housing is made in Solidworks.

5.1 Material selection

The material selection is based on the dedicated chapter of Ashby and Cebon [1993]. Ashby and Cebon [1993] explains there are four steps to choose the most fitting material for a product. The first step is screening the materials based on the constraints, meaning materials that fail the constraints are immediately dropped. The second step is ranking the remaining materials on one or multiple objectives. The objectives are criterion of excellence, these are desirable to either minimize or maximize. Once the materials have been ranked it is time for the final step: documentation. Documentation entails looking into the other properties of the remaining materials and choosing the material based on overall properties.

The design requirements the material should adhere to are: 3D printable, safe for human contact, flexible, transparent. The first three requirements (3D printable, safe for human contact, flexible) must be met under all circumstances. The final requirement (transparency) is great for aesthetics but not mandatory as the other requirements. 3D printable and safe for human contact are constraints which every material should own as property. Flexibility of the material is an objective to maximize. Transparency is taken into account at the documentation step as a highly valuable property.

Screening

Five 3D printing materials have been selected based on their properties to be 3D printable and their biocompatibility. Biocompatibility is the term which ensures safe human contact. The five 3D printing materials are: Detax luxaprint® 3D flex, 3Dresyn Bioflex A70 MF ULWA Monomer Free Ultra Low Water Absorption (3Dresyn bioflex A70), 3Dresyn Bioflex A50 MF ULWA Monomer Free Ultra Low Water Absorption (3Dresyn bioflex A50), elastic resin from Formlabs, Envisiontec E-Clear Series.

Ranking

Arranging the five 3D printing materials based on their flexibility results in the following ranking (1. is highest flexibility and 5. is lowest flexibility):

1. Elastic resin from Formlabs
2. 3Dresyn bioflex A50
3. 3Dresyn bioflex A70
4. Detax luxaprint® 3D flex
5. Envisiontec E-Clear Series

Documentation

Envisiontec E-Clear Series is not used because of the low flexibility. Detax luxaprint® 3D flex has a lack of data and will therefore also be dropped. Therefore, the elastic resin from Formlabs, the 3Dresyn bioflex A50, and the 3Dresyn bioflex A70 are left. The 3Dresyn bioflex A50 and the 3Dresyn bioflex A70 are both transparent and share a lot of physical properties but the 3Dresyn bioflex A50 is slightly more flexible. The elastic resin from Formlabs and the 3Dresyn bioflex A50 have the same hardness of 50A on the shore durometer. For the housing of the filter the elastic resin from Formlabs is chosen as material because the 3D printer at the University of Groningen is from the same brand: Formlabs. Using a resin produced by the company which also manufactured the 3D printer ensures compatibility.

5.2 Solidworks design

Five prototypes have been developed in Solidworks. All prototypes trace a picture of the opening of the nostrils of the subject, and are therefore customized to the nose of the subject. Customizing the housing to other subjects will not be difficult using the method of tracing a picture of the opening of the nostrils. All prototypes have a thick circular edge of $3mm$. The difference between the prototypes is the mechanism to hold the filter in its place. An overview of the qualitative advantages and disadvantages can be seen in Table 3 in appendix A. Only the right wing of the prototypes has been developed to compare the different prototypes and determine the best alternative. The different prototypes can be seen in Appendix B.

The first prototype holds the filter in place with a $1mm$ gap in the thick edge in which the filter can be slid into. The air flows through a honeycomb pattern beneath the filter (Figure 5). The second prototype holds the filter exactly the same as the first prototype but now there is one single hole. There is only a thick edge which holds the filter (Figure 6). The third prototype is the same as the second prototype but the housing is cut horizontally into two parts. The two parts fit into each other with protrusions on the top cut and corresponding holes on the bottom cut. Holes are placed in the filter in the same spots as was done for the bottom part. The protrusions will go through the filter and into the holes, holding the housing together and holding the filter in place (Figure 7). The fourth prototype also holds the filter with a $1mm$ gap but not in the edge of the housing but in the base of an oval form (Figure 8). The final prototype makes use of an exhalation valve and an inhalation valve is optional. The bottom part of the housing is the same as the first prototype and holds the filter in the edge with a $1mm$ gap. The top part of the housing has six holes cut in a circular motion on which a rubber circle can be placed slightly bigger than the circular motion of the holes creating an exhalation valve (Figure 9). A similar rubber can be made for the bottom part to make an inhalation valve.

5.3 Flow simulation

The different prototypes have elements as the size and the sides in common but the difference, as previously mentioned, is the mechanism to hold the filter and with that the structure to pass airflow. There is extra resistance to airflow because, in contrast to breathing without the nasal filter, there is a structure partially blocking the airflow. By determining the extra airflow resistance of the prototypes a quantitative analysis is drawn up, on top of the qualitative analysis, to choose the best design of the prototypes.

In Solidworks an additional tool is present to assess to flow of a part. The flow simulation tool simulates the flow of air current through the housing. A quantitative analysis is done based on the results of the simulations and conclusions are drawn up. The simulations are done by putting only the right wing of the housing into a pipe exactly the size of the right wing itself. The air is pushed from one end of the pipe to the other by creating a pressure difference between the ends of the pipe. The front end of the pipe represents the outside air with an ambient pressure of $101325Pa$. The other side of the pipe represents the inside of the nose with a pressure of $101227Pa$ which is $98Pa$ less than ambient pressure to simulate inhalation (Section 2.2.2).

The volumetric flow rate at the end of the pipe can be seen in Table 3 in the final column. The prototypes with the largest openings have the highest resulting airflow. Prototypes 2 and 3 do not have a base and therefore have the highest resulting airflow ($212.525cm^3/s$). The airflow of prototypes 2 and 3 is the same because the prototype is the same, apart from the filter holding mechanism. The lowest airflow is generated by prototype 5 ($58.880cm^3/s$) because prototype 5 has the smallest area through which air can flow through.

Prototype 3 is chosen as the definite design of the housing because the top priority of the nasal filter is to not hinder breathing through the nose. The housing of the filter plays a part in fulfilling this requirement. Prototype 2 and 3 have an equal airflow at the end of the pipe meaning prototype 2 and 3 have the best breathability. However, in the category of the mechanism to hold the filer, prototype 2 has a disadvantage compared to prototype 3. The mechanism of prototype 3 ensures a better hold of the filter. The fully developed design of prototype 3 can be seen in Appendix B (Figure 10). In the final design the left wing is added and a bridge to hold the right and left wing together. The bridge sticks slightly inwards, making contact with the septum, holding the nasal filter in place in the nose.

5.4 Cost estimation

An estimation of the cost for the nasal filter can be made. For the estimation the different costs are combined and added up. The different costs include: cost of material, operating costs of the machines, labour costs. The cost of material includes the nylon 6,6 polymer, the polypropylene regular filter, and the elastic resin from Formlabs. Operating costs are for the electrospinning machine and the 3D printer. Labour costs are the costs of the operator handling the machines. The total costs for one filter and for the housing are separated as the housing is reusable but the filter clogs after 140 minutes, as explained in Section 4.3.

First, the cost of producing one filter. The cost of material: nylon-6,6, also known as polyamide 66 (PA) is available for 2 to 4 dollar per kilogram. The volume of the solution needed for the electrospinning process is $0.288mm^3$. 20% of the solution is nylon-6,6 thus the volume of nylon-6,6 is $0.0576mm^3$. With a density of $1.14g/cm^3$, the weight of the needed nylon-6,6 is $0.000065655g$ and the associated price will range from 0.0000001313 to 0.0000002626 dollar. A roll of non woven polypropylene used for medical masks has a price range of 1 to 3 dollar per kilogram. The density is 20 grams per square meter. The filter area is not larger than the nostril area which is estimated to be $131.31mm^2$ using Solidworks. The weight of this area is $0.0026262g$ and therefore the price is estimated to be in the range of 0.0000026262 to 0.0000078786 dollar. The cost of running the electrospinning machine is estimated to be €30 per hour. The electrospinning time was set to 10 seconds. The machine cost of making one filter is therefore €0.084.

The labour cost of the operator(s) for electrospinning is estimated to be €20 per hour. The labour time is assumed to be equal to the electrospinning time. The labour costs therefore add up to €0.06.

The total cost of producing one filter consists of: the cost of material of the nylon-6,6 and the polypropylene, the electrospinning cost, and the labour cost of electrospinning. Adding these costs counts up to €0.14.

Next, the cost of producing a housing. The only material used for the housing is the elastic resin from Formlabs. Elastic resin can be purchased on the website of Formlabs for €200 per liter. With Solidworks, the size of the housing is estimated to be $208.09mm^3$. Therefore the price of one housing, in terms of material cost, is estimated to be €0.041618.

The website of Formlabs gives an estimation of the time and cost to print a product. Products of similar size and complexity have an estimated printing cost of around €10. The printing cost includes a labour cost of €20 per hour. However, the 3D printers of Formlabs are prototyping printers and other 3D printers with a better throughout would reduce costs significantly.

The total cost of producing one housing consists of: the cost of material of the elastic resin from Formlabs and the estimated price determined by Formlabs for similar products. Adding these costs, counts up to €10.04 to produce one housing.

The housing is reusable but the filter needs to be changed after 140 minutes. The total costs for using the nasal filter for one week, with the initial purchase of the housing of €10.04, is €12.00. The total cost is based on the estimation that a person goes outside for four hours each day and therefore needs fourteen filters for one week in total, each costing €0.14.

6 Discussion

Kenney et al. [2015] showed that nasal filters significantly improve hay fever symptoms. However, the Allergic Rhinitis and its Impact on Asthma (ARIA) report does not mention nasal filters. Nasal filters require more research because they show effectivity for treating hay fever symptoms. Nanofiltration could be implemented in the nasal filters to improve nasal filter technology.

The results of this research delivers the design characteristics for a nasal filter using nanofiltration. The nanofilter is created by using the electrospinning technique. The parameters for electrospinning have been specified to produce a nanofilter suitable for usage in a nasal filter. To hold the filter, different prototypes of 3D printable customized housings were developed. The prototype which hinders the airflow the least was chosen for the final design.

The nasal filter had to adhere to certain design requirements. The nanofilter and the housing both had respective design requirements. The nanofilter should filter out pollen particles and not hinder breathing through the nose. The material of the housing should be 3D printable, biocompatible, flexible, and transparent. Furthermore, the design of the housing should be customized to the human subject and not hinder breathing through the nose as well.

The current applications of nanofiltration are mostly in production processes but nanofiltration shows great potential for air filters in general and specifically nasal filters as shown by Han et al. [2018]. Electrospinning is a technique greatly used to produce nanofiber and nanofilters. The electrospinning parameters cause resulting nanofilters to be heavily differentiable. Changing one parameter slightly will result in a different nanofilter. Setting the electrospinning parameters to the settings specified in the research results in a nanofilter capabale of filtering out pollen particles while not hindering breathing through the nose. Furthermore, with the personally customized housing the nanofilter will be held in front of the nostrils. Therefore, breathing through the nose will cause the airflow to go through the nanofilter, thus filtering out allergen, the particles which cause an allergic reaction.

The current situation regarding the COVID-19 pandemic impacted the research. Access to the university has been restricted and the nasal filter designed in the research could not be produced and tested. Therefore, the research is limited because there could not be an iterative process to improve the electrospinning parameters optimally or change the design of the housing. Furthermore, the value estimation of one housing is subject to some assumptions including: the electrospinning operating time is estimated to be 10 seconds but set-up time is not included. The labour costs of the operator are based on the same assumption that electrospinning only takes 10 seconds. The cost estimation of the housing is based on the price of products of a similar size and complexity. The actual cost of the housing may differ from the estimation. Furthermore, the 3D printer to estimate this price is a prototyping printer and the cost of printing would drop considerably when industrial sized printers are used.

According to Jones et al. [1989] there is no connection between resistance to nasal airflow and nasal sensation. Therefore a limit of nasal airway resistance can be set for the nanofilter but the feel for breathability will only be understood when tested with human subjects. Therefore, following research would benefit from producing the nasal filter using the parameters set in the research and testing the nasal filter on human subjects.

7 Conclusion

The goal of the research has been reached and a nasal filter has been designed to filter out pollen particles from the air.

First, design requirements were formed based on the size of allergen and the nasal airflow. The size of allergen determined the pore size needed for the nanofilter. Studying the nasal airflow showed the pressure drop or filter resistance the nanofilter could bear without hampering breathing through the nose too much. Not hindering breathing through the nose was a highly prioritized design requirement by the initiator of the project. The parameters for electrospinning the nanofilter were based on other relevant research papers. Creating the nanofilter by following the parameters set in the research, should, theoretically, result in a filter which adheres to the design requirements of filtering out hay fever allergen while not hindering breathing through the nose.

Second, design requirements were made for the housing of the nanofilter to hold the filter in place and install the nasal filter into the nose. The material of the housing had to be 3D printable, biocompatible, flexible, and transparent. While searching for compatible material a selection was made of five suitable 3D printable materials, also known as resins. The five resins were ranked based on flexibility and the most flexible material was chosen for the housing, based on further documentation as well. The next step was to design the housing. The Computer Aided Design (CAD) software program Solidworks was used to design five different prototypes. The third prototype was chosen for the housing because of qualitative advantages and a quantitative analysis of the airflow through the housing. Prototype 3 had the highest airflow after the filter, meaning the airflow would be hindered the least with prototype 3.

Finally, a cost estimation of producing one nasal filter was drawn up. The different cost elements were added up to a total of €12.00 as the cost per week, including the initial purchase of the housing. The total cost is based on the estimation that a person goes outside for four hours each day and therefore needs two filters per day.

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A Appendix

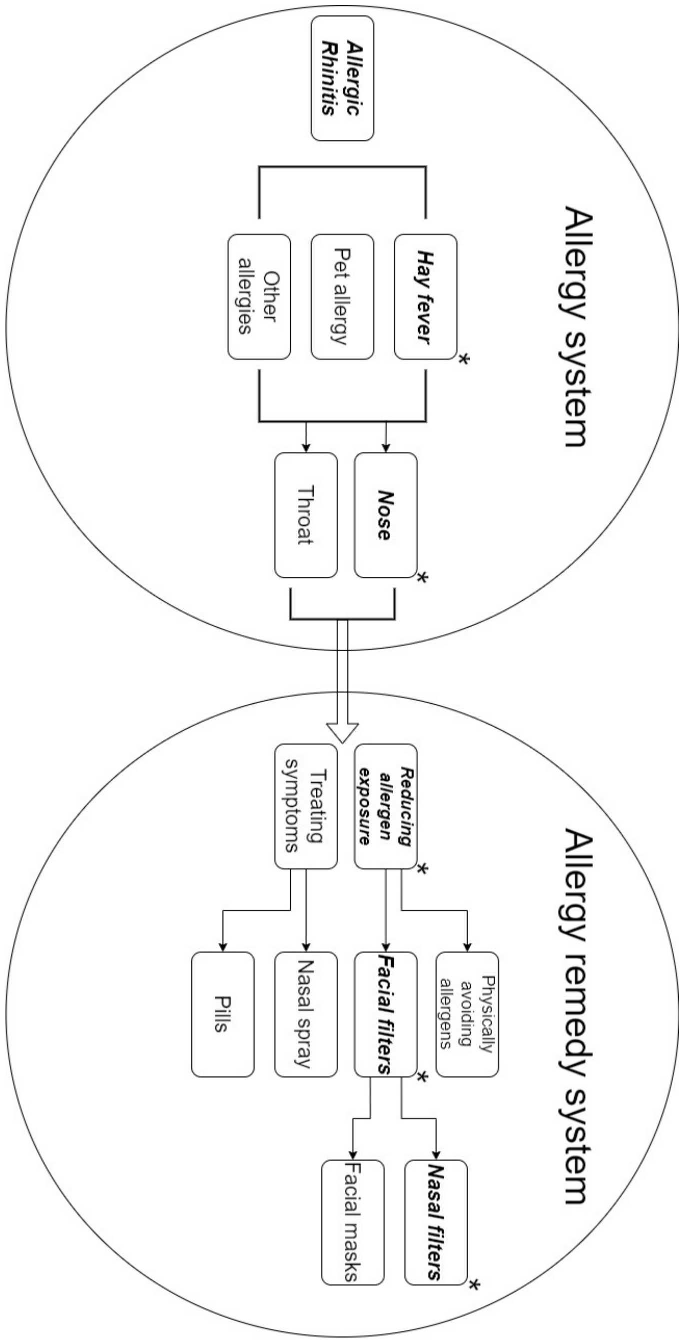

Figure 3: System Description

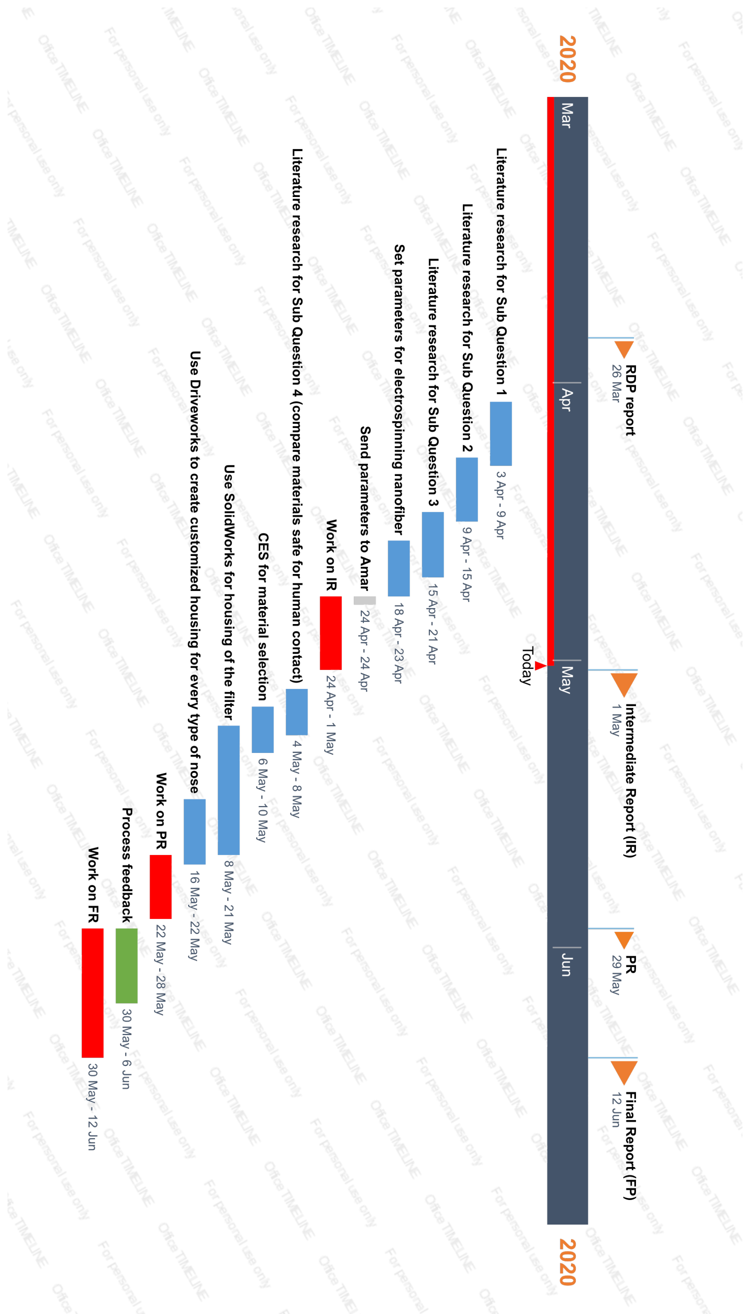

Figure 4: Research Planning

Table 1: Overview of electrospinning parameters and their effects by Zhu et al. [2017].

	Parameters	**Change in morphology or fiber (resulting from high parameter)**
Solution parameters	Concentration	Fiber diameter increases
	Viscosity	
	Conductivity	Straight fibers, fiber diameter decreases
	Surface tension	No conclusive link
Processing parameters	Electric field strength	Decrease in fiber diameter
	Tip-to-collector distance	Higher electric field strength (thus, decrease in fiber diameter)
	Feed rate	Bead generation, increase in fiber diameter
Ambient parameters	Humidity	Increased number of pores
	Temperature	Decreasing fiber diameter

Table 2: Nylon-6,6 concentration, viscosity, conductivity, surface tension, fiber size by Li et al. [2006].

Concentration (wt%)	**Viscosity (Pa*s)**	**Conductivity (mS/cm)**	**Surface tension (mN/m)**	**Fiber size (nm)**
15	0.5	4.62	41.21	-
20	1.5	4.30	42.33	120
25	2.4	3.55	42.57	300
30	8.7	2.90	41.44	700

Table 3: Advantages and disadvantages of the four different prototypes for the housing.

	Advantages	Disadvantages	Volumetric flow rate (cm^3/s)
1	- Filter stays in place - High filter surface - Simple structure		109.850
2	- Very high filter surface - Simple structure, less printing	- Housing not strong enough to keep filter in place	212.525
3	- Very high filter surface - Simple structure, less printing	- Structure relies on adhesion to stay together and could pose problems in removing the parts	212.525
4		- Odd shape of housing - No room for holes - Difficult structure	73.0584
5	- Exhalation valve - (Inhalation valve) - Simple structure	- Difficult to cut rubber suitable for valve function	58.881

B Housing prototypes

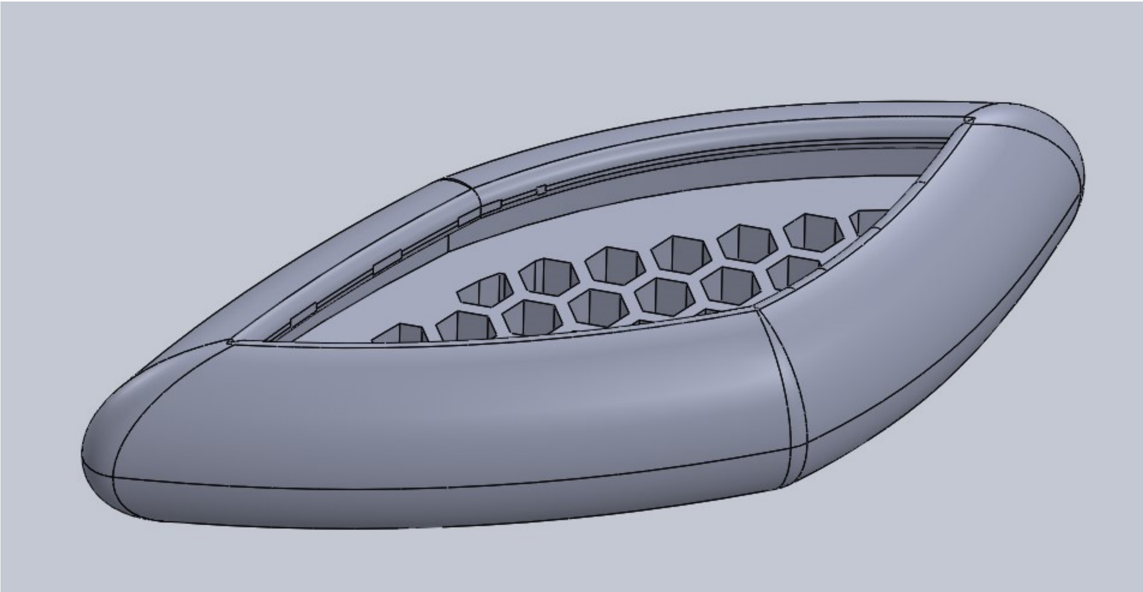

Figure 5: Prototype 1: 1*mm gap to hold the filter. Honeycomb hole pattern for airflow.*

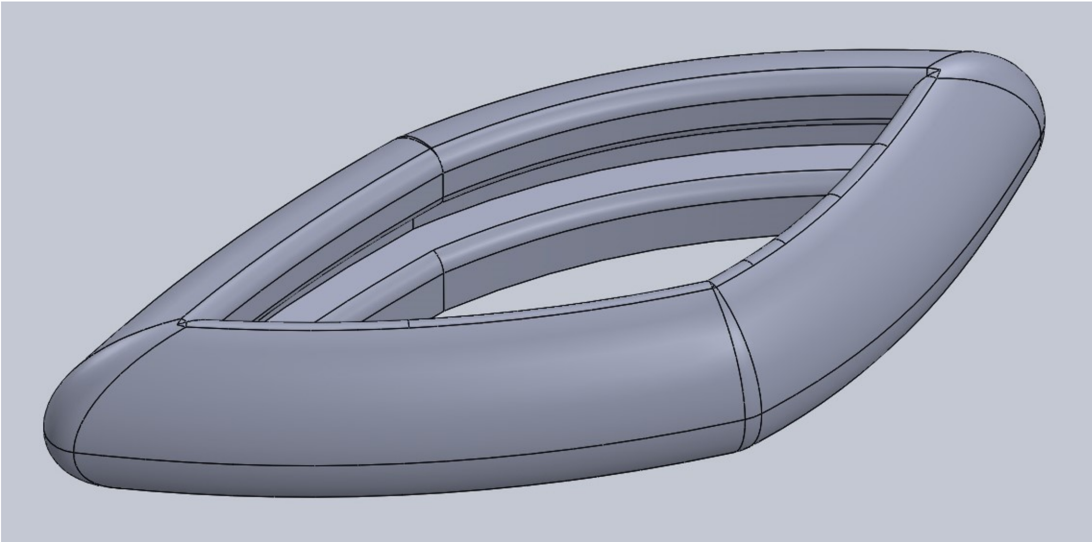

Figure 6: Prototype 2: 1*mm gap to hold the filter. Single hole for airflow.*

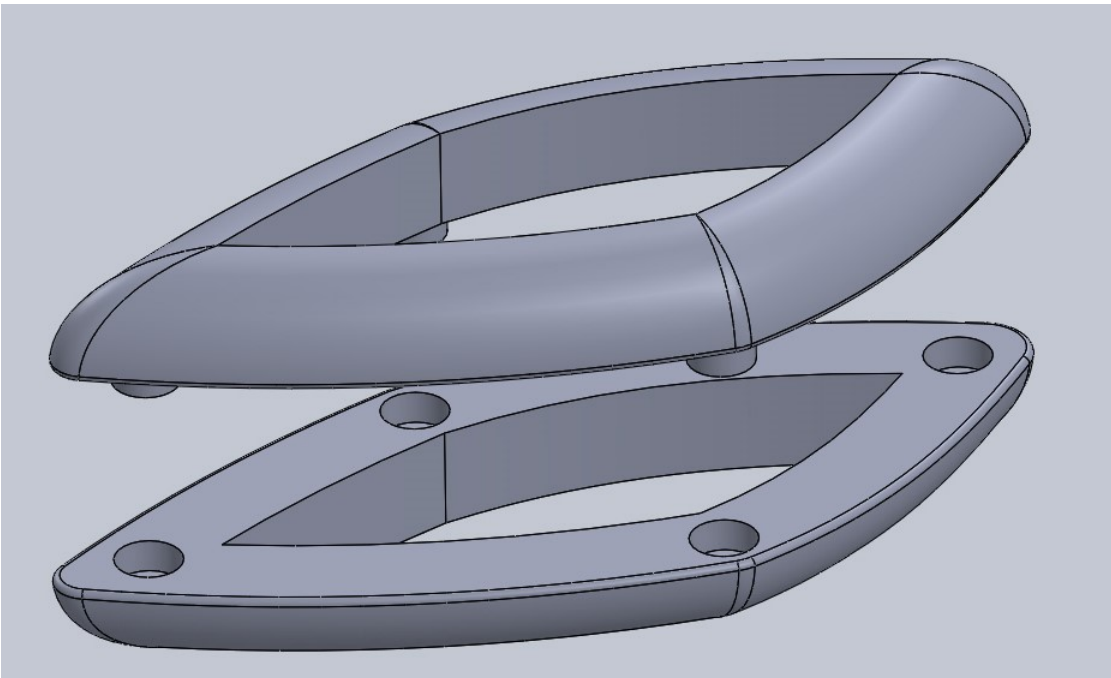

Figure 7: Prototype 3: Two parts fit into each other by means of protrusions, filter is cut with similar holes to hold the filter. Single hole for airflow.

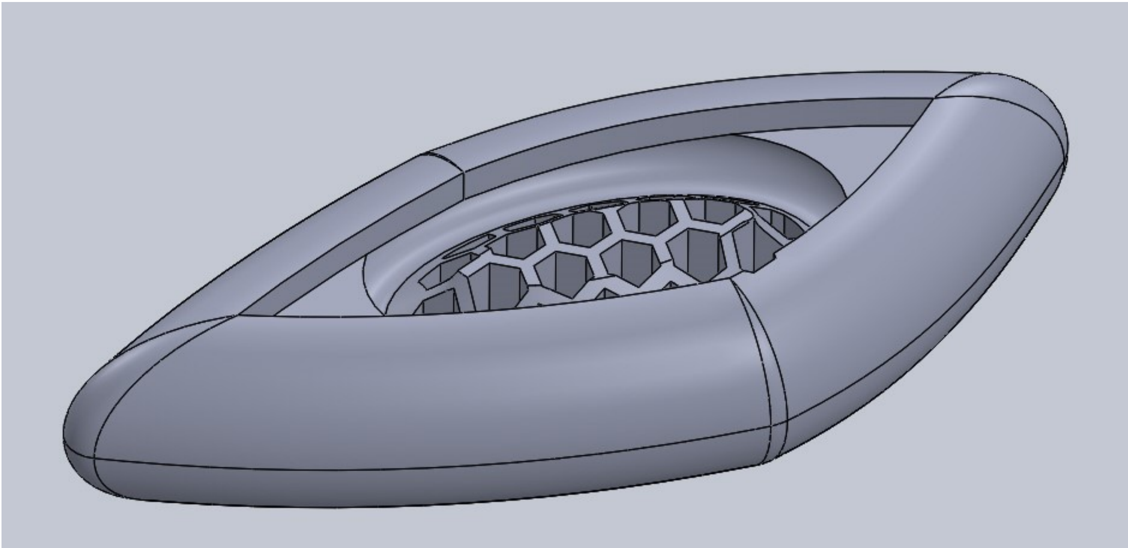

Figure 8: Prototype 4: 1*mm gap, in a oval base, to hold the filter. Honeycomb hole pattern for airflow.*

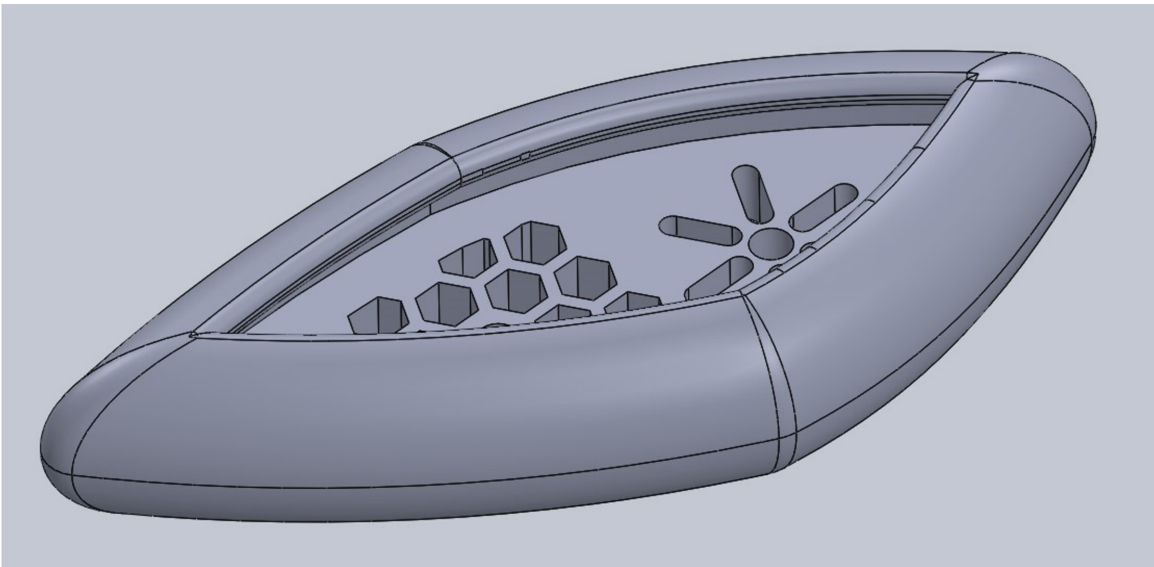

Figure 9: Prototype 5: 1*mm gap to hold the filter in the bottom part. Honeycomb hole pattern for airflow. Top part includes holes suitable for an exhalation valve*

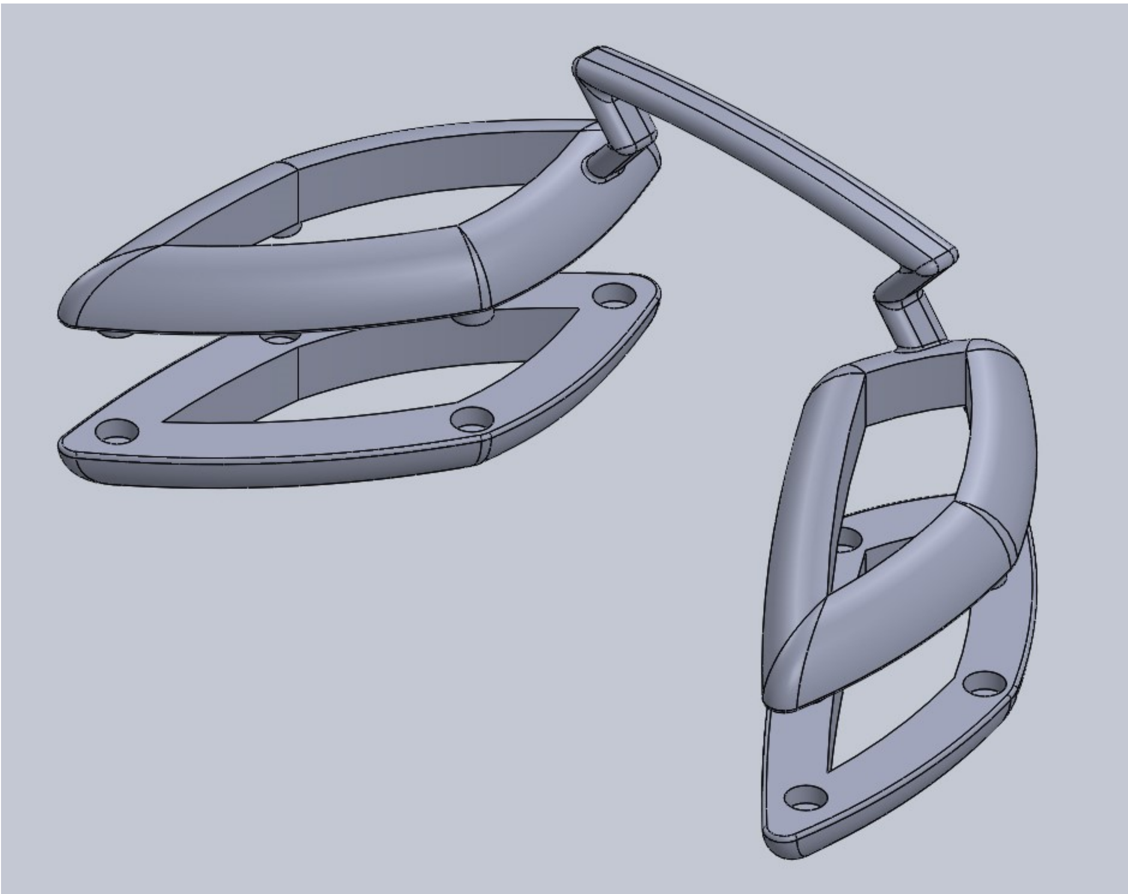

Figure 10: Final design including all parts: right wing, left wing, and the bridge.