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Airstacking Machine

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Abstract

Background: Patients with a restriction in the use of the muscles associated with the respiratory system are prone to complications. To prevent these complications a technique called airstacking has been developed. This technique requires the manual use of a resuscitator. However for some patients with restrictions in the hand function, airstacking is only possible with help of a caregiver.

Design: To make the procedure of airstacking more available and comfortable for the patients with limited hand function, it was decided to develop an airstacking machine. However, before a design would be made, a validation of the technique of airstacking was needed. A small group of patients at the hospital showed a definite increase in maximum airflow. This indicates that airstacking works and validates the request for a machine. In the development it was decided to use a resuscitator as a base, as this is currently used to airstack and therefore a proven concept. Experiments were done to find the most optimal shape of the pressure piece and method to generate the compressing motion. Several principles of compression and transmission have been considered, but it has been found that curved pressure pieces in combination with a toothed rack were the most viable construction for the prototype.

Conclusion: Patients with a lowered PCF will benefit from airstacking. For patients with a disability in their hand function this technique is impossible to do. Therefore a machine was designed, taking into account the patient specific adaptability of the machine. At this moment the machine is in its construction phase and cannot be assembled and tested yet. Therefore no final conclusions can be made at this moment. If the machine is proven to work, it will, without a doubt, be an improvement for the patients with a limitation in hand function who require airstacking.

Preface

In this bachelor thesis for Technical Medicine, a research has been done to develop an airstacking machine for patients with a neuromuscular disease. This research has been done for the Center of Mechanical Ventilation at Home of the UMC Utrecht.

We would like to thank our medical supervisor dr. Michael Gaytant and our technical supervisor dr. ir. Frans H. C. de Jongh for their effort and support. Also, we would like to express our appreciation to Nicole Rommens BSc who helped us manage our teamwork and evaluate the group process. Futher we would like to thank Erik Koning and Wendy Klinkhamer of the Center for Mechanical Ventilation at Home for their support in the development of the airstacking machine. We want to thank John van Veldhuijzen for the making of the draught and assembling the machine. Finally we would like to thank Bert Lemstra, who helped us to programm the motor.

Contents

1. Introduction

In the Netherlands 100.000 people suffer from a neuromuscular disease [2]. Most of them will also be troubled with respiratory dysfunction. Eventually, they will need to be treated with home mechanical ventilation. In the Netherlands around 3000 people are treated with mechanical ventilation. In 2011, 83% of those patients were actually treated at home, the remaining 17% are living in nursing homes or other facilities [3]. A technique called airstacking has been developed, primarily to improve the cough flow of those patients. By improving their cough flow the risk pulmonary complications, like airway infections and atelectasis, can be reduced. This, in combination with an increased thoracic and pulmonary compliance, because the Maximum Insufflation Capacity (MIC) is reached more often, can lead to postponing mechanical ventilation and an improved quality of life [4]. Nearly all patients who are treated with mechanical ventilation could profit from airstacking. Also patients in the preliminary treatment of home mechanical ventilation, who have an ailment which sooner or later leads to a treatment with mechanical ventilation could benefit. The group of patients in a preliminary treatment is a group of around 1000 patients in the Netherlands [5].

1.1 Airstacking

By airstacking the patient increases his Inspiratory Vital Capacity (IVC) by stacking several breaths. The patient uses his oropharyngeal and laryngeal muscles to close his glottis between the breaths. For airstacking, it is essential that the patient is able to control these muscles [6, 7]. Because most of the neuromuscular patients have less function of the respiratory muscles and cannot fully inflate their lungs, a resuscitator is used to obtain those breaths. The patient inhales as far as he can and then compresses the resuscitator to obtain more inflation. The glottis is closed to hold the breath. For the next breath, the resuscitator is compressed at the same time the patient relaxes his glottic muscles. This is done between two and four times until the MIC is reached [6]. The standard advise for airstacking is 3 times per day a session of 5 times airstacking.

The main goal of airstacking is to improve the cough flow. The cough flow is influenced by the IVC and the strength of the expiratory muscles. Because the IVC is increased by airstacking, the cough flow is also increased. In a healthy person, the inspiration before a cough is 85-90% of the Total Lung Capacity (TLC). After that, the glottis is closed by the glottic muscles. Then, the expiratory muscles build up an intrapleural pressure of 200 cm H_2O. When the glottis is opened, a cough flow of 300–1200 L/min is generated, causing the airway secretions to be expulsed [6]. A less effective cough flow leads to an increased risk of airway infections, which leads to more hospitalization [7]. Patients will start airstacking when the Peak Cough Flow (PCF) falls below 270 L/min, when the predicted value of the Vital Capacity (VC) reaches below fifty percent or when it falls below 1.5 L [8].

Another goal is to improve the pulmonary compliance. When the MIC is reached, the chest and lungs are fully expanded. When this is done more frequently, the thoracic and pulmonary compliance will increase [9]. Also, the risk of atelectasis will be reduced as collapsed alveoli will be reopened. An increased compliance will make it easier for the lungs to inflate, causing the IVC to improve as well [10]. An increased compliance leads to less hospitalization and postponing the need of mechanical ventilation. Patients with Duchenne Muscular Dystrophy (DMD) for example, start airstacking between the ages of six and eight. Normally, they have to be treated with mechanical ventilation around the age of 20. However, when they start airstacking at an early age, that treatment can be postponed a few years [4, 5]. Also by training the glottic muscles, airstacking will become easier. By training those muscles, also the voice volume and duration will improve [11].

1.2 Problem definition

When the patient loses hand function because of the disease, manually compressing the resuscitator becomes impossible for the patient. Therefore a caregiver is needed to help the patient with airstacking. For successful airstacking a good communication between the patient and the caregiver is essential. For example timing is very important, as the patient has to relax his glottic muscles at the same time the caregiver compresses the resuscitator. Also, every patient uses different volumes and a different frequency for airstacking. They develop a personal method, which they think is pleasant. For some patients who suffer from a neuromuscular disease, good communication can be very hard. This, in combination with poor handling by the caregiver may cause the airstacking to be less efficient. When the patient has a partner who can help him airstacking, they can practise and learn to understand each other. However, when the patient does not have a partner, or lives in a facility where he is dependent of up to 30 different caregivers, airstacking can be an problem. They are 30 different people who all communicate differently, making it very hard for the patient to develop an own effective way of airstacking [12].

Normally, airstacking is advised to be done three times a day. When a patient has a lot of mucus retention however, airstacking about 20 times a day is desirable [5]. This costs a lot of time and for the patient it can feel very inconvenient to call a caregiver 20 times a day. The extra care that the patients get, also have additional health care costs as a result.

The health care costs will also increase when the airstacking is less effective. The patient will be more often hospitalized due to mucus retention with a pneumonia as a result [13, 14]. An airstacking machine will indirectly have better care as a result, since pneumonias can be avoided. This will also lead to fewer hospitalizations, which will reduce the healthcare costs.

A solution can be using a machine, which the patient can use for airstacking. Patients who are using home mechanical ventilation are able to use their ventilator for this purpose. However, not all types of ventilators are suitable. One of the older types, the PLV-100 is suitable. This machine has an adjustable volume, flow and frequency [15]. This way, patients can choose the settings they prefer and they can start airstacking whenever they want. However, this machine will no longer be supported after 2017, because it is obsolete. Most of the newer mechanical ventilators are not suitable for airstacking, because they are equipped with a safety feature that prevents the pressure in the lungs to build up to high. A simple solution would be a function on the new mechanical ventilators to block the safety feature, but the manufacturer doesn't want to cooperate here [5]. This means for patients with the older mechanical ventilators that, when the old machine has to be replaced for a newer one, they have to start airstacking with a resuscitator handled by a caregiver. This causes a major restriction in the autonomy of the patient.

Another machine that can be used is the cough assist (also called coughlator or mechanical in- and exsufflator). This machine first inflates the lungs by producing a positive pressure and then deflates the lungs by producing a negative pressure [16]. However, this machine is developed with the aim of airway clearance only, while the aim of airstacking is airway clearance and also improving the compliance. Besides that, a cough machine costs about €4500. In the Netherlands using a cough assist is still an experimental treatment which is not covered by the insurance companies. Therefore the cough assist is preferably used in hospital with patients using tracheastomal ventilation [5].

An airstacking machine, a machine developed for the purpose of airstacking, would solve a lot of problems. The patient will be able to airstack in his own way, by adjusting the tidal volume and the frequency. When such a machine is easy to operate, also for patients with decreased skeletal muscle function, patients would be less dependent of caregivers. A machine may also increase the adherence of therapy, because it would be easier for the patient to use.

Considering all these issues, the following research question has been phrased:
How can an airstacking machine be developed for patients with decreased cough flow due to a neuromuscular disease, which can be operated by patients with a decreased function of skeletal muscles?

To answer these questions the following issues will be examined:

- Which patients would profit from airstacking?
- What risks are associated with airstacking?
- What is the optimal method to produce the air flow?
- How can air volume and frequency be regulated?
- How can high durability of the machine be achieved?
- How can the machine be made user friendly for patients with severe limited hand function?

1.3 Patient group

Between the 3000 and 4000 patients could profit from airstacking [1]. The patient group consist of nearly all patients with mechanical ventilation and around 1000 patients who are in the preliminary stages. This group mainly exists of patients with a neuromuscular disease; however, patients should still be able to control their glottic muscles. Patients with a tracheastomal cannula are excluded for airstacking. In figure 1 is shown that the size of the group of patients with a neuromuscular disease with mechanical ventilation at home increases rapidly.

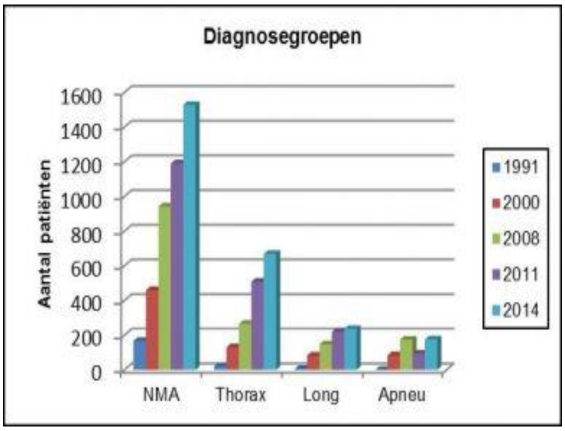

Figure 1: Numbers of patients treated with chronically mechanical ventilation: A division between patients with a neuromuscular disease (NMA), patients with a thoracic handicap (Thorax), patients with lung disease (Long) and patients with sleep apnoea (Apneu) [1].

This leads to more patients for whom airstacking would be beneficial. Airstacking could also be beneficial for other patients with neuromuscular diseases without mechanical ventilation.

The patients with a neuromuscular disease who are currently airstacking, suffer from different diseases: Duchenne Muscular Dystrophy, Steinert's disease, Spinal Muscular Atrophy, Amyotrofic Lateral Sclerosis and Post-Polio Syndrome. Also patients with Paraplegia and ribcage disorders (like kyphoscoliosis) are airstacking. Furthermore there are several rarer diseases like Glycogen storage disease type II (also known as Pompe disease) to whom the airstacking machine may also be beneficial.

1.3.1 Duchenne Muscular Dystrophy (DMD)

DMD is a progressive, X-chromosome linked disease. 70% of the cases is inherited, 30% are de novo mutations [17]. This mutation causes a lack of the protein dystrophin, an important protein in muscle function. The process of muscle deterioration starts with the proximal muscles of the limbs, spreading perifericallly. Because of this the hand function will decline as well.

The respiratory muscles will also deteriorate, because of this the patients will have to start with mechanical ventilation [18]. The decline in respiratory muscle function causes a decline in cough strength and compliance as well. Therefore airstacking is taught to these children at the age of six [5]. The Incidence of DMD in the Netherlands in male births is 23-24/100.000 [18].

1.3.2 Steinert's disease

Steinert's disease, also known as myotonic dystrophy, is a muscular disease caused by an autosomal dominant mutation. This mutation also has a property called anticipation, this causes an increase in seriousness of the disease over the generations [19]. The disease eventually causes progressive muscle weakness, however the course of the disease is very variable. In more serious cases the disease may cause a weakness in the respiratory muscles, which in turn may cause pneumonia [20]. To prevent this, airstacking is prescribed for patients who are at risk [5]. The prevalence of Steinert's disease in the Netherlands is 10/100.000 [20].

1.3.3 Spinal Muscular Atrophy (SMA)

SMA is a disease caused by a defective autosomal recessive mutation on chromosome 5. This gene, called SMN1, is essential for survival of motor neurons [21]. When the motor neurons degenerate, the control and innervations of the muscles degenerates as well. This starts with problems in peripherical regions, spreading proximally. The prevalence of SMA in the Netherlands is about 20/100.000 [22].

1.3.4 Amyotrophic Lateral Sclerosis (ALS)

ALS, also known as Lou Gehrig's disease, is caused by the degradation of motor neurons. The first signs are a weakness in the muscles of the limbs. This degradation of motor neurons continues throughout the body, eventually also affecting the respiration. The incidence of ALS in the Netherlands is 2-3/100.000/year [23].

1.3.5 Post Polio Syndrome (PPS)

PPS is a disease that develops decades after a patient has had an infection with poliomyelitis and is caused by a degeneration of nerve endings. In a small part of the cases this disease causes a respiratory insufficiency. In these cases airstacking may be a useful therapy to prevent a further increase of the insufficiency. The prevalence is about 70-100/100.000, as said only in a few of these patients the respiratory system will be affected [24].

1.3.6 Paraplegia

An injury to the spinal cord may result in paraplegia, the higher the injury, the more organs will be affected. The respiratory muscles are affected when the injury is at thoracic or cervical level. Paraplegia above C7 results in both respiratory and hand function impairment. The number of cases is low and the specific consequences are variable [25].

1.4 The effect of airstacking

To see what is the effect of airstacking on patients with a neuromuscular disease an afternoon was spent in the outpatient clinic for airstacking at UMC Utrecht. During the consultations the IVC and the PCF before airstacking were measured, after airstacking the PCF was measured again as well as the MIC. The IVC and the MIC were determined with a hand spirometer and the PCF with a PCF-measurement device.

The measurements of seven patients are presented in table 1. These values are a good example of the effect of airstacking on patients with a neuromuscular disease. In the table is shown that the MIC increased in all patients. On average, the MIC after airstacking was 729 ml higher than the IVC before airstacking. The PCF after airstacking improved on average 111 l/min in comparison with the PCF before airstacking.

Table 1: The effect of airstacking for patients with a neuromuscular disease.

	Male/ Female	Age	Diagnosis	IVC *(ml)*	MIC *(ml)*	PCF *(l/min)*	PCF after MIC *(l/min)*
1	Male	56	Steinert's disease	1220	1460	170	320
2	Male	20	Limb Girdle muscular dystrophy 2E	2390	2590	260	370
3	Male	62	ALS	2200	2540	250	375
4	Female	53	Steinert's disease	1830	2920	175	250
5	Female	53	ALS	1230	2620	210	320
6	Male	47	ALS	1750	2830	130	160
7	Male	24	DMD	1560	2320	110	290

1.5 The risks of airstacking

According to Bach et al. [4, 9], there or not a lot of risks associated with airstacking. No barotraumas or other complications were reported in 1000 patients in the last 28 years. There are only two reports about risks of airstacking. One report is about intestinal barotrauma in a nine-month-old infant with neuromuscular weakness. The passive lung inflation with a one-way valve led to a perforation of the duodenum as well as an incidental annular pancreas [26]. Another report is about a pulmonary barotrauma caused by airstacking. A 72-year old woman with PPS, torsion scoliosis and infrequent asthma attacks had a suddenly developed pneumothorax [11].

2. Methods

2.1 List of demands

First, a list of demands for the airstacking machine was composed. Hereby a clinician, a technologist, a mechanical engineer and a number of patients were involved. An afternoon was spent in the outpatient clinic for airstacking at UMC Utrecht. Patients were asked what they would think of an airstacking machine and what they would expect of it. Also, one patient was interviewed more extensively. Then a selection was made of each party's requirements. The requirements are divided in which are demanded for the prototype and which are demanded for further production. Also, the desires for the prototype or the further production are categorised.

2.2 Pressure part

Then, the shape of the part that will pinch the resuscitator, which will be called the pressure part, was determined. Therefore, the properties of the resuscitator needed to be investigated. A gas flow analyzer was used to determine the volume, the flow and the airway pressure when the resuscitator is deflated. To obtain realistic values, the resuscitator was connected to artificial lungs. The gas flow analyzer was placed between the artificial lungs and the resuscitator. Three study subjects squeezed the resuscitator to measure the effect of different hand size on deflated volume. Also, the effect of using one or two hands was measured.

Then, several possibilities for the pressure part were tested: rectangular pieces of plastic with a width of 20, 40, 60 and 80 mm, a point with a diameter of 15 mm, a spherical piece of plastic with a diameter of 100 mm, a cylinder with a width of 50 mm and a belt. The volume and flow curves of the different pressure part were compared. Then a selection was made of suitable possibilities. To make a final decision, the forces needed to compress the resuscitator were measured, as described under 'motor specification'.

2.3 Linear driving

An electric motor will be used to drive the system. The axis of the motor has a circular movement and for the compression of the resuscitator a linear movement is needed, therefore the circular movement has to be converted into a linear movement. For this linear driving a list is composed with current possibilities for converting circular to linear driving. This list was made based on our own knowledge and by the use of two different internet sites [27, 28]. Some types of drivers were not included because they were too complex or not feasible for this project. After the list was composed, a selection of possible feasible drivers was made, which was based on the list of demands. The remaining drivers were further elaborated, the advantages and disadvantages were explored and the costs investigated. For all of the remaining drivers a 3D drawing was made, using SketchUp 2015. All these ideas were presented to the concerned parties and the most suitable driver was selected.

2.4 Motor specification

It was decided to use a stepper motor for the airstacking machine, because this type of motor is easiest to program using Arduino. A servomotor was not suitable, because it is not developed for multiple rotations. A DC motor would be less durable due to the use of carbon brushes which need to be replaced after a certain amount of revolutions.

To establish the required motor specifications, the force needed to compress the resuscitator was measured. This was done, simply by using a weighing scale. The resuscitator was placed on the weighing scale and then compressed. The mouth piece of the resuscitator was partially covered up, to generate a resistance that is estimated to be similar to the lungs when they are almost fully inflated. Also, the forces were measured without any resistance. This is estimated to be the resistance when a patient starts airstacking, when the lungs are at functional residual capacity.

The electric motor has to fulfil several specifications. First of all it has to make enough revolutions in order to achieve the required speed. Besides the speed it also needs enough angular momentum (torque) to overcome the force needed to press the resuscitator. To transmit the force from the motor to the linear driving, transmission is needed. The explanation of the calculations of the motor specifications and transmission is attached in appendix 1.

2.5 Motor Control

A script was built to program the motor in such a way that it controls three parameters: the tidal volume, the length of a breath and the flow. The script was loaded onto the ATMega chip of an Arduino, which in turn controls the motor. The Arduino was used, because it is an easy tool for prototyping. It also contains the logic which is needed for the control of the three parameters.

The script was written in the programming language C. It was not written in Matlab, because Matlab is an intermediate step which converts its script also into C, most likely with its own libraries. Now there is full control of the final product. When the code is written to the ATMega chip, it saves the program. To use it in another environment, it only needs to be powered. To provide enough power to the motor, which the Arduino cannot do on its own, a motor control shield was used [29].

2.6 Validation

Because the prototype was not finished in time, additional measurements were done to estimate the function of the airstacking machine. The force, the pressure and the flow, that is produced by the resuscitator during airstacking by two healthy persons, were measured. Also the PCF was measured, before and after airstacking. The forces needed to compress the resuscitator were measured by using a weighing scale, as described under ‘motor specification’. The resuscitator was compressed manually, by using a fist. A gas flow analyzer was placed between the output of the resuscitator and the mouth piece to measure the pressure and the flow. Three measurements were done by two healthy persons. To simulate a restricted thoracic compliance, a lashing strap was bound around the chest.

3. List of demands

The list of demands is divided in demands for the prototype, wishes for the prototype and demands for a series product. In appendix 3 a brief overview is shown of the list of demands. First the demands for the prototype will be discussed.

3.1 Demands for the prototype

The objective is to build an airstacking machine that can be used by patients at home. Most patients in the patient group have a neuromuscular disease, and therefore have a limitation in the use of their muscles. This may lead to an impaired hand function. Therefore the patient needs to be able to operate the device as easily as possible. The device needs to be adaptable for patient specific operation, therefore we will use a computer and a switch. This operation of the device includes the regulation of the volume, frequency and flow. This regulation is needed to make the machine adaptable to the patient's wishes. Adaptation to the patient's wishes also means that the breaths should be able to be taken within a short period of each other. This also means that the compartment which gives the volume must be refilled in a short period, and at least be as fast as a resuscitator.

For the materials needed, the following requirements are set: it must be possible to use standard materials in the tube from the machine towards the mouthpiece. This is chosen to be able to use and adapt pressure valves, one-way valves and different mouth pieces. This also makes it possible to select the best available tube for each situation.

As will be explained under 'Design', the machine must be able to deliver at least 1400 ml for every breath. This is because 1400 ml is about the maximum someone is able to deliver manually with a resuscitator. Some patients are used to this volume and the goal is that these patients do not need to adapt their customs when they start airstacking with an airstacking machine.

The materials used must be hardwearing and durable. This means low maintenance, so the dependence of the patient on other persons is limited.

The final requirement for the materials is the price. Some of the treatments used, are not paid for by insurance companies. Therefore it is important that the device will be both effective and affordable for patients and the health facilities.

The safety class of our system must at least fulfil class II, this means a double insulation, in such a way that it is impossible that a single failure can cause a shock to the patient. Therefore we will use double insulation of all parts that are using and transporting electricity. This also means a residual-current circuit breaker is not necessary. Another safety measure is that if the patient stops the input, the machine should stop as well. Pressure limitations will be put in place by elements used in the tube.

The drive must be electric-mechanically driven and operated by the patient. The main power source will be primarily a power socket, and secondary an internal power source is preferable.

3.2 Wishes for the prototype

For the prototype there are some wishes as well. First of all, it should have easily removable and interchangeable parts. Not only for the adaptations, but to use the parts in another (manual) system as well, in case the device is broken and needs to be repaired. The labour for maintenance should be as low as possible, this implies a low number of moving parts. This is also important for the hygiene of the device.

Furthermore, there is a wish to make a holder for the mouthpiece. This gives a certain resistance so the patient can use a face mask instead of a mouth piece for example.

Considering the interface, it is known that several types are available. Therefore it is a wish that the prototype is adaptable to these different interfaces. An example is the mini-joystick on certain types of wheelchairs.

For transportation or purposes when there is a power cut, an internal battery is desired.

3.3 Demands for series

There should be a fool- and children proof interface and maintenance, to prevent unwanted changes or failures in maintenance. Also there should be a possibility to use the device without hand function, this is important for patients without hand function, so they can trigger the airstacking machine by inhalation. Adaptability of the machine is important as each patient is different, and therefore each patient's needs. Because of this we wish to make the device expandable with standard additions.

Furthermore operation on different voltages is preferred because the use of this device is not limited to the local market, but also to patients abroad. Thereby the patients who are helped by this device might also want to travel. Also the device will have to fulfil all the legal requirements, for example the requirements of the guidelines 93/42/EEG.

3.4 Wishes for the series

There are also some wishes for the serial production. The device has to become watertight, so patients can take it with them on their wheelchair. When it can be taken on the wheelchair it has to become compact and light. Also it should be shockproof to make travelling easier. A possibility is to add an air filter to prevent unwanted particles to come into the machine.

4. Design

At the outset, it was decided to use a resuscitator as the base of the airstacking machine. This was decided to keep the costs for the machine as low as possible. A turbine model would have been less affordable. A model with a pressure compartment was considered as well, but that model would not have been compact enough. The resuscitator is currently used for airstacking and is therefore easily replaceable as its accessories are already available. When using a resuscitator as the base, only a compressing mechanism had to be developed.

4.1 Pressure part

The deflated volume by squeezing the resuscitator with both, one hand and two hands are shown in figure 2. With all three subjects, using one hand resulted in clearly more deflation than using two hands. This was expected, because with using one hand, the resuscitator was placed on the table while the subject squeezed it using his whole hand. When using two hands, the subject only used his fingers to squeeze the resuscitator. Most patients and caregivers however, use both hands, because that is the easiest way to manage the resuscitator.

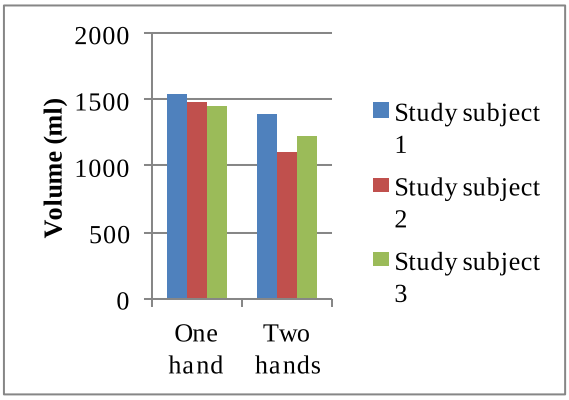

Figure 2: Volume compared to compressing the resuscitator with one or two hands.

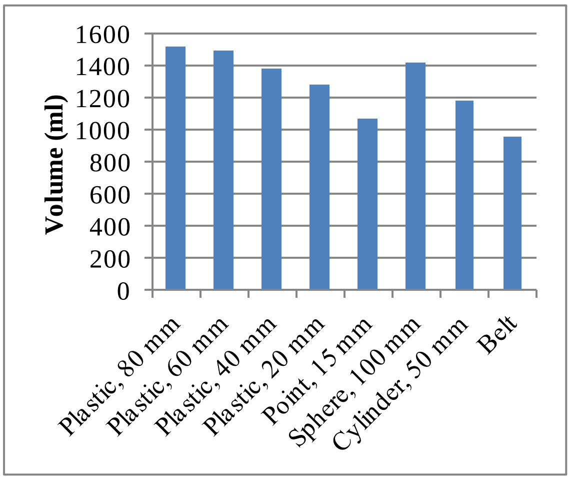

Figure 3: Volume compared to different shapes of pressure pieces.

The maximum volume that was deflated using both hands was around 1400 ml. That means some patients are used to airstacking using a volume of 1400 ml each breath. For the airstacking machine this means it should be able to deliver 1400 ml in one deflation. As shown in figure 3, the 40 mm and 20 mm plastic, as well as the point, the cylinder and the belt do not meet that requirement. Also it was clearly sensed that using a belt to squeeze the resuscitator takes much more force. Three possibilities remained: the 80 mm and the 60 mm piece of plastic and the sphere. Therefore it was decided that the forces needed by using a flat pressure piece or by using a spherical pressure piece should be measured first. For measuring these forces, a flat hand was used to simulate a flat pressure piece and a fist was used to simulate a spherical pressure piece. As shown in figure 4, using a fist costs much less force than using a flat hand. The average force needed without resistance by using a fist was 28 N. The average force needed without resistance by using a flat hand was 47 N. With a resistance the force needed by using a fist was 58 N and by using a flat hand was 87 N. Therefore a spherical shape of the pressure piece was chosen.

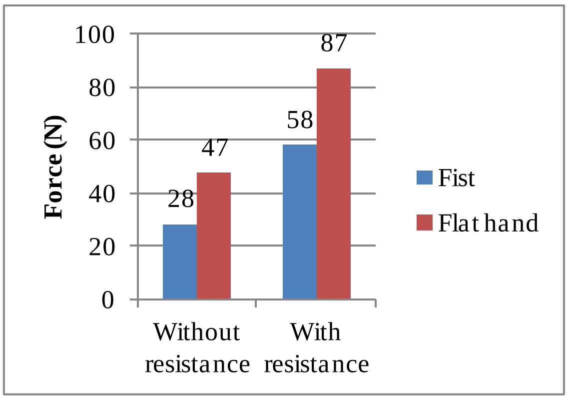

Figure 4: Forces for compressing with a fist compared to compressing with a flat hand.

4.2 Compression movement

There are two ways to compress the resuscitator. The first is to make the compression from two sides, the other is to compress from one side. The first has the advantage that the resuscitator will not move, and thus that all the external links will be on fixed positions. However this also has a major disadvantage, as the movement has to originate from both sides. This implicates an organized and calibrated mechanism, which is complicated. Therefore our choice has gone to the compression system from one side. This will not need a calibration nor organization. The concession we will have to make is that in the prototype the tube to the patient will vary in position during operation. This does cause extra wear on the tube, however as this is a prototype we will take that for granted.

4.3 Linear driving

The next kinds of circular to linear driving were found: a toothed rack, chain, cable coiling, rigid chain actuator, crankshaft, trapezoidal thread, roller screw, linear actuator and scotch yoke. Four of these options were not included in de final selection because they didn't fit to the list of demands or they had too much disadvantages in comparison with other options. One of the drivers that was not included was the chain (fig. 5a) The mechanism is similar like the mechanism of cable, but needs al lot more lubrication. More lubrication has the result that the airstacking machine needs al lot more maintenance, while one of the demands is to keep the maintenance as low as possible. Another mechanism that was excluded was the trapezoidal thread (fig. 5b). The trapezoidal thread is similar to the mechanism of the rack and pinion, but the toothed rack is less complex than a trapezoidal threat and is much easier to obtain. The third mechanism that was not included was the roller screw (fig 5c). This system has an insufficient speed; it is not fast enough to apply in the airstacking machine. The last mechanism that was excluded is the scotch yoke (fig. 5d). If this system has to reach the desired trajectory of the compression, it will become an extensively large system and therefore it will not be compact enough. The driving-systems that remain to be elaborated are the toothed rack, cable coiling, rigid chain actuator, crankshaft and linear actuator [27, 28].

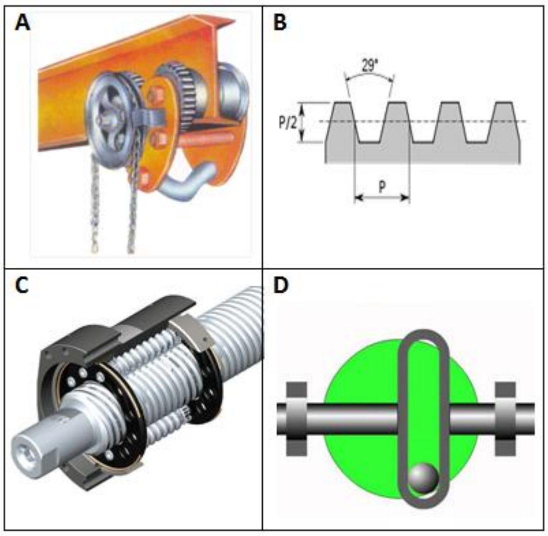

Figure 5: Four types of linear driving: A chain, B trapezoidal thread, C roller screw, D scotch yoke. [34, 35, 36, 37]

4.3.1 Linear actuator

The first driving that will be elaborated is the linear actuator (fig. 6). The axle of the linear actuator moves in a horizontal motion. With this actuator there will be no need to establish a circular to linear movement transmission, all of the other driving will need this transmission. On the top of the axle the pressure part will be secured. The linear movement establishes the compressing of the resuscitator. The expected dimension of the case with a linear actuator will be 450 mm x 250 mm x 300 mm. An advantage is only one part is needed for the driving, because no transmission is needed. This also means less maintenance is needed, because there is only one moving part. The regulation of the tidal volume is another advantage, the tidal volume is easily adjustable. The biggest disadvantage of a linear actuator is the costs in comparison with the speed. A linear actuator costs about €185,-. This actuator can reach a speed up to 45 mm/s, this is too slow to apply in the airstacking machine [30]. Some actuators can reach the speed of 130 mm/s, only these cost about €600,- and that's too expensive. Another disadvantage of a linear actuator is that some actuators tend to be unreliable.

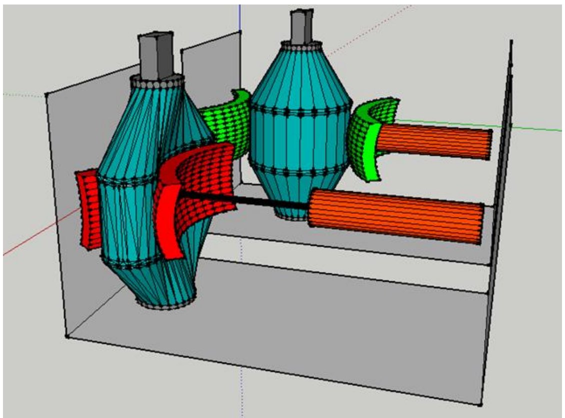

Figure 6: Linear actuator

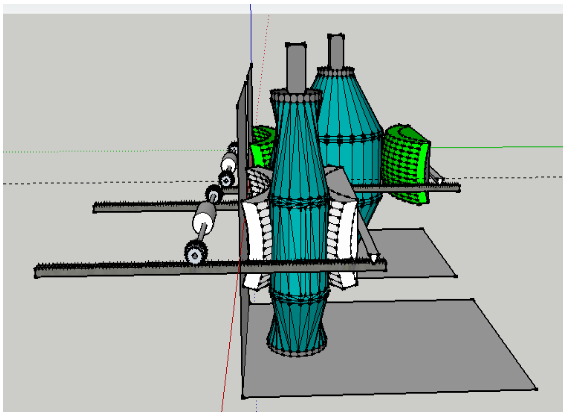

Figure 7: Toothed rack

4.3.2 Toothed rack

The second driving will be the toothed rack (fig. 7). In this system a cog-wheel runs over a rack and this provides a linear motion of the rack. When the pressure part is attached between two racks, a linear motion of the rack results in a motion of the pressure part; this motion provides the compressing of the resuscitator. The expected dimension of the case with a the toothed rack will be 450 mm x 250 mm x 300 mm. The toothed rack is a cheap and readily available system, also the tidal volume is easily adjustable. Another advantage is that the toothed rack driving can reach the target speed. A disadvantage of this driving is that lubrication is needed, but this can be solved by the use of synthetic material for the rack and cogwheel. Another disadvantage is the dimensions of the case. Because moving racks are used, the size has to be at least twice the trajectory of the compression.

4.3.3 Rigid chain actuator

The third driving is the rigid chain actuator; the rigid chain is a chain that can push (fig. 8). The rigid chain consists of interlocking links that behave like a chain. When aligned and pushed in the right direction the links behave like a bar, because they lock into each other.

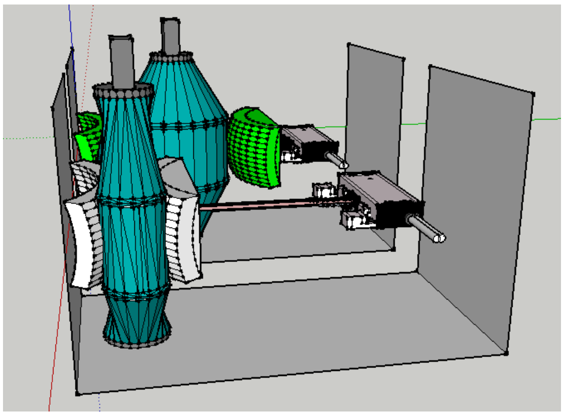

Figure 8: Rigid Chain Actuator

Therefore it is a compact telescopic actuation mechanism [31, 32]. The expected dimensions of the case are 350 mm x 250 mm x 300 mm, so it would become a more compact machine. Another advantage is that the tidal volume is well adjustable and it can reach the target speed [31]. One of the disadvantages it that the rigid chain actuator is difficult to obtain. The biggest disadvantage of the rigid chain actuator is the price. The rigid chain actuator that can reach the target speed has to be custom made. Therefore the price of a single actuator is €1500,- and serial prices go down to €400,- or less [33].

4.3.4 Crankshaft

The fourth driving is the crankshaft. (fig 9) The crankshaft has a shaft with a protrusion which is positioned eccentrically. A crank is attached to the

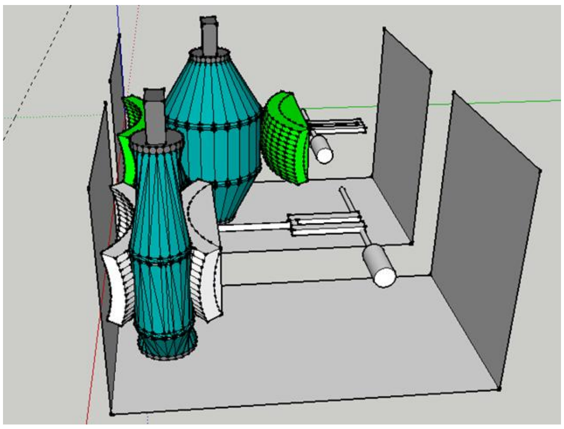

Figure 9: Crankshaft

shaft. When the motor starts running, the shaft rotates and this results in a back and forth motion of the crank. The pressure part is attached to the top of the crank and this provides the compressing of the resuscitator. The expected dimensions of the case will be 400 mm x 250 mm x 300 mm. The advantages of a crankshaft are that it is cheap and it can reach the target speed. The size of the crankshaft is a disadvantage; it almost takes as much space as the toothed rack. Also the motor will be more burdened, because it doesn't make complete strokes. This disadvantage is to solve by the use of a transmission. This transmission should be of synthetic parts, otherwise lubrication is needed. The biggest disadvantage of the crankshaft is that the tidal volume is difficult to regulate.

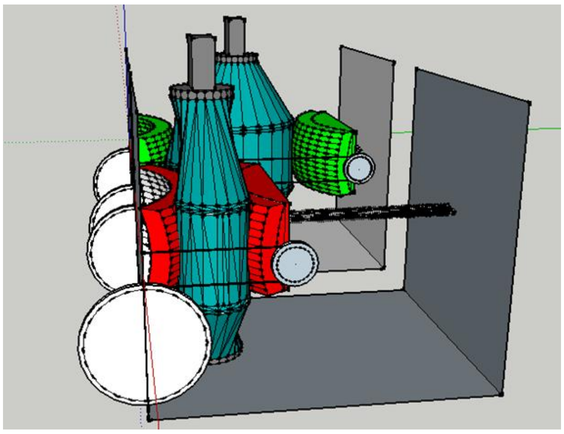

Figure 10: Cable Coiling

4.3.5 Cable Coiling

The last driving is cable coiling (fig 10). A cable is attached to the wall of the case, runs over an cogwheel attached to the pressure part and is coiled on another cogwheel. When the last cogwheel starts to turn, the cable is coiled and the pressure part is attracted. The resuscitator is positioned between the pressure part and the wall and therefore the attraction of the pressure part causes the compression of the resuscitator. The expected dimension of the case with this drive is 300 mm x 250 mm x 300 mm. This driving can reach the target speed and the tidal volume is well adjustable. It is a cheap and compact system. A disadvantage is that the cable and the contact surfaces between the cable and cogwheels will undergo wear, because of the forces that will work on them. Another disadvantage is the difficult regulation of the recoiling.

4.3.6 Driving choice

The linear actuator and the rigid chain actuator are too expensive in comparison with the other options. One of the demands is the good regulation of the tidal volume, which excludes the crankshaft. Both the cable coiling and the toothed rack are good options for the linear driving. However, the cable coiling had conductor bars needed. If this adjustment is made in the first draft, the system looks a lot like the toothed rack, but with many more parts. This is why the toothed rack was chosen to be the linear driving of the airstacking machine.

The design of the system with a toothed rack is changed to make the case more compact. The toothed racks will be fixed to the walls of the case. The cogwheels will run over the racks. The pressure part will be attached to the axle between the two cogwheels en therefore create the compression (fig 11).

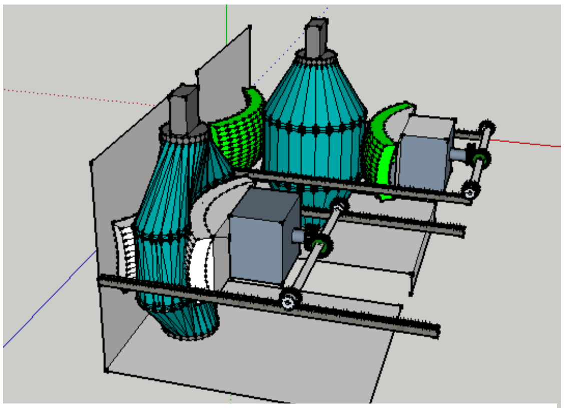

Figure 11: Final design

4.4 Motor specifications and transmission

It was calculated that the maximum force needed to compress the resuscitator was 65 N. This results in a total torque of 1.345 Nm, which can be divided over several revolutions, which can be changed by increasing the angular speed and simultaneously decreasing the arm. Therefore the calculations pointed out that five revolutions per second (300 rpm) would be sufficient, if the transmission would be 1:5 as well, resulting in a torque of 0.269 Nm. The motor specifications are therefore: 300 rpm with a torque of 0.269 Nm, with an overall transmission of 1:5.

It is known that the distance to cover is 130 mm, and the motor has a speed of 5 revolutions per second. Therefore one rotation of the motor will result in a fifth of the 130 millimetres. There are several methods to create a transmission of 1:5. In the final design it was decided to use toothed pulleys of 16.17 mm and 64.68 mm. To complete the transmission to 1:5 a final cogwheel of 33 mm was needed on our rack. The complete calculations for the motor specification and the transmission are shown in appendix 2.

4.5 Motor control

To control the compression of the resuscitator a button and a rotary switch will be used. The rotary switch will be used to control the speed of compression. When the button is pushed, the compression will occur, when the button is released, the pressure part will go to its original position. Both actions occur by the use of a stepper motor.

A stepper motor has a changing magnetic field, which leads to the rotational force of the motor axis. To change the magnetic field continuously, a combination of a motor shield and stepper code from the Arduino library are used. Six of the ATMega pins are used; four to control the shield and two (button and rotary switch) are used to receive user input.

When the button is pushed, the ATMega chip receives a high input signal. The ATMega chip sends a signal to the motor control shield, which initiates the rotational force of the stepper motor. The chip counts how many steps are taken and limits it to a set maximum. This maximum is to prevent overheating of the stepper motor, because when the resuscitator is maximally compressed, the motor will continue to give power, whilst the pressure part cannot move any further. When the button is released, the motor will transverse backwards to the original position. When the motor is back to its original position the power to the motor will be cut. When this happens the coils are demagnetized and the internal resistance is lower, so the resuscitator might push the pressure part back further if needed.

The rotary switch controls the speed of the compression. The rotary switch is a potentiometer. When it is fully open the resistance is minimal, when fully closed the resistance is high. When it’s fully closed, zero voltage can pass, which has the maximum speed as a result. The maximum speed is set at 200 rotations per minute. When the switch is closed, the resistance is lowest and a voltage of 5 V passes. This will result in the minimal speed of 25 rotations per minute. The position of the switch controls the full range of 25-200 rotations per minute [29]. The complete script is attached in appendix 4.

5. Design Validation

The final validation will be beyond the deadline of this report, therefore it has been decided to make a validation based on what is known so far. The used motor fulfils the requirements, however at this moment it has been limited to 67% of the speed. The precise regulation will depend on the flows that will be generated, as these should be limited due to safety. The speed of the motor, and therefore the flow is regulated within safe ranges by a potentiometer, which can be altered to the wishes of the patient. The said flow is only generated when the patient presses the button. This button activates the motor, which powers the machine. One problem that has to be solved is the fact that the used batteries will heat. A possible solution can be found in the use of one bigger accu with more power. The thickness and material type of the case may be altered in the following models as this prototype is designed to show the mechanism. Therefore in future prototypes and serial production there are other requirements for the case.

The testing trials of the prototype will start after the machine is built. However the interface and the motor seem to work correctly and according to the list of requirements.

A goal was to produce a prototype as cheap as possible. The total costs for the materials were €602,52. Costs were also made for the service of a mechanical designer. Those costs are yet unknown, because the prototype has not been assembled yet. A complete overview of the costs for the materials is shown in appendix 5.

Additional measurements were done to estimate the function of the airstacking machine. As shown in table 2, the average PCF of study subject 1 increased by 67 L/min after airstacking. The PCF of study subject 2 increased by 96 L/min. The average PCF of study subject 2 decreased from 372 to 297 when wearing a lashing strap. The forces needed to compress the resuscitator, when the study subject was wearing a lashing strap, only increased during the third compression. More force was needed to fully inflate the lungs, because the thoracic expansion was restricted by the lashing strap. However, the force needed was still less than the 65 N earlier calculated. Therefore it is expected that the selected motor provides enough force.

Table 2: Average PCF and compression force measured in two healthy study subjects and a study subject with a lashing strap to simulate a restricted thoracic compliance.

	Study subject 1	Study subject 2	Study subject 2 with lashing strap
PCF before *(l/min)*	240	372	297
PCF after *(l/min)*	307	458	392
Compression force 1 *(N)*	23,9	20,3	19,9
Compression force 2 *(N)*	32,0	29,1	28,4
Compression force 3 *(N)*	27,5	31,9	37,0

6. Discussion

After performing a test in order to find the most optimal form of the pressure part, a spherical shape was chosen. However, the most optimal curvature of the spherical shape was not examined. The curvature of the pressure piece was estimated to be comparable to the curvature of a fist. This is an estimation however, it is not sure whether this is the most optimal curvature. To determine the most optimal curvature of the pressure part, more tests have to be done.

To verify whether the made assumptions were correct, a validation measurement was done. During this measurement a lashing strap was used to try to simulate a patient with restricted thoracic compliance. This measurement was estimated to be comparable, but it is not sure whether the results are reliable, because it is hard to simulate a reduced respiratory muscle function. If a patient was involved in this measurement, the measurement would be much more reliable.

The choice of the motor was based on the specifications which were needed according to the calculation of the motor specifications. This is a calculation and it fits theoretically, however, the actual motor specifications often deviate from the specifications indicated by the manufacturer. The force delivered by the motor may not be sufficient enough. Another specification of the motor is the velocity; it is not certain what maximum speed is needed. The value of 300 Rpm was calculated by the use of the estimated value for the minimum compression time. To determine the minimal compression time and therefore the maximum speed of the motor, tests have to be done in order to determine what the minimal compression time is. This could lead to the conclusion that the estimated time of one second is too low.

The total material costs were €602,52 (an overview of the costs can be found in appendix 5). The highest material costs were the costs for the perspex plates. There have not been any calculations about the thickness of the plates, but it was sure this thickness could bear the forces it has to endure. If calculations had been done, the plates could have been less thick and therefore the costs and the weight could have been lower. For this prototype clear perspex plates were used, to create the possibility to show what happens inside the case during airstacking. For the final product the case will be made of other, not clear, material and will therefore be less expensive. When another material is used, material can be chosen that is lighter than perspex, so it will become more suitable for patients to take it with them. The material for the case has to be strong enough to withstand the forces, but also as light as possible. When the machine will be produced in series, all the material costs will be reduced, because price agreements can be made.

Also, the safety of the machine is not optimal yet. Some risks are already taken into account when the motor was programmed. But the risk of a motor that runs wild is not taken into account yet. A security for the patient, when this happens, could be a pressure valve. When the pressure gets too high, this valve opens. This valve makes sure that the pressure in the patient’s lungs will not built op to high.

7. Conclusion

All patients with a lowered PCF and who still have control of their glottic muscles, will benefit from airstacking. Most patients can do this by using a resuscitator, however a lot of patients with neuromuscular diseases such as ALS and DMD will benefit from a machine, as their hand function diminishes.

It was decided to use a resuscitator as the flow generator of the machine. Spherical pressure pieces were designed to compress the resuscitator, as these give the highest flow for a relatively low force. To drive the machine a stepper motor in combination with a toothed rack has been used. This system is relatively resistant to wear, making it durable. This system can be easily adapted and regulated, and therefore the flow, volume and frequency can be altered easily. By using an internal computer, in the prototype an Arduino, the machine can easily be retrofitted and adapted to specific patients.

This way, it is possible to design an airstacking machine for patients with decreased cough flow and hand function. However, at this moment it is difficult to make a definitive conclusion about the use of this machine as it is not finished yet. However, given the found data and demands, the design should work properly. It is acknowledged that not all wishes have been used in the design, however these can be easily retrofitted with small adaptations. The interface is very flexible as the internal computer can easily be altered to use other input devices.

If the machine is proven to work, it will, without a doubt, be an improvement for the patients with a limitation in hand function who require airstacking.

8. Recommendations

After the building a lot of recommendations can be done for improving the prototype. First of all, some further research has to be done. The optimal curvature of the pressure part has to be determined.

The validation measurement should be performed with a patient, to obtain more reliable values. Also research has to be done to determine the minimal compression time and therefore the maximum rotation speed of the motor. A material for the case has to be found that is strong enough to withstand the forces, but is as light as possible. Also the safety of the machine has to be optimized.

The Arduino was used, because it is an easy tool for prototyping. A disadvantage is that there are multiple cables and several loose parts. When the airstacking machine is produced at higher scale, the Arduino should be replaced by a specially designed circuit board for the airstacking machine. When a circuit board is used, there will be less loose cables and also the costs will decrease.

Another part of the machine that has to be replaced is the power source. The motor gets power from the batteries, but these warm up during the running of the machine. These batteries have to be replaced by an internal accu. By the use of an internal accu, the patients can take the airstacking machine to different places. Also the round rack could be replaced, the rack is made of stainless steel. If the rack could be made of synthetic material it would be lighter and probably less expensive. This will also contribute to the safety class of double insulation, because synthetic material conducts no electricity. All the demands of the prototype have been applied to the prototype, but not all the wishes could be applied. Further there should be a possibility to place a holder for the mouthpiece with a possible resistance, when a patient cannot hold the mouthpiece correctly. The prototype is adaptable to different interfaces, like using a mini-joystick on the wheelchair. Therefore a wireless receiver will have to be built in first. Finally, it has to be checked whether the prototype fulfils the requirements of the guidelines 93/42/EEG considering medical aides.

If the airstacking machine goes into serial production then further demands have to be fulfilled. Every caregiver must be able to do the maintenance, therefore the instructions may not be interpreted wrong, this can be done by using different colours or different components. No components must be able to be interchanged, so the maintenance cannot go wrong. Furthermore operation on different voltages is preferred, because the use of this device is not limited to the local market, but also to patients abroad or by patients who want to use this device when they travel. Therefore it has to operate at 230V, 12V, 24V (the power supply of the wheelchair) and 110V (in North-America and Japan). Of course the device will have to fulfil the legal requirements and will have to receive CE certification. Another demand for the serial production is that the device becomes child proof. A child should not be able to do any harm to the machine or should not be harmed by the machine.

The airstacking machine should also obtain the possibility to be used for patients without a hand function. This could be done by triggering the airstacking machine by inhalation. The machine should always be on stand-by. Behind the mouth piece a sensor has to be placed which can be triggered by inhalation. When the patient partially inhales, the machine should start working.

A last recommendation is made for travelling with the device. The airstacking machine must become a light device, so it can be a portable system. It also has to become drop resistant, because when it is a portable system, there is a possibility it could fall or that it has to endure severe shock. A final requirement is that it has to be watertight, so patients can take it with them on their wheelchair when desired.

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Appendix 1: Explanation of calculations for motor specifications and transmission

The trajectory of the compression will be the diameter of the resuscitator, which is 13 centimetres. This needs to be taken into account as the compression time is set at 1 second. Therefore the cogwheel has to travel an average of 0.13m/s when the motor is operated at maximum speed. The desired turning speed of the driven cogwheels depends on the diameter. Therefore:

$$\frac{Rad}{s} = \frac{v}{r} = \frac{2v}{D}$$

$$Rpm = \frac{v}{\pi D} \times 60$$

With:

$$v\ in\ m/s$$
$$D\ in\ m$$

Besides the driving speed of the cogwheels, the force to drive them should also be reckoned with. This force is related to the pushing force and the arm, resulting in the following equation to calculate the necessary torque:

$$\tau = r \times F \times \sin{(\theta)}$$

With:

$$\tau = Torque\ in\ N \cdot m$$
$$r = arm\ in\ m$$
$$F = Force$$
$$\theta = angle\ of\ the\ gears$$

The r in the formula for torque equals half the value of D in the previous equation. An angular factor is not needed as the force will be exerted at 90°, giving a multiplication factor of 1. Therefore the equation will be:

$$\tau = {}^{1}/_{2}\, D \times F$$

With τ giving the needed amount of torque for the given gear diameter.
The number of rotations per minute (Rpm) and the amount of torque needed can be further adjusted by further transmission. This will alter the Rpm, torque and cogwheel diameter needed. If the transmission is 1:2, the Rpm needed will be doubled, whereas the needed torque will be half.

To transmit the force from the motor to the linear driving, transmission is needed. The overall transmission can be determined by the rotation speed of the motor and the linear trajectory. When the motor gives a certain amount of revolutions per minute (rpm), the final cog will have to travel a certain distance. The number of revolutions that the final cogwheel will need to complete distance depends on its diameter.

$$Number\ of\ revolutions = \frac{d}{\pi D}$$

With:

$$d = distance$$
$$D = Diameter$$

The time in which this number of revolutions will have to be made is the compression time. This time will be put in minutes, so it can be compared to rpm of the motor.

$$Transmission\ ratio = \frac{rpm\ (cogwheel\ on\ rack)}{rpm\ (motor)}$$

This number, noted as x:y, gives the overall ratio of the transmission. However this can be divided over several transmissions. To find a suitable set of cogwheels it is important to keep this overall ratio in mind. There are more possibilities to make this transmission ratio.

Appendix 2: Calculations for motor specifications and transmission

The main specification of the motor will be the power it needs to transmit. It is known that power is the angular speed times the torque. Therefore there will be started with calculating the needed torque as if the distance will be covered in one revolution.

The arm equals the radius of the final cogwheel, which can be calculated from $r = d/2\pi$ where d equals 0.13 metres. This gives a radius of 0.0206 metres.

The amount of torque needed is calculated by $\tau = r \times F \times \sin(\theta)$, where θ = 90 degrees, so sin(θ)=1. Therefore the torque is 0.0206 metres multiplied by the needed 65 newton of force measured, which gives a maximum torque of 1.345 Nm.

In this case the angular speed is 2π rad/s, therefore the power that the motor needs to provide is: 2π*1.345=8.45 Watt. This is the same result as $W = F \times \Delta x$ will give.

This also means that if the arm will be halved, the torque needed will also be halved. However the travelled distance will be halved as well. The consequence is that the angular velocity should be doubled, as can be seen in the following formula:

$$Number\ of\ revolutions = \frac{d}{\pi D}$$

Therefore we can say that for a doubling of the number of rotations, the size of the final rotation part and the torque can be halved.

$$\frac{1}{a}\tau = a\frac{rad}{s}$$

Overall we can say that $\frac{rad}{s}/\tau$ will result in a constant.

From this function the motor and a corresponding transmission can be chosen. The ratio can be found according to the following formula:

$$Transmission\ ratio = \frac{rpm\ (cogwheel\ on\ rack)}{rpm\ (motor)}$$

Normally the angular speed for motors is given in rotations per minute (rpm). The method to calculate rpm from rad/s is multiplying by 60/2π.

At this point the choice was made for a stepper motor in. The motor does fit the power requirements, but to be completely sure another calculation will be made. It is known that the motor can deliver a torque of 0.3 Nm at 1000 steps per second. Each step is 1.8 degrees, which means that this motor gives 1800 degrees per second, which is a frequency of 300 rpm or 5 rotations per second, 5 Hz. This means that for each rotation of the motor, the distance travelled by the final cogwheel should be a fifth of the 0.13 meters. This also means that the torque delivered by the motor should be a fifth of the 1.345 Nm. This means the necessary torque is 0.269 Nm, which is lower than the 0.3 Nm that can be delivered by the stepper motor. Hereby we have determined that the motor can be used to power our airstacking machine.

To effectively move the power from the motor to the cogwheels on the rack, a transmission is needed. In the system of the airstacking machine there will be three transmissions: transmission A, from the motor to the axle and transmissions B and C from the axle to the racks. Therefore B and C will be equal (and will be named B further on). For each revolution of the motor, a fifth of the distance, or 2.6 centimetres should be covered. The transmission is defined by both A and B. Now the size of B can be determined for each of the transmission-ratios for A. This is a formula as there is more than one way to make the transmission, depending on the used cogwheels.
We can say that the angular speed of the axle depends on the transmission as follows:

$$\frac{Frequency\ motor}{Transmission\ factor} = Frequency\ axle$$

The size of B is determined by the next formula:

$$\frac{0.13m}{frequency\ axle \times \pi} = Diameter\ B$$

With these formulas several transmission factors were calculated, because for the prototype only standard parts will be used. In the end the most suitable transmission was a 1:4 transmission for A, with a diameter of 33 millimetres for B.

Appendix 3: List of demands

	Demands	Wishes
Prototype	Usable at home	Mouthpiece holder
	Adjustable tidal volume, frequency and tidal volume	Easily removable and interchangeable parts
	Operating trough open contact	Different interfaces
	Standard material for resuscitator	Internal power supply
	Able to control with minimal hand-function	Mouthpiece has to be able to take resistance
	As cheap as possible	Low maintenance
	Machine must deliver 1400 ml	Easy to clean
	Breaths taken within an short period of each other	Requirements of the guideline 93/42/EEG
	Safety class 2	
	If input stops, machine should stop	
	Pressure limitations	
	Electric-mechanically driven	
	Hardwearing and durable materials	
Serial production	CE certificated	Watertight
	Low noise	Compact and light
	Standard extensible	Shockproof
	Suitable for 230V, 12V, 24V and 110V	Air filter
	Easy maintenance	
	Child proof	
	Traceable	
	Usable by patient with absent hand function	

Appendix 4: Script Arduino

```
/* This script is build by L.R. Lemstra, A.N. Idsardi, B. Witjes and G.
Hengeveld. This script is used to control
a stepper motor in order to actuate a pressure part of the first prototype
of an airstacking machine.
2015-06-12 */

int enA         = 3;  // the Enable pin 1/A on Motor Control Shield
int enB         = 9;  // the Enable pin 2/B on Motor Control Shield
int dirA        = 2;  // Direction pin dirA on Motor Control Shield
int dirB        = 8;  // Direction pin dirB on Motor Control Shield
int button      = 4;  // Button pin
int potPin      = A5; // potentiometer pin
int steps       = 25; // step 25 steps per iteration of the loop
int sensorValue = 0;  // initalize variable for sensor
byte motorPos   = 0;  // keeps the position of the motor

#include <Stepper.h> // include stepper library
const int stepsPerRevolution = 200; // 360 degrees / 1.8 degrees of the
stepper motor = 200 steps/rotation

// initialize stepper libarry on dirA, dirB
Stepper myStepper(stepsPerRevolution, dirA, dirB);

void setup() {
  // put your setup code here, to run once:

  // Declare pinmodes (input/output pin)
  pinMode(enA, OUTPUT);
  pinMode(enB, OUTPUT);
  pinMode(dirA, OUTPUT);
  pinMode(dirB, OUTPUT);
  pinMode(button, INPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
  // check button state
  if (digitalRead(button) == HIGH) {
    // enable motor
    digitalWrite (enA, HIGH);
    digitalWrite (enB, HIGH);

    // check if motor is at maximum action range
    if (motorPos <= 40) { // 5*200=1000, 1000/25=40, after 5 revolutions
stop
      // increment position
      motorPos++;

      // Read the value of the potentiometer into sensorValue
      sensorValue = analogRead(potPin);

      // Map the sensorValue 0 resistance is maximum (200) speed, 1023 is
minimum speed (1)
      sensorValue = map(sensorValue, 0, 1023, 200, 25);

      // set motor speed
      myStepper.setSpeed(sensorValue);

      // step 25 steps ahead
      myStepper.step(25);
```

```
    }
    else { // motor is at maximum action range, wait a few moments and
check again
      delay(20);
    }
  }
  else { // if button not depressed, or failure
    // set motor speed
    myStepper.setSpeed(200);

    // if the position of the motor is higher then 0
    if (motorPos > 0) {
      // step 25 steps backward
      myStepper.step(-25);

      // decrement the motor position value
      motorPos--;
    }
    else { // motor position is 0
      // turn off power to the motor, so internal resistance is lessened
      digitalWrite(enA, LOW);
      digitalWrite(enB, LOW);
    }
  } // end button check
} // end program loop
```

Appendix 5: Cost overview

Requirements	Units	Product	Total Price
Motor:	1	Qmot Hybrid Stepper motor	€ 37,00
Motor control:	1	Arduino Kit Workshop Base	€ 57,84
	1	Arduino motor shield Velleman	€ 23,13
	1	Jackplug-adapter jackplug female	€ 2,21
	1	Jackplug-cable jackplug male	€ 1,48
	10	9V battery (block)	€ 12,39
Transmission:	4	UBC bearing	€ 5,24
	1	Toothed pulley D=16,17 mm	€ 7,80
	1	Toothed pulley D=64,68 mm	€ 15,98
	1	Toothed belt (100 Teeth)	€ 3,10
	2	Cogwheels D=33 mm	€ 9,85
	2	Round RVS rack	€ 163,85
Plate work:		Rigid PVC dark block	
	3	*235 x 75 x 50 mm*	€ 83,25
		Clear perspex plates:	
	3	*450 x 300 x 12 mm*	€ 55,80
	3	*450 x 350 x 12 mm*	€ 65,10
	3	*350 x 300 x 12 mm*	€ 43,50
		Emballage	€ 15,00
Total price:			€ 602,52