EPS - PROJECT

TITLE: PEDIATRIC AND NEONATAL LUNG SIMULATOR PROJECT

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The current report has been written for the Lung Simulator Project, carried out during the 2015 European Project Semester (EPS).

The goal of this report is to offer to all interested parties an overview of the proposed solution and how it has been developed after one semester (between February and June 2015). The project has been supplied by the ‘Children’s Hospital Sant Joan de Déu’, represented by Pedro Brotons, and university ‘Universitat Politècnica de Catalunya (UPC)’, represented by Cristobal Raya and Nidia Berbegal. This was the second year of cooperation with the hospital within EPS program. The project team consisted of Robert Balassan, Alejandra Rios, Hannah Azizan, Jolien Verbeke and Michiel Meyfroot.
The Lung Simulator is a project provided by collaboration between the San Joan de Deu Children’s Hospital in Barcelona and the Universidad Politécnica de Cataluña. The hospital specializes in neonatal and pediatric medical care and is also one of the leading medical hospitals for teaching in Europe.

The aim of this project is to design a neonatal and pediatric Lung Simulator in accordance with the project scope agreement. The proposed solution should be able to represent various clinical scenarios.

Research on existing simulators, state of the art, and prototyping, has been conducted in order to produce a final simulator that includes all the characteristics required by the hospital.

The compliance, spontaneous breathing, leakage and resistance will be motorized and able to be remotely controlled.

Parameters can be changed accurately by motor control, allowing more different clinical scenario’s to be simulated. The wireless control gives the user more freedom to manipulate the Lung Simulator from different places. The use of this new Lung Simulator is to be made intuitively and user friendly.
1. INTRODUCTION
Simulation in medicine is one of the most effective ways for students to acquire practical knowledge. It is also helpful for a hospital’s medical staff to practice certain clinical scenarios if needed, before facing them in a real field environment. The current project is aimed on creating the possibility of a simulation of the scenario in which a pediatric or neonatal patient needs to be assisted by mechanical ventilation.

This can be accomplished with a lung simulator. The main purpose of the simulation is to offer the students the possibility of interpreting the graphs and signals that the ventilator is emitting, while it is connected to a patient. The need of a new lung simulator comes with the high prices of the advanced types already available on the market and with the limited possibilities offered by the cheaper versions.

The prototype designed during the project offers a cheap solution that includes most of the features needed to ensure the realism of the simulation. The prototype was designed using procedures already known for the development of the lung simulators, in a very innovative way. The prototype is designed to improve the actual training methods used by the hospitals. Children’s Hospital Sant Joan de Déu is the company that demanded the production of this prototype.
1.1. ABOUT THE COMPANY

Children’s Hospital Sant Joan de Déu is the institution that has required the design of a new pediatric lung simulator. It is one of the leading medical centers in Europe for childhood and adolescence and offers a comprehensive and multidisciplinary approach to health care from birth through 21 years of age. The pediatric centre of the University of Barcelona is associated with the Clinic Hospital being the hospital alliance most well-known in Spain and one of the international references for highly specialized hospital care, teaching and research.

Currently the hospital is attending annually more than 25,000 inpatient admissions, 200,000 outpatient visits and 115,000 emergencies. It performs every year more than 14,000 surgical procedures and is attending around 4,000 births. The institution promotes innovation among professionals and gives them support so that they can carry out their ideas, patent them and make the prototype. At the moment the hospital has developed twelve patents that have generated two spin-offs.

1.2. BRIEF AND PROBLEM STATEMENT

The existing lung simulators are very expensive and sophisticated to be incorporated in a simulation room for educational needs. While the simplest ones does not meet some of the hospital requirements and do not have a good sensitivity calibration of parameters which is needed in order to teach different clinical situations of the patients.

The main idea of the project is to create a lung simulator which is able to operate passively, physically and mechanically simulating the real lung functions, not from a computerized mathematical model of a lung simulator. It must be able to connect to the air source which will be introduced from the hospital air source ventilation system and manipulate the air through the changing of the parameters, simulating the real function of the lungs in various clinical scenarios.

Sant Joan de Deu Hospital has provided a briefing for the project with the main features that the designed lung simulator must accomplish to cover their current needs:
The aim of the project is to design a reliable, economical and portable neonatal and pediatric lung simulator, which will be used for educational and research purposes. The principal objectives that had to be achieved within the project are:

1. Design an internal mechanism that can support all the required clinical situations
2. Design an eco-friendly product
3. Deliver a compelling and user experience that raises customer approval ratings
4. Increase the knowledge acquired by students while using a reliable lung simulator

The main conditions of the project were the cooperation between the members of the team and supervisors from the hospital and the university and were presented in detail in a ‘Project Agreement’ which was signed by all parties.

The constraints were related to the available time for the design of the prototype and the lack of financial resources and the lack of background in mobile application development. Those were also mentioned in the ‘Project Agreement’.
2 RESEARCH
Medical simulation is a modern day methodology of reenacting real medical situations through the use of advanced educational technology and is used for learning or training in many different medical fields. The main goal of medical simulation is to train students or professionals to reduce the number of mistakes during medical operations. It has always been very difficult to simulate real human organs, however, thanks to technological advances the simulations get more and more realistic over the years. Studies have shown that learning with medical simulations will reduce the chance of accidents significantly.

During a simulation students enter into a realistic medical setting where a high-tech patient mannequin is being operated by medical and technical staff. The patient simulation is recorded for playback during the debriefing process. The educator provides the voice of the patient and also guides the control of the mannequin. He, then, debriefs the students utilizing video playback to recap performance outcomes and to identify errors and successes.

In the next section will be explained what the main virtual simulation types are, and what the latest simulations include. [2]
2.1. SIMULATION IN MEDICAL STUDIES / What is?

There are three types of simulation:

- **Human Simulation**: it is role playing to simulate illnesses
- **Virtual Simulation**: it is a simulation on the computer
- **Mechanical Simulation**: done with the help of a machine simulating illnesses

The main focus is the use of mechanical simulation because that is the kind of simulation that has to be developed.

Mechanical simulation gives the students the chance to use mannequins so the treatment process feels real. The mannequin is connected to the simulation device and looks like a person. In this case the students can try to treat the mannequin without endangering a human life. Because of the simulations the students are obligated to work as a team to improve their skills for team work.

Due to the new technologies and material science the mannequins had become very realistic in appearance and they had made a large number of different scenarios available for accurate simulation. [3]

2.2. EFFECTS OF LEARNING WITH SIMULATIONS / Benefits

By using simulations, the medical scenarios became more realistic, making the students react more naturally on patients’ problems.

Even if simulation lessons are more costly than the traditional ones, it offers some instructional advantages which can justify any extra expense under the right circumstances:
Standardized teaching and evaluation can be assured in medical simulation. Variations in instructors’ teaching abilities and grading practices are not a problem because an identical system can be used for all students in all settings.

To varying degrees, all three forms of medical simulation can be structured to respond constructively to different errors that students are likely to make.

Mechanical and virtual systems can also evaluate students’ responses to hazardous conditions that would not be allowed in learning environments where humans were present, for instance: dealing with an accidental release of mercury, responding to the explosion of a medical gas.

The simulations is also useful during lectures and presentations, so the students can see how things are working while the professor is explaining the correct usage. That can improve the attention and results of the students.

ADVANTAGES OF SIMULATION

The application of simulations should allow the teacher to see if the students are able to react as needed and if they know how to handle the situation. Also it allows them to see if the students are able to use the acquired knowledge into practical skills. Using simulations aslo gives students the opportunity to try real-life situations without getting someone’s life in danger.

This is a chance to let students treat rare and uncommon illnesses, so they understand better how to react on special cases as they already treated a similar uncommon disease.

By doing simulation scenarios the students are able to learn how to communicate with each other in emergency situations, and also improve their confidence in their communication skills. They learn as well how to communicate with other specialties doctors and for that reason other priorities. It is very important to learn how to think effectively meaning students can make the right choice during the treatment of a patient.

The simulation also helps the students understand all the equipment they have to use, and it becomes easier for them to learn how to work while nobody’s life is depending on it. They have to treat the simulation mannequin as good as possible, like a real person, but they can make mistakes if they use some instrument for the first time, without risking lives.

By training how they have to react and think, the students develop a kind of specific way of thinking; critical thinking. With it they can learn to make the right decisions when the life of a patient depends on it. However it is also good that they can rely on their theoretical knowledge at the right time to put the steps for the treatment in the right order to save their patient.\(^\text{[4]}\)
2.3. **HUMAN RESPIRATORY SYSTEM**

**How does it work?**

**THE RESPIRATORY SYSTEM**

The human respiratory system is a series of organs responsible for taking in oxygen and expelling carbon dioxide. The primary organs of the respiratory system are lungs, which carry out this exchange of gases as we breathe.

The respiratory tract is the path of air from the nose to the lungs. It is divided into two sections: the upper respiratory tracts are the (Nostrils, Nasal Cavities, Pharynx, Epiglottis, and the Larynx). The lower respiratory tract consists of the (Trachea, Bronchi, Bronchioles, and the Lungs). [5]

**FUNCTIONS OF THE LUNGS**

The lungs are a pair of cone-shaped organs made up of spongy, pinkish-gray tissue. They take up most of the space in the chest, or the thorax (the part of the body between the base of the neck and diaphragm). They are enveloped in a membrane called the pleura.

The left lung is composed of two lobes: upper and lower lobe, as well as the lingula which is a small remnant next to the apex of the heart. The right lung has three lobes: upper, middle and lower.

When we breathe:

**THE AIR:**

- Enters the body through the nose or the mouth.
- Travels down the throat through the voice box (larynx) and windpipe (trachea).
- Goes into the lungs through tubes called main stem bronchi. One main stem bronchus leads to the right lung and one to the left lung. They are divided into smaller bronchi called bronchioles. The bronchioles end in tiny air sacs called alveoli. The oxygen transported through the respiratory system is finally transferred to the bloodstream at the alveoli.
## Respiratory Tracts

| **Nose** | The openings through which air enters and exits the body. |
| **Mouth** | The openings through which air enters and exits the body alternative to the nose. |
| **Sinuses** | Air-filled chambers within the bones of the face which help keep the nose moist and free of dust and bacteria. |
| **Pharynx** | The cavity behind the mouth. |
| **Larynx** | Is the upper part of the windpipe, which contains the vocal cords. |
| **The Windpipe (Trachea)** | Provides a pathway for air to enter and exit the lungs. |
| **Epiglottis** | A flap that covers the trachea during swallowing in order to prevent food from entering the lungs. |
| **Bronchioles** | Stretchy “branches” expansion from bronchi that transport air throughout the lungs. Bronchioles get smaller as they go deeper into the lungs. |
| **Alveoli** | Clusters of balloon-like air sacs at the ends of the airways. |
| **Blood Vessels** | Tubes that carry blood to the lungs and throughout the body. Tiny blood vessels surround the air sacs, allowing an exchange of oxygen and carbon dioxide. |
| **Pleural** | An area between the lungs and chest wall, lined on both sides by tissue called pleura. |
| **Diaphragm** | A muscle in the abdomen that contract and relax which helps with breathing. |
| **Mucus** | Sticky substance made by cells in the lining of the airways. It traps dust, smoke, and other particles from air breathed in. |
| **Cilia** | Tiny hairs on the cells of the airway lining. They sweep mucus up the airways and to the throat. In Cilia mucus gets swallow |

Table 1: Respiratory Tracts
Breathing Process

Ventilation is the overall term to describe that oxygen is coming into the body, and carbon dioxide is leaving the body. The lungs are the central exchange place for ventilation to occur. The mechanical processes that support ventilation are two-fold:

Inhalation - the lungs inflate with air, bringing oxygen into the body.
Exhalation - the lungs deflate and let go of air, releasing carbon dioxide out into the environment.

The breathing process is aided by a large dome-shaped muscle under the lungs called the diaphragm. During inhalation, the diaphragm contracts downward, creating a vacuum that causes a rush of fresh air into the lungs. The opposite occurs with exhalation, where the diaphragm relaxes upwards, pushing on the lungs, allowing them to deflate. [5]

Breathing Mechanics

The mechanics of breathing follow Boyle’s Law which states that pressure and volume have an inverse relationship.

The process of inhalation occurs due to an increase in the lung volume (diaphragm contraction and chest wall expansion) which results in a decrease in lung pressure in comparison to the atmosphere; thus, air rushes in the airway.

The process of exhalation occurs due to elastic recoil of the lung tissue which causes a decrease in volume, resulting in increased pressure in comparison to the atmosphere; thus, air rushes out of the airway. [5]

Breathing in Babies

By about 35 weeks gestation, most babies have developed adequate amounts of surfactant, a substance normally released into the lung tissues to lower surface tension in the airways. This helps keep the air sacs in the lung open.

An important part of lung development in babies is the production of surfactant. This is a substance made by the cells in the small airways and consists of phospholipids and protein. By about 35 weeks gestation, most babies have developed enough surfactant. Surfactant is normally released into the lung tissues where it helps lower surface tension in the airways. This helps keep the lung alveoli (air sacs) open. Premature babies may not have enough surfactant in their lungs and may have difficulty breathing. [6]
The respiratory mechanism of the pediatric patient varies from the adult in both anatomy and physiology. As children grow, the airway enlarges and moves more caudally as the c-spine elongates.

One of the important distinctions is the narrowest point in the airway in adults is at the cords versus below the cords for children. Some of the important anatomic differences are listed below:

<table>
<thead>
<tr>
<th>ANATOMY</th>
<th>PEDIATRIC</th>
<th>ADULT</th>
</tr>
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<tbody>
<tr>
<td>TONGUE</td>
<td>Large</td>
<td>Normal</td>
</tr>
<tr>
<td>EPIGLOTTIS SHAPE</td>
<td>Floppy, omega shaped</td>
<td>Firm, flatter</td>
</tr>
<tr>
<td>EPIGLOTTIS LEVEL</td>
<td>Level of C3 – C4</td>
<td>Level of C5 – C6</td>
</tr>
<tr>
<td>TRACHEA</td>
<td>Smaller, shorter</td>
<td>Wider, longer</td>
</tr>
<tr>
<td>LARYNX SHAPE</td>
<td>Funnel shaped</td>
<td>Column</td>
</tr>
<tr>
<td>LARYNX POSITION</td>
<td>Angles posteriorly away from</td>
<td>Straight up and down</td>
</tr>
<tr>
<td>NARROWEST POINT</td>
<td>Sub-glottic region</td>
<td>At level of vocal cords</td>
</tr>
<tr>
<td>LUNG VOLUME</td>
<td>250 ml at birth</td>
<td>6000 ml as adult</td>
</tr>
</tbody>
</table>

Table 2: Anatomic differences
**COMPLIANCE OF THE LUNGS AND CHEST WALL**

Considerable structural changes in the chest wall may vary from neonates to pediatrics and is also related to respiratory failure, lung injury, and ventilation associated lung injury. The orientation of the ribs in infant is horizontal and by 10 years of age, the orientation is downward.

During the first year of life, the compliance of the respiratory system increases by as much as 150% (mainly lung). The infant chest wall is remarkably compliant and compliance decreases with increasing age. \[7\]

**RESISTANCE**

An important aspect of the narrow airway in children is that resistance is significantly increased. The formula is \( R = \frac{8l}{r^4} \) (where \( R = \) resistance, \( l = \) length, \( r = \) radius). Therefore, small changes in the airway radius will increase the resistance to the power of four and small amount of post-extubation sub-glottic edema will significantly increase the work of breathing for an infant. \[4\]

![Figure 6: Lung resistance of infants vs adults](image)

The main site of airway resistance in the adult is the upper airway; however, it has been shown that peripheral airway resistance in children younger than 5 years of age is four times higher than adults. On the other hand, the major site of resistance in the children is the medium sized bronchi.

**PULMONARY FUNCTION VOLUME**

Functional Residual Capacity (FRC) is the volume of air present in the lungs at the end of passive expiration. It is determined by the static balance between the outward recoil of the chest wall and the inward recoil of the lung. Children also have a smaller forced residual capacity (FRC) defined as the residual volume plus the expiratory reserve volume. Physiologically, FRC occurs when the outward pull of the chest wall equals the inward collapse of the lungs. In infants, the outward recoil is quite small, and the inward recoil is only slightly less than that in adults. This situation is amplified in pediatric patients because of a compliant chest wall, small thoracic cage, and large abdominal contents. \[7\]
Lung function tests or also known as Pulmonary Function Tests (PFTs) are noninvasive diagnostic tests that provide measurable feedback about the functionality of the lungs. By assessing lung volumes, capacities, rates of flow, and gas exchange, PFTs provide information that could help the doctors to:

**HELPS:**

- Determine how much air in the lungs can hold, how quickly does air move in and out of the lungs, and how well the lungs put oxygen into and remove carbon dioxide from the blood.
- Diagnose lung diseases, measure the severity of lung problems, and check to see how well treatment for a lung disease is working.

Some of the more common values that may be measured during pulmonary function testing include:

- **Tidal Volume (VT):** This is the amount of air inhaled or exhaled during normal breathing.
- **Minute Volume (MV):** This is the total amount of air exhaled per minute.
- **Vital Capacity (VC):** This is the total volume of air that can be exhaled after maximum inspiration.
- **Functional Residual Capacity (FRC):** This is the amount of air remaining in lungs after normal expiration.
- **Total Lung Capacity:** This is the total volume of lungs when maximally inflated.
- **Forced Vital Capacity (FVC):** This is the amount of air exhaled forcefully and quickly after maximum inspiration.
- **Forced Expiratory Volume (FEV):** This is the volume of air expired during the first, second, and third seconds of the FVC test.
- **Forced Expiratory Flow (FEF):** This is the average rate of flow during the middle half of the FVC test.
- **Peak Expiratory Flow Rate (PEFR):** This is the maximum volume during forced expiration.
Spirometry is the most frequently used measure of lung function and is a measure of volume against time. The spirometer is an instrument that measures the amount of air breathed in and/or out and how quickly the air is inhaled and exhaled from the lungs while breathing through a mouthpiece. The measurements are recorded on a device called a spirograph.

Other tests, such as residual volume, gas diffusion tests, body plethysmography, inhalation challenge tests, and exercise stress tests may also be done to determine lung function.

2.6. **CHILDREN’S LUNGS**

Children's lungs are still growing and they breathe differently from adults. Their immune systems are not fully developed, and so infections are common.

Some children are born with under-developed lungs, for example because of prematurity, while others are born with a lung condition. Some children develop lung conditions, and there are different causes and risk factors. Some conditions are episodic (this means that they come and go) while others are long term conditions.
2.6.1. RESPIRATORY SYNCYTIAL VIRUS (RSV)

RSV is the most common cause of bronchiolitis (inflammation of the small airways in the lungs) and pneumonia in babies.

It is spread from respiratory secretions through close contact with infected people or contact with contaminated surfaces or objects. Infection can occur when infectious material contacts mucous membranes of the eyes, mouth, or nose, and possibly through the inhalation of droplets generated by a sneeze or cough. The incubation period (time from exposure to symptoms) is about four to six days.

The early phase of RSV in infants and young children is often mild, somewhat like a cold. In children younger than 3, the disease may progress into the lower airways and cause coughing and wheezing. In some, the infection progresses to a severe respiratory disease requiring hospitalization to help the child breathe. [10]

2.6.2. BRONCHIOLITIS

Bronchiolitis is a common infection of the upper airway (bronchiole or air tube) that most commonly affects babies and young children. It is usually caused by a virus called respiratory syncytial virus (RSV).

The infection causes the bronchioles (airways) to become inflamed (swollen), with an increase in mucus production. The swelling and mucus can then block the airway. This makes it more difficult for air to get to the lungs and it can cause breathing difficulty.

Babies and young children are more likely to get bronchiolitis because their airways are small.

2.6.3. PNEUMONIA

Pneumonia is an inflammation of the lungs caused by bacteria, viruses, or chemical irritants. It is a serious infection or inflammation in which the air sacs fill with pus and other liquid.

Lobar pneumonia. This affects one or more sections (lobes) of the lungs.

Bronchial pneumonia (or bronchopneumonia). This affects patches throughout both lungs.

The main types of pneumonia are: Bacterial pneumonia, Viral pneumonia, Mycoplasma pneumonia. Symptoms of pneumonia differ by the cause, but some symptoms include chills, fever, fatigue, chest pain, sore throat, and coughing. [9]
2.6.4. NEONATAL AIR LEAK SYNDROME

Air leak syndrome is a phenomenon when air escapes from the tracheobronchial tree and collects in various body spaces where it is not normally present. The escaping air tracks along various pathways and localizes in different body spaces leading to different types of air leaks, including:

* Pneumothorax - where the air is trapped inside the chest between the chest wall and the lung, causing the lung to collapse.

* Pneumomediastinum - where air is trapped in the middle part of the chest.

* Pulmonary Interstitial Emphysema (PIE) - where air is trapped between the tiny air sacs, encircling the smallest blood vessels and bronchi.

Babies most at risk for air leak syndrome are:

* Babies with other lung diseases such as respiratory distress syndrome (RDS)

* Babies on mechanical ventilators.

* Premature babies whose lung tissues are more fragile.

* Babies with meconium aspiration, because the meconium plugs the airways, causing areas of the lungs to collapse. [9]

2.6.5. ASTHMA

Asthma is a chronic, inflammatory disease in which the airways become sensitive to allergens (any substance that triggers an allergic reaction). Several things happen to the airways when a child is exposed to certain triggers:

The lining of the airways becomes swollen and inflamed

The muscles that surround the airways tighten

The production of mucus is increased, leading to mucus plugs

All of these factors will cause the airways to narrow, thus making it difficult for air to go in and out of your child’s lungs and causing the symptoms of asthma.

The most important symptoms of asthma are:

- Cough: caused by the need to cough up mucus stuck in the lungs or from the irritation of the airways (twitchiness)

- Shortness of breath

- Chest tightness or pain

- Wheezing: (whistling noise in the chest). [9]
2.6.6. RESPIRATORY DISTRESS SYNDROME

Respiratory Distress Syndrome (RDS) is the most common lung disease of premature infants which occurs in babies with incomplete lung development. The more premature the infant is, the greater the chance of getting RDS.

It is due to insufficient surfactant in the lungs. Surfactant is a material normally produced by the lung that spreads like a film over the tiny air sacs allowing them to stay open. Open air sacs are essential for oxygen to enter the blood from the lung and for carbon dioxide to be released from the blood into the lung for exhalation. Premature babies born with inadequate production of pulmonary surfactant have stiff lungs that are hard to inflate at birth.

The baby will have difficulty breathing as well as:

- rapid breathing and grunting
- pulling in of the ribs and center of the chest with each breath, called retractions.
- widening of the nostrils with each breath, called flaring. [9]

2.6.7. OBSTRUCTIVE SLEEP APNOEA (OSA)

Obstructive sleep apnea occurs when a child stops breathing during periods of sleep.

In children, the most common cause of obstructive sleep apnea is enlarged tonsils and adenoids in the upper airway. Infections may cause these glands to enlarge, consequently may completely block the nasal passages and make breathing through the nose difficult or impossible.

Sometimes, the inability to circulate air and oxygen in and out of the lungs results in lowered blood oxygen levels. If this pattern continues, the lungs and heart may suffer permanent damage. It is most commonly found in children between three to six years of age. It occurs more commonly in children with Down syndrome and other congenital conditions affecting the upper airway (for example, conditions causing large tongue or small jaw).

The symptoms may include:

- Loud snoring or noisy breathing during sleep
- Mouth breathing. The passage to the nose may be completely blocked by enlarged tonsils and adenoids. May also speak with a nasal voice.
- Restlessness during sleep.
- Excessive daytime sleepiness or irritability. Because the quality of sleep is poor, the child may be sleepy, hard to wake from a nap, or irritable in the daytime.
- Hyperactivity during the day. May also experience behavioral, school, or social problems. [9]
2.6.8. CHILDREN’S INTERSTITIAL LUNG DISEASE (chILD)

Children’s Interstitial and Diffuse Lung Disease (chILD) is not a single disease. Instead, it is a group of rare lung diseases found in infants, children, and adolescents. There are different types of chILD that vary in their severity and in their long term outcomes. In general, all types of chILD decrease a child’s ability to supply oxygen to their body.

There are various forms of chILD, some of symptoms are:

- Fast breathing
- Use of “helper” muscles while breathing (The child’s ribs or neck muscles may stand out while breathing in, showing he or she is working harder to get air into the lungs.)
- Abnormal chest X-rays or CT scans
- Needs supplemental oxygen
- Failure to gain weight and/or height (also known as failure to thrive)
- Persistent crackles, wheezing or other abnormal sounds when listening to the lungs
- Recurrent pneumonia
- Recurrent bronchitis
- Recurrent cough [11]

2.6.9. PRIMARY CILIARY DYSKINESIA (PCD)

It is a rare inherited condition which affects the cilia; these are tiny hair-like structures that line the airways (air tubes). Usually, the cilia move mucus towards the mouth where it can be coughed out or swallowed. This is part of the lungs’ self-defence process. In PCD, the cilia do not beat normally and therefore cannot remove unwanted mucus effectively. This leads to recurrent respiratory tract infections.

2.6.10. BRONCHOPULMONARY DYSPLASIA (BPD)

This can occur in babies who are born very early and whose lungs have not yet developed fully. BDP is sometimes called chronic lung disease of prematurity. Such babies may need extra oxygen to help them breathe, and have a higher risk of respiratory infection. Lung function improves with age, but damage to the lungs may continue into adulthood. [12]
3 LUNG SIMULATORS
In medicine, mechanical ventilation is a method to mechanically assist or replace spontaneous breathing. This may involve a machine called a ventilator or the breathing may be assisted by a registered nurse, physician, physician assistant, respiratory therapist, paramedic, or other suitable person compressing a bag or set of bellows. Mechanical ventilation is termed “invasive” if it involves any instrument penetrating through the mouth (such as an endotracheal tube) or the skin (such as a tracheostomy tube).[12]

Mechanical ventilation is indicated when the patient’s spontaneous ventilation is inadequate to maintain life. It is also indicated as prophylaxis for imminent collapse of other physiologic functions, or ineffective gas exchange in the lungs. Because mechanical ventilation serves only to provide assistance for breathing and does not cure a disease, the patient’s underlying condition should be correctable and should resolve over time.

A mechanical lung simulator is described (an extension of a previous mechanical simulator) which simulates normal breathing and artificial ventilation in patients. The extended integration of hardware and software offers many new possibilities and advantages over the former simulator. The properties of components which simulate elastance and airway resistance of the lung are defined in software rather than by the mechanical properties of the components alone. Therefore, a more flexible simulation of non-linear behaviour and the cross-over effects of lung properties is obtained. Furthermore, the range of lung compliance is extended to simulate patients with emphysema. The dependency of airway resistance on lung recoil pressure and transmural pressure of the airways can also be simulated. The new approach enables one to incorporate time-related, mechanics such as the influence of lung viscosity or cardiac oscillation. The different relations defined in the software can be changed from breath to breath.[13]
The next figure is representing a lung simulator system including the devices that could be used and the parameters that must be shown:

The Mannequin

The mannequin is used during the medical simulations. It can be noticed that the mannequin has ventilation possibilities. The mannequin is capable of reproduction of heart sounds (including rated and intensities). Bilateral, branchial and femoral pulses that vary with blood pressure and pulses can be synchronized with the ECG. The rate and depth of respiration can be controlled remotely with the lung simulator.
THE VENTILATOR

A medical ventilator (or simply ventilator in context) is a machine designed to mechanically move breathable air into and out of the lungs, to provide the mechanism of breathing for a patient who is physically unable to breathe, or breathing insufficiently.

While modern ventilators are computerized machines, patients can be ventilated with a bag valve mask, a simple hand-operated bag-valve mask.

Ventilators are chiefly used in intensive care medicine, home care, and emergency medicine (as standalone units) and in anesthesia (as a component of an anesthesia machine).

In its simplest form, a modern positive pressure ventilator consists of a compressible air reservoir or turbine, air and oxygen supplies, a set of valves and tubes, and a disposable or reusable “patient circuit”.

The air reservoir is pneumatically compressed several times a minute to deliver room-air, or in most cases, an air/oxygen mixture to the patient. If a turbine is used, the turbine pushes air through the ventilator, with a flow valve adjusting pressure to meet patient-specific parameters. When overpressure is released, the patient will exhale passively due to the lungs’ elasticity, the exhaled air being released usually through a one-way valve within the patient circuit called the patient manifold. The oxygen content of the inspired gas can be set from 21 percent (ambient air) to 100 percent (pure oxygen). Pressure and flow characteristics can be set mechanically or electronically. Ventilators may also be equipped with monitoring and alarm systems for patient-related parameters (e.g. pressure, volume, and flow) and ventilator function (e.g. air leakage, power failure, mechanical failure), backup batteries, oxygen tanks, and remote control. The pneumatic system is nowadays often replaced by a computer-controlled turbo pump. [14]

DISPLAY INTERFACE

The display interface is where all the parameters like compliance, resistance, leakage and spontaneous breathing intensity are monitored and where the ventilation parameters are shown. With the ventilator’s settings certain parameters related to the patients profile can be modified. [44]
Computer control of mechanical ventilators includes the operator-ventilator interface and the ventilator-patient interface. New ventilation modes represent the evolution of engineering control schemes. The various ventilation control strategies behind the modes have an underlying organization, and understanding that organization improves the clinician's appreciation of the capabilities of various ventilation modes and gives an idea of what we can and should expect for the future.

All modern ventilators use closed-loop control to maintain consistent pressure and flow waveforms in the face of changing environmental conditions. Closed-loop control is accomplished by using the output as a feedback signal that is compared to the operator-set input. The difference between the two is used to drive the system toward the desired output. For example, pressure-controlled modes use airway pressure as the feedback signal to control gas flow from the ventilator. Manufacturers typically do not use flow at the airway opening as a feedback signal, because they do not trust the flow sensors available for that purpose. Instead, they measure flow inside the ventilator, near the main flow-control valve. Closed-loop control (also called feedback control) uses a sensor to measure the output of the effector. This signal is passed to a comparator (represented by the circles in Fig. 6) that essentially applies a simple equation: error input–output. If the error in the effector output is large enough, an error signal is sent to the controller. The controller then adjusts the effector so its output is closer to the desired input (ie, makes the error smaller). The advantage of closed-loop control is that the output is continuously and automatically adjusted so that disturbances are not a problem. The greater complexity of that system makes it more expensive to build and maintain. A feedback signal can be electrical (eg, from an electronic pressure transducer) or mechanical (eg, pressure regulators and continuous positive airway pressure valves). In mechanical devices a spring provides the input setting, and the position of the diaphragm (a measure of the gas pressure) is the feedback signal. When the force caused by the pressure exceeds the spring load, the diaphragm deflects and vents gas to the atmosphere to relieve the pressure.\[41\].\[43\].\[44\]

Figure 16: Schematic diagrams of closed-loop control of a mechanical ventilator.

A: Pressure control.
B: Flow control.
C: The flow signal is integrated to provide a signal for volume control.
D: Flow/Volume control using a calibrated gas-control valve instead of a flow sensor.
Spontaneous breathing is the movement of gas in and out of the lungs that is produced in response to an individual’s respiratory muscles or in other words, natural breathing. During the process of spontaneous breathing, the patient inhales to allow oxygen to enter the lungs normally without assistant from the mechanical ventilation.

Through spontaneous breathing, the volume of the lung is increased due to normal contraction of the diaphragm and respiratory muscles. This creates a negative pressure in the lungs and air being pulled or drawn in. Whereas, in artificial ventilation, the patient is intubated and being connected to the ventilator. The ventilator creates a negative pressure and thus pushes the air into the lungs.

When the patient starts to breath normally (spontaneously), the ventilator must adapt to the patient’s condition and not vice versa. Disturbance of spontaneous breathing by artificial ventilation must be reduced as minimum as possible.\(^\text{16}\)

Airway resistance is the resistance of the respiratory tract to airflow during inspiration and expiration. It can be indirectly measured with body plethysmography.

Airway resistance is not constant in which it could be affected by changes in the diameter of the airways. Therefore, diseases affecting respiratory tract can increase airway resistance such as:

- During an asthma attack, the airways constrict causing an increase in airway resistance.
- In emphysema there is destruction of the elastic tissue of the lungs which help hold the small airways open. Therefore during expiration, particularly forced expiration, these airways may collapse causing increased airway resistance.

The other factors affecting airway resistance are: viscosity and density of the gas mixture, length, and ventilator flow rate and flow pattern whether laminar or turbulent.

If the inspiratory flow is constant and known with accuracy, then the airway resistance may be estimated. (unit: cm H2O/L/sec) \(^\text{17}\)
Air leaks can be defined as a gas leakage from the upper airway during assisted ventilated support. There is a high possibility of air leakage to occur during invasive and non-invasive ventilation. Air leakage particularly become troublesome during noninvasive ventilation because the noninvasive interfaces (such as masks, nasal prongs and nasal pillow), causes sealing problem. In neonatal cares, gas leaks occur very often especially:

- When uncuff endotracheal (ETT) tubes are used in invasive ventilation.
- The usage of nasal prongs during non-invasive ventilation, requiring clinicians to continually adjust ventilator settings.

The air leaks causes the reduction of the amount of gas volume which should enter the lungs in each breath. Besides, it may lead to disynchronization between spontaneous breathing efforts and ventilator’s response, consequently increase the time the patient is ventilator dependent.[16]

Compliance is the measure of the ease of inflation, distensibility, or the ease with which the lungs can stretch or inflate.

- Increasing compliance means the lungs are easier to inflate, (medically desirable).
- Decreasing compliance means the lungs are getting stiffer (medically undesirable).

Elastance is a measure of lung stiffness which is opposite of compliance. It is also called elastic resistance which is the resistance of the lungs and chest wall to being stretched. Therefore, increase elastance indicates stiffer lungs and vice versa.

The normal value for compliance is 100 to 200 ml/cm H2O. It is calculated by dividing the patient’s exhaled tidal volume (VT) by the pressure needed to provide that same tidal volume. (unit: ml/cm H2O) [18]
3.3. ANALYSIS OF EXISTING LUNG SIMULATORS

This section is focusing on analysis of lung simulators available in the market nowadays. Lung simulators have undergone a series of evolutions and advancements which helped to improve training and education in the medical field. They exist in various forms, features and specific specifications:

3.3.1. BABI-PLUS NEONATE LUNG

The first test lung designed to simulate the physical conditions of a neonate lung. It is calibrated in accordance to different compliances and various airway resistances for neonates.

Changeable silicone elbow comes with four airway-simulation resistors (90, 145, 300 or 600 cmH2O/L/s) together with shell panel enable it to simulate lung resistance and compliance. It is an ideal neonate test lung for equipment testing, product demonstration and medical personnel training. [19]

**FEATURES:**
- Anatomical design and two different lungs for more precise simulation
- Great compliance consistency
- Pressure monitoring port for accurate pressure
- Lightweight, easy and convenient for use and storage

3.3.2. ADULT/PEDIATRIC DEMONSTRATION LUNG

Hands-on portable two-bellows lung simulator with easy control of compliance, resistance, and leak settings to simulate a wide spectrum of patient scenarios. [20]

**FEATURES:**
- Compact and portable
- Easy to set up.
- Simply open the lid and select the settings
- Two bellows system provides realistic simulation
- Pressure gauges show differences between airway and lung compartment pressure
3.3.3. IMT MEDICAL SMART LUNG INFANT

The imtmedical SmartLung have the same performance as large, expensive test lungs, but is extremely simple to use and so compact that it can be directly connected to the ventilator tubing system. It is ideal for ventilator manufacturers validating the safety of their products, for ventilator training and for biomedical engineers performing general service procedures. [21]

**FEATURES:**

- Adjustable resistance, lung compliance and leakage.
- Pressure, flow and volume specifications can be measured through combination with FlowAnalyser from Imtmedical.
- Affordable and versatile general purpose test lung.
- Available with an additional test lung (TestLung Infant) used to verify neonate as well as infant ventilators.

Figure 19: Imt Medical Smart Lung Infant

3.3.4. ASL 5000 BREATHING SIMULATOR

ASL 5000, allows the users to create real life respiratory scenarios from neonatal to adult patients. It is one of the world’s most sophisticated breathing simulators, with a software tool designed to simplify and enhance simulation management. [22]

**FEATURES:**

- The ability to simulate spontaneous breathing while being ventilated enables it to simulate full spectrum of breathing simulation challenges including: coughs, apnea, active exhalation, playback of actual patient recordings and even snoring.
- Portable: the components are mounted on a mobile cart.
- Changes in patient parameters can be made using a convenient script file, or interactively.
- It is highly accurate and use for: teaching, research, product development, and as well as the basis for a sophisticated test

Figure 20. ASL 5000 Breathing Simulator
3.3.5. RESPITRAINER INFANT

Specially designed product to simulate pediatric and infants patients. It can be used with ETView for video intubation training, skills trainer for teaching, assessing basic and advanced airway skills, as well as bag-valve-mask ventilation. [23]

Adaptable lung with variable compliance, resistance and leakage settings

Realistic representation of human infant anatomy, tissue and skin, enables hands-on training transferable to the clinical setting

High-fidelity infant respiratory simulation with an easy setup and cost

Train proper manual ventilation with graphic feedback on actual delivered rates, pressures and volumes

3.3.6. NEOLUNG – INFANT TEST LUNG

Passive Lung Simulator with two independent compartments for simulating neonatal and infant patients in a very intuitive and fashion way. Not intended for ventilator calibration or performance verification. [24]

Variable compliance, resistance, leak settings, and overdistension threshold can be quickly changed for simulating a wide range of clinical scenarios.

Easy setup

Able to create realistic clinical scenarios with quick adjustments to compliance, resistance, leaks, and volume, simulate conditions such as stacked breaths, overdistention, "stiff" lungs, and leaks.

Demonstrates high-frequency ventilation.
3.3.7. **QUICKLUNG PRECISION TEST LUNG**

It meets the need for a test lung that quickly simulates realistic patient conditions, yet is compact, accurate, easy to use and cost effective.\(^{[25]}\)

---

**Features:**

- Adjustable, precision test lung for ventilator testing and training.
- High accuracy and cost effective.
- Realism: Volume capacity (up to 1.2 liters) allows it to simulate pediatric to adult patients. No additional accessories required.
- Examine ventilator response to patient inspiratory efforts with the QuickTrigger.
- Easy set up. Works accurately from a table or suspended from a ventilator.
- Regulatory compliance: Easily adjustable parabolic resistance and compliance settings.

---

Figure 23: QuickLung Precision Test Lung
<table>
<thead>
<tr>
<th>Specifications</th>
<th>BABI.PLUS NEONATE LUNG</th>
<th>ADULT/ PEDIATRIC DEMONSTRATION LUNG</th>
<th>IMT MEDICAL SMART LUNG INFANT</th>
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<tbody>
<tr>
<td><strong>ADULT/ PEDIATRIC DEMONSTRATION LUNG</strong></td>
<td>Neonatal</td>
<td>Adult Children Neonatal</td>
<td>Adult Children Neonatal</td>
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<tr>
<td><strong>Resistance</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>(90/145/300/600 cmH2O/L/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compliance</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Leakage</strong></td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Spontaneous Breathing</strong></td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td><strong>Mode of Operation</strong></td>
<td>Manually</td>
<td>Manually</td>
<td>Manually</td>
</tr>
<tr>
<td><strong>Portable</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Dimension (mm)</strong></td>
<td>125 x 105 x 35</td>
<td>318 x 230</td>
<td>270 x 115 x 40</td>
</tr>
<tr>
<td><strong>Weight (g)</strong></td>
<td>43</td>
<td>-----</td>
<td>285</td>
</tr>
<tr>
<td><strong>Price (€)</strong></td>
<td>-----</td>
<td>-----</td>
<td>475</td>
</tr>
<tr>
<td>ASL 5000 BREATHING SIMULATOR</td>
<td>RESPITRAINER INFANT</td>
<td>NEOULNG - INFANT TEST LUNG</td>
<td>QUICKLUNG PRECISION TEST LUNG</td>
</tr>
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<td>---------------------</td>
<td>--------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Adult Children Neonatal</td>
<td>Children Neonatal</td>
<td>Neonatal</td>
<td>Adult</td>
</tr>
<tr>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>(programmable, 3 to 500 cmH2O/L/s)</td>
<td>YES</td>
<td>(100-350 cm H2O/L/s at 10 L/min flow)</td>
<td>(5, 20, 50 cm H2O/L/s)</td>
</tr>
<tr>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>(programmable)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>YES (manually)</td>
</tr>
<tr>
<td>Parameter file scripts, Interactive,</td>
<td>Manually and graphic feedback</td>
<td>Manually</td>
<td>Wireless</td>
</tr>
<tr>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>(heavy)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>425 x 219 x 310</td>
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<td>216 x 165 x 76</td>
<td>185 x 277 x 58</td>
</tr>
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<td>10000</td>
<td>-----</td>
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<tr>
<td>28107</td>
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</tr>
</tbody>
</table>

Table 3: Comparison of lung simulators available in the market.
4 REQUIREMENTS
4.1. CONTEXT OF USE

THE SIMULATION ENVIRONMENT

To be able to design a neonatal and pediatric lung simulator, the context of use must be clear. The prototype was designed by taking into account the actual training environment. One of the training rooms at Children’s Hospital Sant Joan de Déu has been made available and presented to the designing team before the work process started. In the following figures Darwin Simulation Centre of Sant Joan de Déu Hospital can be seen with its equipment and mannequin.

The main purpose of the lung simulator is to replicate real patient scenarios in a simulation environment. It’s goal is to train future professionals in understanding the patient’s condition and interpreting the equipment graphs, so the right decisions can be made in a real scenario.
The storyboard shows the steps on how the lung simulator is going to be used.

The first step the doctor checks the room to see if everything is there and gets the lung simulator out of the package placing it in the right spot of the room. Next the doctor connects the air supply and the respirator to the lung simulator. The doctor will check if the parameters of the respirator are set right, after which he turns the lung simulator on. Once the lung simulator is on he starts the application, and goes to the control room. The students stand around the bed with the patient.
At the moment everybody is in the right place, the doctor starts making adjustments to the parameters which means that the simulation has started and the students have to start making diagnostics and treating their patient. If they find the right diagnostic or the time is over, the doctor turns the application off and goes back to his students, so he can tell them what they did right and what they did wrong. In the end, the doctor disconnects the lung simulator from the air supply and the respirator and puts the lung simulator back in its package.
The lung simulator is designed to be used by several profiles of users, as it is very easy to operate, yet, the main users of the lung simulator will be the professors or doctors of the hospital, which are responsible with the training process.

The following graphics illustrate one of the most common user profiles for the lung simulator.

**PERSONA:**

**DR. JOHN WHITE**

**PEDIATRIC CARE MEDICINE**

---

**ABOUT ME**

53 years old.
Barcelona, Spain.

Work: San Juan de deu Pediatrics Hospital.
3 days a week he works at the hospital as Doctor, the other 3 days he teaches medical students in the simulation room, there he awaits the students and describes the stages of the simulation.

---

**EXPERTISE SKILLS**

Assessment of the child and normal teenager.
Conducting clinical history
History and examination of children and adolescents with comorbid.
Interpretation of clinical analysis.
Reanimación cardiorrespiratoria.
Interpretation of diagnosis by image
Intestinal, renal and liver biopsies

---

**HEALER**

“Being prepared is important, know to expect it is even more, but seize the right moment is the key to life”.
Arthur Schnitzler

---

**LUNG SIMULATOR / EXPERTISE SKILLS**

**MULTIPLE PATIENT SCENARIOS**

**ADJUSTABLE FOR EGES FROM 0-16**

**PORTABLE**

**WIRELESS**

**EASY TO USE**

---

**HOBBIES**

TRAVELING PHOTOGRAPHY MUSIC RESEARCH
The doctor connects the lung simulator and prepares the room for the simulation. The doctor manipulates the lung simulator during the simulation and decides the parameters of the test. He recovers and saves the data of the simulation and he disconnects all the devices.

**BACKGROUND**

JEESSE BROWN
22 years old.
He lives in Sitges, Spain
He is on the basketball team of the university, and every 2 weeks he plays competitively.
He is in his last year of pediatric care medicine in the UAB university.
He takes the train 3 days a week to San juan de deu Hospital in Barcelona for his internship.

**USE**
The student gets into the room to perform the simulation.
He interprets the information on the screen of the respirator and acts accordingly.

**MUST DO**

+ Useful both for research and educational purposes.
+ Easy to operate
+ Intuitive software
+ Pre-defined common clinical scenarios with several degrees of severity.
+ Light to carry (portable)
+ Fast connection between the app and the lung simulator
+ Long time battery

**MUST DO NEVER**

- Difficult to understand
- Heavy, no portable
- No represent the clinical scenarios appropriately
- Failure in data recover
- Difficult connection to the ventilator and respirator
- Take so long to respond the commands
- Turn off in the middle of the test

**CONTEXT**

Simulation room is designed to provide realistic simulations for teaching medical students. The room is separated in 2 parts by one-way glass.
In one side of the room we can find all the realistic medical equipment for the students and the other part is the control room for the simulation.

**LUNG SIMULATOR**
4.3. **Tasks**

**Using the simulator**

**WHAT DOES EVERY USER HAVE TO DO OR ACCOMPLISH WITH THE LUNG SIMULATOR**

**Professor and doctors:**

- Control the statistics of the simulation
- Supervise the simulator
- Give lectures about the illnesses which are simulated
- Evaluate how student treat illnesses

**Students:**

- React in the right way, treat in the right way
- Get practical experience
- Get knowledge about the respirator
- Improve diagnosis skills

**Environment**

The main environment of the lung simulator is the Darwin simulation lab in Sant Joan de Deu hospital (Barcelona). It is a room they use to train residents in the training to pediatric and obstetric doctors, by let them train on realistic simulations. So they can learn how to react quick and right to changes in specific statistics changes.

The room is provided with different simulations, and build in that way that the teaching doctor out of another room can look what the residents are doing and change the statistics. The training is recorded so the doctors can discus after the simulation what they did right and what they have to change. So are the students able to learn of their mistakes and they can see what they did good so they can keep that in their work method.

The main focuses of the training are:

- Training teamwork
- Training technical skills
- Training in decision-making
- Relational skills
DARWIN SIMULATION LAB

All the space available for the simulation in the hospital occupies about 150m² and it can be found in the vicinity of San Joan de Deù, more specific, in the teaching building. The simulation space has multiple training functions, so they can use one room for different specialities. The room is built so that it looks like a real hospital room. This is because it has to seem as real as possible to have better results in real situations. The simulation area has the ability to record their activity in audio and video and also make video streaming and broadcasting anywhere in the world.

The equipment and tools in the lab are:

- Two multipurpose rooms for advanced simulation:
  * Box paediatric ICU; Neonatal
  * Neonatal ICU
  * Box of emergency
  * Delivery Room

- A specific room for individual skill training and coaches of various techniques
- A control room
- A room for viewing and debriefing

The space is equipped with simulators, venting and medical support equipment:

- Material for advanced training in clinical settings for all paediatric ages’ simulation
- Advanced simulation equipment to recreate obstetrics scenarios
- Respirators and lung simulators for training in paediatric and neonatal ventilation
- Simulators for training of basic life support
**PEDIATRIC AND NEONATAL LUNG SIMULATION**

The current lung simulator available at the hospital has basic functions and the manipulation of parameters is limited.

The lung simulations for lung problems are manually operated and this is not practical while training students, because they can just look at the professor and check what he is doing. In this case, students could never learn to identify specific diseases.

![Figure 27: Actual lung simulator](image1)

![Figure 28: Actual lung simulator](image2)

**OTHER ENVIRONMENTS**

Laboratories of the university: Those aid students in doing projects in the medical university. It is where medicine students practice and where the simulator might be used. The professor or the person responsible for one particular laboratory needs to oversee all the actions of the students during the practical session so the person has to be able to hold the situation under control, and all the expensive medical equipment is kept in good condition for future students.

Conference rooms: the lung simulator might also be needed in lectures about lungs so the professor should be able to carry it to the conference room. This way, they can explain visually the problems they are talking about. It could be used to lecture students as well as explaining illnesses to other doctors.
5. Design Process
Brain

Functionalities
- Automatic
- Feedback
- Spontaneous breathing
- Electric valves
- leaks
- Realistic
- Remote controlled
- Compliance
- Parameters
- Resistance
- Realistic feedback
- Electric components

Appearance
- Medical
- Technological
- Component fitting
- Nice design
- Shape
- Colors
- User friendly

Spontaneous breathing
-肺
-心
-脑

Brain simulator
-肺
-心
-脑

Functionalities
-自动
-反馈
-自发呼吸
-电动阀门
-泄漏
-逼真
-远程控制
-符合
-参数
-阻力
-逼真反馈
-电动元件

外观
-医疗
-技术
-组件适配
-漂亮设计
-形状
-颜色
-友好

电
-肺
-心
-脑

Brain simulator
-肺
-心
-脑
During brainstorm sessions, sketches of the possible shapes were made. The mechanical part of the lung simulator had multiple solutions, yet most of them proved to be either problematic in sustaining all the features required or very expensive to produce so the prototype would have been no different than the actual lung simulators on the market.

In the following figures some of the first designs can be seen.
In figure 29 one of the first considered versions of the lung simulator can be seen. Adding two bags, one for the neonatal one for the pediatric with individual sealing to offer the possibility of switching between them, has been considered. The very different sizes for the bags (50ml and 250ml) imposed some restrictions on the mechanism producing the spontaneous breathing. Adding a motor for each bag as can be seen in figure 30 was the first solution that came up, but this would have affected the price of the prototype, so the final decision regarding this was to implement a single motor for the spontaneous breathing mechanism. The second solution can be seen in the same figure: adding two bags with different diameters and same lengths with two separate airways. This solution was not possible because when the neonatal bag was used, the motor was still pushing the pediatric bag (larger one), and then the different compliance values for the pediatric and the neonatal were not possible anymore.

Figure 31 represents the sketch considering just one changeable bag. In this design a connection to the end of the tube containing the bag was considered but then the bag would have been hard to design as it needed to have a passage through it for the connection to be possible. Moving the connection from the middle to the side of the container of the bag can be seen in figure 32 The final sketch was created because the connection between the motor and the end side of the bag container created problems in changing the pediatric and neonatal bags.

Figure 33 is a representation of the final version for the lung simulator prototype and the version which was further produced. The sketches represent the motor pushing the front side of the bag container which is placed inside a case with clips. The main role of the clips is to be able to fix the end side of the bag container for two different sizes, as the neonatal and pediatric bag sizes are very different, but also to fix the container to the side that is actioned by the motor. The whole system must be fixed both sides inside a case so the motor could action the bag container.

Figure 34 is a very basic representation of the actual lung functions and how they work. To shortly explain them, the motor’s role is double. It has to action the bag system to produce the spontaneous breathing and it also has to adjust the position of the bag to sustain the compliance.
The compliance of the lungs is simulated by internal pressure, as the actual bag container is completely sealed in middle position (inside pressure = atmospheric pressure). When the container extends the volume inside is getting bigger so the internal pressure drops. The bag inside the container is expanding, tending to equal the pressures again. The elastic material of the bag is limiting the expansion of the bag, so it can simulate the lung compliance. When compressing the bag, the process is reversed, but this time the high pressure inside will limit the expansion of the bag instead of it’s elasticity. Depending on the extension level of the bag, the compliance gets different values.

For the resistance of the airways and the leakage, proportional electric valves are used, which can easily be controlled remotely.

The following picture is a detailed 3D representation of the lung simulator components, followed by a compact 3d representation of the actual complete mechanism.

The figures don’t include the casing of the lung simulator.
5.2. PROTOTYPE Test functionalities

During the work process, a physical test prototype was created to be able to clearly understand and test the basic functionalities of the lung simulator. The test lung simulator was created after previously described figure 31 and is not required for any further progress on the project.

The prototype works by moving a motor back and forth wherefore the lungs inhale and exhale. The air of the respirator and for that reason also the resistance but also the leakage are connected to the opposite side of the simulator than the motor, the resistance and leakage are simulated with proportional valves. The compliance is simulated by limiting the movement of the motor, what means limiting the expanding of the lung. The spontaneous breathing of the patient is simulated by moving the motor before the respirator can blow air inside, so the lung sucks air in.

But this prototype still had too much faults. For instance, the fact that the motor has to keep moving all the time is a big disadvantage. So it has been decided to keep improving the design.
5.3. **FIRST IDEA**  Working mechanism

The first idea for the mechanism is very similar to the final idea but this idea was using a worm gear which enables that the bag moves to create inspiration and expiration.

This mechanism imitates the action of the lungs:

- The air bag = the lungs,
- Bendable rubber tube = thoracic wall,
- The vacuum space = thoracic cavity
- Worm gear = the diaphragm and abdominal muscle.

The cylinder = the closed system: (the lungs, the thoracic cavity and the thoracic wall)

In relaxed or initial position, the pressure inside the cylinder equals to the pressure outside, and the air bag (lungs) is flaccid.
6 FINAL DESIGN
In the following figure, the detailed components of the lung simulator’s case and mechanism can be seen. The linear motor is the mechanism that has the function to action the whole system when spontaneous breathing is needed, or when the position of the rubber tube has to be modified for a different compliance (pressure inside the tube) value. Its connection to the tube includes a connection rod, and a cover with a clipping possibility of the bag inside the cover part. This is needed to assure the possibility of bag changing, as it needs both pediatric and neonatal sizes.

The airbag is connected to the tube as seen previously in the assembled system representation. The connection should be perfectly sealed to assure a vacuum inside of the rubber tube.

The rubber tube is the container of the airbag, assuring the pressure variations after sealing it in middle position (at atmospheric pressure). Its material assures a flawless bending back and forward.

The air tubes are connected to the air bag inside the container and have no connection to the air inside the rubber tube as they are opened before the connection to the medical equipment available in the hospital’s training room. They have also attached the electrical proportional valves to them, to offer the remote control of the leakage and the resistance.
1 - LINEAR MOTOR
2 - CASE
3 - LOGO ILLUMINATED BY LED
4 - AIR BAG
5 - CONECTION TO THE COVER DISK
6 - AIR WAY TUBES
7 - SOLENOID ELECTRO VALVES
8 - ON / OFF BOTTON
9 - MECHANISM BASE
10 - BOTTON OPEN CASE
11 - L HOLDERS
12 - ARDUINO
13 - CYLINDER TUBE
14 - HANDLES
15 - ENTRANCE TUBE

Figure 43: Explosive of the final design
6.1.1 THE DIMENSIONS

The dimension can be represented for the whole system. The following figure is a simple but clear representation of the system’s dimensions for the pediatric bag. The dimensions are represented in millimeters, so it can be seen that the whole mechanism has 46 [cm] length and 9 [cm] height. Those dimensions assure the portability requirement for the prototype.
6.2. **PRODUCT APPEARANCE**

**MOODBOARD HOSPITAL DEVICES**

An analysis of the products available on the market has been made. Thanks to this, the main things that had to be implemented in the prototype have been made clear.

The important features resulted from market research:

Easily replaceable parts, stability, clean design, understandable visual codes, ergonomics based on the human hand, neutral colors.
- The exchange between neonatal and pediatric bag is easy thanks to the clipping mechanism

- The cover is equipped with an ON/OFF button

- Easy interchange of neonatal and pediatric bags due to the clipping mechanism

- At bottom, there are two supports for the lung simulator, providing the possibility to hang the prototype to the side of the respirator

- The power button can be seen in green (on/off)

- For easy transportation of the device have two handles on each side

- When the device is turned on, the logo of the lung simulation can be seen, illuminated in blue LED light
The air bag is the main component of the lung simulator which represents the lung of the patient. It is the most essential part of the prototype that enables it to simulate the function and characteristics of the real lung in breathing process.

The air bag has an ellipsoid shape and is located inside a vacuum rubber tube. It is made of rubber which enables it to inflate and deflate easily. With its specific elastic property, the air bag is going to expand double of the initial size. This feature enables it to have the minimum and maximum lung volumes.

6.3. THE AIR BAG

The volume of the air bag must be able to accommodate to two sizes of lungs (pediatric and neonatal) and it is crucial to ensure that the size of the air bag is adaptable to its volume range. Therefore, two sizes of changeable air bags which are going to be used in this prototype are:

**PEDIATRIC:**
125 TO 250 ML

**NEONATAL:**
25 TO 50 ML

The volume of the air bag is calculated by applying the formula of ellipsoid. It can be calculated using the length axis radius (R1), height axis radius (R2) and width axis radius (R3) of the ellipsoid.

The ellipsoid volume formula is given as:

\[
\text{Volume of the Ellipsoid} = \frac{4 \times \pi \times R_1 \times R_2 \times R_3}{3}
\]
6.3.2. CALCULATIONS AND RESULTS

6.3.2.A. PEDIATRIC AIR BAG

By taking into account all factors and characteristics of the real lungs, it has been decided to use a bag made of rubber material which could expand double of its initial size. This elastic property would be able to ensure that the air bag is adaptable to the specific volume range. Hence, the initial size of the air bag use will be the minimum size volume in which could expand to double of its initial volume when air goes into it (inspiratory) and reach the maximum volume.

**PEDIATRIC**

\[
V_{\text{MIN}} = 125 \text{ ML} = 125 \text{ cm}^3
\]

\[
V_{\text{MAX}} = 250 \text{ ML} = 250 \text{ cm}^3
\]

Considering the minimum and maximum volume of the air bag sizes, the dimension of the ellipsoid air bag has been calculated using the following formula:

WHERE:

\[
V = 125\text{cm}^3 \quad R_2 = R_3 = 2.5\text{cm}
\]

Rearranging the formula to calculate the length axis radius \((R_1)\):

\[
(R_1) = \frac{3 \times V}{4 \times \pi \times R_2 \times R_3}
\]

\[
= \frac{3 \times 125}{4 \times \pi \times 2.5 \times 2.5}
\]

\[
= 4.77\text{cm}
\]

The final dimension of the pediatric air bag (considering minimum volume as the initial size):

[unit: mm]
6.3.2. B. NEONATAL AIR BAG

**NEONATAL**

\[ V_{\text{min}} = 25 \text{ ML} = 25 \text{ CM}^3 \]
\[ V_{\text{max}} = 50 \text{ ML} = 50 \text{ CM}^3 \]

Considering the minimum and maximum volume of the air bag sizes, the dimension of the ellipsoid air bag has been calculated using the following formula:

\[
V = \frac{3}{4} \pi R_1^2 R_2 R_3
\]

Where:

\[ V = 25\text{ cm}^3 \quad R_2 = R_3 = 1.3\text{ cm} \]

Rearranging the formula to calculate the length axis radius \((R_1)\):

\[
(R_1) = \frac{3 \times V}{4 \times \pi \times R_2 \times R_3}
\]

\[ = \frac{3 \times 25}{4 \times \pi \times 1.3 \times 1.3} \]

\[ = 3.53\text{ cm} \]

The final dimension of the neonatal air bag (considering minimum volume as the initial size):

(Unit: mm)

Figure 53: Minimum and Maximum neonatal Air bag Volume
6.4. **SPONTANEOUS BREATHING**

The spontaneous breathing is the condition when the patient connected to the ventilator started to recover and breathe normally.

At this stage, the ventilation system will detect the changes and readjust the input air in order to adapt to the patient’s normal breathing rate. Disturbance of spontaneous breathing by artificial ventilation must be reduced to the absolute minimum.

The spontaneous breathing control system must be able to fulfill important requirements in order for it to be able to simulate the real spontaneous breathing conditions or characteristics including:

- The ventilator is able to detect the beginning of a spontaneous breathing process once the lung (air bag) volume is increased to at least 10 ml.
- The control system is able to simulate the spontaneous breathing within duration of about 2 minutes to allow the ventilator to adapt to the breathing rate.
- Considering the different breathing pathologies of patients, the system must be able to adjust the rate of breathing from the range of 10-70 respirations per minute.

### 6.4.1. THE MECHANISM

For this prototype, the spontaneous breathing is simulated through the movement of a linear actuator. It is controlled by the movement of the shaft connected to the cover disk producing movement back and forth, expanding and contracting the cylinder tube outside. This action causes the cylinder tube free space (thoracic cavity) to increase and decrease, consequently changing the pressure inside it and enables air to be pulled in and out alternately.

Applying the Boyle’s law principle, which states that at constant temperature, for a fixed amount of gas, the pressure and volume are inversely proportional. Mathematically, it can be stated as:

\[ P = \frac{k}{V} \quad \text{or} \quad PV = k \]

Where \( P \) is the pressure of the gas, \( V \) is the volume of the gas, and \( k \) is a constant.

In other words, when we increase the volume of a ‘container’ or a closed system, the pressure will decrease and vice versa.
This mechanism imitates the action of the lungs:

- **Air bag** = the lungs,
- **Cylinder tube** = thoracic wall,
- **The cylinder tube free space (closed system)** = thoracic cavity
- **Linear actuator** = the diaphragm and abdominal muscle.

In relaxed or initial position, the pressure inside the cylinder equals to the pressure outside, and the air bag (lungs) is flaccid.

**INSPIRATION**

When the linear actuator is pulled to the maximum level, the volume inside the cylinder increases and the pressure is decreases. Air is forced into the air bag(lung) from outside, lowering the volume inside the cylinder and stretching the air bag until the pressure inside and outside of the cylinder is equal. The air bag is inflated.

**EXPIRATION**

When the linear actuator is pushed to the minimum level, the volume inside the cylinder decreases and the pressure increases, forcing the air out of the air bag until it is deflated.
6.4.2. CONTROL SYSTEM

The speed of the motor inside the linear actuator controls the breathing rate of the lung simulator system. The higher the speed of the motor, the higher is the breathing rate and vice versa. Certain range of breathing rate will be programmed inside the android application so that it can manipulate different breathing rates and simulate different breathing pathologies of patients.

The range of the breathing rate which are required in order to simulate various condition of spontaneous breathing for specific categories are:

**BREATHING RATES**

(BREATHS/MIN)

<table>
<thead>
<tr>
<th>PEDIATRIC:</th>
<th>NEONATAL:</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 - 40</td>
<td>40 - 70</td>
</tr>
</tbody>
</table>

6.4.2.A. LENGTH OF EXTENSION

The volume of the cylinder tube free space (thoracic cavity) $V_T$ will remain the same before and after complete inflation of the air bag. Therefore, the relation between the length of expansion of the cylinder tube, $l$ and the changing of volume of the air bag, $V_B$ can be calculated as follows:

$$V_T = \text{Total volume of the cylinder tube} - \text{Volume of the air bag(lung)}$$

$$V_T = \left( \frac{\pi x d^2 x l}{4} \right) - V_B$$

**COMPLETE EXHALATION CONDITION**

$$V_{T0} = \left( \frac{\pi x d^2 x l_0}{4} \right) - V_{B0}$$

**WHERE:**

<table>
<thead>
<tr>
<th>$V_{T0}$</th>
<th>$V_{B0}$</th>
<th>$d$</th>
<th>$l_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of the cylinder tube free space at initial condition</td>
<td>Volume of the air bag at initial condition</td>
<td>Diameter of the cylinder tube</td>
<td>Initial length of the cylinder tube</td>
</tr>
<tr>
<td>(cm³)</td>
<td>(cm³)</td>
<td>(cm)</td>
<td>(cm)</td>
</tr>
<tr>
<td><strong>NEONATAL</strong></td>
<td><strong>PEDIATRIC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Exhalation condition
At initial state, the air bag for the neonatal and pediatric is going to be considered to have an initial volume of 6ml and 10ml, although in real life the amount of functional residual volume of the lung after complete exhalation is a bit higher.

Substitute all the values in order to find the total volume of the cylinder tube free space (thoracic cavity)

\[
V_{T0}^{\text{(pediatric)}} = \left( \frac{\pi \times 9^2 \times 16}{4} \right) - 10 = 1007.876 \text{ cm}^3
\]

\[
V_{T0}^{\text{(neonatal)}} = \left( \frac{\pi \times 6^2 \times 11}{4} \right) - 6 = 305.018 \text{ cm}^3
\]

**COMPLETE INHALATION CONDITION**

Since the volume of the cylinder tube free space is constant before and after complete inhalation, it is possible to find the required length of extension of the cylinder in order to have a maximum air bag volume (complete inhalation condition).

\[
V_{Tf} = \left( \frac{\pi \times d^2 \times l_{\text{max}}}{4} \right) - V_{B_{\text{max}}}
\]

**WHERE:**

\[
V_{Tf} = V_{T0}
\]

<table>
<thead>
<tr>
<th>Table 5: Inhalation condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{Tf})</td>
</tr>
<tr>
<td>(V_{B_{\text{max}}})</td>
</tr>
<tr>
<td>(d)</td>
</tr>
<tr>
<td>(l_{\text{max}})</td>
</tr>
</tbody>
</table>

All the values are substituted into the equation in order to find the maximum length of the cylinder expansion.
NEONATAL

\[305.018 \text{ cm}^3 = \left( \frac{\pi \times 6^2 \times l_{\text{max}}}{4} \right) - 50\]

\[l_{\text{max}} = 12.556 \text{ cm}\]

Therefore, \[\Delta l = l_{\text{max}} - l_0 = 12.556 \text{ cm} - 11 \text{ cm} = 1.556 \text{ cm} \approx 2 \text{ cm}\]

PEDIATRIC

\[1007.876 \text{ cm}^3 = \left( \frac{\pi \times 9^2 \times l_{\text{max}}}{4} \right) - 250\]

\[l_{\text{max}} = 19.733 \text{ cm}\]

Therefore, \[\Delta l = l_{\text{max}} - l_0 = 19.733 \text{ cm} - 16 \text{ cm} = 3.773 \text{ cm} \approx 4 \text{ cm}\]

At initial state of expansion, due to the elasticity property of the air bag balloon, it requires a certain amount of force in order to overcome its initial stiffness and inflate smoothly. Therefore, the length of the cylinder tube extension would be a bit longer than the theoretical value which is about (2 to 3) cm for neonatal and (4 to 5) cm for pediatric.

As a conclusion, the air bags which act as the lungs will be fully inflated when the cylinder tubes are extended to two centimeters length (for neonatal) and five centimeters length (for pediatric).

6.4.2.B. SPEED OF EXTENSION

The range of speed required in order to simulate various breathing rates can be calculated as follow:

NEONATAL

The total travel distance required to fully inflate the bag \[\Delta l = 2.5 \text{ cm} / \text{ breath}\]

The range of neonatal breathing rate \[40 \text{ to } 60 \text{ breaths} / \text{ min}\]

\[V_{\text{min}} = \frac{40 \text{ breaths}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{2.5 \text{ cm}}{\text{breath}} = 1.67 \text{ cm} / \text{s}\]

\[V_{\text{max}} = \frac{70 \text{ breaths}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{2.5 \text{ cm}}{\text{breath}} = 2.92 \text{ cm} / \text{s}\]
PEDIATRIC

The total travel distance required to fully inflate the bag = \( \Delta l = 4.5 \text{ cm} / \text{breath} \)

The range of paediatric breathing rate = \( (12 \text{ to } 40) \text{ breaths} / \text{min} \)

The total speed required to simulate the pediatric breathing rates are:

\[
V_{\text{min}} = \frac{12 \text{ breaths}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{4.5 \text{ cm}}{\text{breath}} = 0.9 \text{ cm} / \text{s}
\]

\[
V_{\text{max}} = \frac{40 \text{ breaths}}{\text{min}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{4.5 \text{ cm}}{\text{breath}} = 3 \text{ cm} / \text{s}
\]

Therefore, a very specific and various pattern of breathing rates can be simulated by adjusting the speed of the linear actuator motor in the following range:

<table>
<thead>
<tr>
<th>BREATHING RATE (BREATHS /MIN)</th>
<th>MOTOR SPEED (CM/S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 to 70</td>
<td>1.67 to 2.92</td>
</tr>
<tr>
<td>12 to 40</td>
<td>0.90 to 3.00</td>
</tr>
</tbody>
</table>

Table 6: Breathing rates
Compliance is the measure of the ease of inflation, distensibility, or the ease with which the lungs can stretch or inflate. In other words, it is the resistance of the lung and chest wall to being stretched.

It is calculated by dividing the patient’s exhaled tidal volume, by the pressure needed to provide that same tidal volume; the transpulmonary pressure:

\[
\text{COMPLIANCE} = \frac{\text{exhaled tidal volume change (ml)}}{\text{pressure change (cm H2 O)}} = \frac{\Delta V_t}{\Delta P}
\]

Where \( C \) is the compliance, \( \Delta V_t \) is the change in the lung tidal volume, and \( \Delta (P_{alv} - P_{ip}) \) is the change in the transpulmonary pressure; which is the difference between the alveolar pressure, \( P_{alv} \), and the intrapleural pressure, \( P_{ip} \).

- Increasing compliance means the lungs are easier to inflate.
- Decreasing compliance means the lungs are harder to inflate (getting stiffer).

### 6.5. THE MECHANISM

The lung simulator prototype, enables the user to manipulate the lung compliance parameter in a wide range of values. The compliance is controlled by the internal pressure of the cylinder as well as the positioning of the linear actuator shaft. Applying the Boyle’s Law principle, \( PV=k \), the pressure inside a container decreases when the volume increases and vice versa. The pressure produced, creates a surface tension to the air bag walls which simulates the role of the ‘alveolar surface tension’ inside the lung and affects the compliance.

The cylinder is a closed system which is completely sealed. In the middle (relaxed) position, the pressure inside of the cylinder is equal to the atmospheric pressure (outside). The positioning of the linear actuator enables the volume and pressure of the cylinder to be altered; consequently control the amount of space in which the air bag can expand.

**HIGH COMPLIANCE**

When the cylinder is extended, the volume inside increase and the pressure decrease. The air bag expands until the pressure inside and outside of the cylinder is equal. The low pressure in the cylinder tube produces a low surface tension to the air bag wall. Hence, the air bag is easy to inflate and the compliance increases.

In this condition, the air bag can be stretch to the maximum volume and the only factor which limits the expansion would be the elasticity property of the material which limits its expansion.

**LOW COMPLIANCE**

When the cylinder is compressed, the volume inside decreases and the pressure increases. The high pressure inside the vacuum space produce a high surface tension to the air bag wall and impede the air bag from expansion.

Besides that, reducing the size of the cylinder will cause the air bag harder to inflate due to the resistance produced and limitation of space inside it, causing a decrease in compliance.
6.5.2. CONTROL SYSTEM

The compliance can be manipulated by changing the volume of the cylinder tube and consequently it produces certain amount of pressure towards the air bag wall which affects its expansion.

<table>
<thead>
<tr>
<th>COMPLIANCE (ml / cm H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>neonatal</td>
</tr>
<tr>
<td>pediatric</td>
</tr>
</tbody>
</table>

Table 7: Compliance table

6.5.2.A. THE PRESSURE AND VOLUME (P-V) RELATION

The relationship between the pressure and the volume inside the cylinder (thoracic cavity) can be calculated by considering the cylinder tube free space as a closed system and applying the ideal gas law equation.

\[
P \times V = n \times R \times T = \text{constant}
\]

\[
P_T \times V_T = n \times R \times T = \text{constant}
\]

WHERE:

- \( P_T \) = Pressure in the cylinder tube closed system [Pa]
- \( V_T \) = Volume in the cylinder tube closed system [m³]
- \( n \) = Number mol of gas [mol]
- \( R \) = Universal gas constant = 8.3145 JK⁻¹ mol⁻¹
- \( T \) = Absolute temperature of the gas [K]

At the initial position or initial state, the pressure inside the cylinder tube is equals to the atmospheric pressure outside and the volume of the cylinder tube free space (closed system) is known based on the initial volume calculated in section Spontaneous Breathing (6.4) The system is considered as an isothermal system (constant temperature) and the temperature is assumed to be around 21 °C which is the average room temperature.

\[
P_T = P_{\text{atm}} = 101325 \text{ Pa}
\]

\[
P_T = V_{T0 \text{ (neonatal)}} = 3.0501177 \cdot 10^{-4} \text{ m}^3
\]
The P, V, R and T values are substituted into the ideal gas law equation in order to find the unknown n value. Since it is a closed system, the number of moles inside the free space will remain the same throughout the whole process. Rearranging the equation,

\[ n = \frac{P_T \times V_T}{R \times T} \]

\[ n_{\text{(neonatal)}} = \frac{101325 \text{ Pa} \cdot 3.0501177 \cdot 10^{-4} \text{ m}^3}{8.3145 \text{ JK}^{-1} \text{ mol}^{-1} \cdot 294.15 \text{ K}} = 0.012637 \text{ mol} \]

\[ n_{\text{(pediatric)}} = \frac{101325 \text{ Pa} \cdot 1.007876 \cdot 10^{-3} \text{ m}^3}{8.3145 \text{ JK}^{-1} \text{ mol}^{-1} \cdot 294.15 \text{ K}} = 0.041756 \text{ mol} \]

Therefore, the P-V relation can be written as follow:

**NEONATAL**

\[ P_T \cdot V_T = 0.012637 \text{ mol} \cdot 8.3145 \text{ JK}^{-1} \text{ mol}^{-1} \cdot 294.15 \text{ K} = 30.905916 \text{ [J]} \]

\[ P_T \cdot V_T = 30.905916 \text{ [J]} \]

**PEDIATRIC**

\[ P_T \cdot V_T = 0.041756 \text{ mol} \cdot 8.3145 \text{ JK}^{-1} \text{ mol}^{-1} \cdot 294.15 \text{ K} = 102.123038 \text{ [J]} \]

\[ P_T \cdot V_T = 102.123038 \text{ [J]} \]

The volume of the cylinder tube will remain the same at each complete inhalation process. However, throughout the process in which before it reaches the final complete inhalation condition (fully inflate air bag), the volume varies as the length of the cylinder tube increases and decreases. Hence, the pressure inside the cylinder tube is manipulated.

The equation of the ideal gas law is combined with the total volume of the cylinder tube free space (thoracic cavity) equation.

**NEONATAL**

\[ P_T \cdot V_T = 30.905916 \text{ [J]} \]

**PEDIATRIC**

\[ P_T \cdot V_T = 102.123038 \text{ [J]} \]

\[ V_T = \left( \frac{\pi \times d^2 \times l}{4} \right) - V_B \]
The manipulated variable is the volume of the cylinder tube, \( V_T \), and it is affected by the change of the cylinder tube length, \( l \) and the volume of the air bag, \( V_B \). While, the responding variable is the pressure produced inside the cylinder tube.

It is manipulated by adjusting the length of the cylinder tube, \( l \) between (8 to 14) cm length for the neonatal and (12 to 20) cm for the pediatrics.

At the same time, for each neonatal and pediatric category, two types of graphs are plotted in the same graph in order to present the P-V relation for two different conditions.

The change of \( P_V \) at initial state, before the air bag expansion (exhalation), \( P_B = P_{B0} \)

The change of \( P_V \) at final state, complete air bag expansion (complete inhalation) \( P_B = P_{B_{\text{max}}} \)

Based on the graphs, we can conclude that the pressure is inversely proportional to the volume of the cylinder tube free space. Increasing the length of the cylinder tube, increases the volume, consequently reduces the pressure inside it and vice versa.

In general, the pressure of the cylinder tube (thoracic cavity) is a bit lower at initial state in which the air bag is deflated, on the other hand the pressure is higher when the air bag is fully inflated (maximum volume).

The expected values of the compliance are going to be obtained by adjusting the position of the linear actuator, changing the volume and the pressure inside the cylinder tube free space. However, due to limited information about the pressure inside the air bag (lung) and the variation of pressure against time, it is difficult to find the exact values of compliance for the lung simulator prototype. Those values can only be obtained experimentally by adjusting the linear actuator at the hospital, testing it, at the same time synchronize it with the programming of the Arduino control system.
6.6. **Resistance**

Resistance (R) is the measure of impedance of air flow in the respiratory tract. It is defined by the change of driving pressure, $\Delta P$ per volumetric flow rate, $V$.

$$\text{RESISTANCE (Raw)} = \frac{\text{Pressure Change}}{\text{Volumetric flow rate}} = \frac{\Delta P}{V}$$

The change of driving pressure consists of the difference between atmospheric pressure and the alveolar pressure. The volumetric flow rate and the alveolar pressure change constantly during respiratory cycle. In the table below presents the average normal value of the airway resistance which depends on the child age:

<table>
<thead>
<tr>
<th>AIRWAY RESISTANCE ( MBAR/L/S )</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Newborns</td>
<td>30 - 50</td>
</tr>
<tr>
<td>Infants</td>
<td>20 - 30</td>
</tr>
<tr>
<td>Small children</td>
<td>20</td>
</tr>
</tbody>
</table>

However, the normal values of airway resistance are variable due to the large changes of the lung volume and methodological differences. The factors which can alter the lung airway resistance are:

- **Physiological factors:** Changes in smooth muscle tone, secretion of mucus, or inflammation.
- **Physical factors:** Changes in airway diameter due to radial traction or transmural pressure changes which usually related with the breathing cycle.

Therefore, after consulting the professional doctors at Hospital Sant Joan de Déu, it has been agreed upon that the values of the airway resistance which need to be simulated by the lung simulator is in between the range of (10 to 70) mbar/l/sec and they can be presented in percentage value.
By taking into account all the requirements of the lung simulator, a proportional electro valve has been selected in order to simulate the resistance mechanism. The capability of the electro valve which can be remotely controlled and does not require manual operation makes it the best option for the resistance control system.

Considering the fact that the resistance should not exist in a healthy or normal airways, a normally opened two-ways proportional valve is used. It is connected to the entrance of the air bag lung simulator controlling the entrance of the air flow. The electro valve is available in a broad range of configuration and materials on the market. These include different positioning of input and output port, power consumption, pressure resistance, different material casing and types of coils.
The principle operation of the two-way normally opened solenoid valve:

The air or gas flow enters the solenoid valve through the inlet port. The air must flow through the orifice before continuing into the outlet port. The orifice which controls the air flow is closed and opened by the plunger.

- De-energized → When the valve is switched off, the plunger stay at its initial position and air flows from one port to another.

- Energized → When the valve is switched on, the plunger lifted up by an electromagnetic field produced by the coil and ceases the air flow through the orifice.

6.6.2. CONTROL SYSTEM

By using a proportional electro valve, the amount of air flow can be remotely controlled. The performance depends on the current that goes in the coil. When the voltage is increased, the current flows through the coil are increased and consequently alter the positioning of the plunger. As a result, the air flow through the orifice is restricted and the resistance of the air ways is increased.

The capability of the proportional electro-valve to be adjusted in a wide range of values helps to increase the sensitivity and provides various range or option for the manipulation of the resistance parameter.

However, in mobile electrical systems the voltage is not controlled, instead it varies around the nominal battery voltage. To assure the voltages of the coil are used correctly, the electric valves are connected to an Arduino which has been programmed and controlled by Bluetooth serial communication system. The resistance parameter is altered through a mobile application which is connected to the Arduino and Bluetooth system.

The electric valve has a voltage not more than 12 V in order to ensure that it can be connected and controlled by the Arduino.
The programming control system for the resistance parameters are needed to be checked experimentally due to the fact that the measuring of the resistance airflow requires the measuring of simultaneous changes in the pressure and volume in the air bag lung simulator. In addition, the feedback and adaptation of the ventilator towards the lung simulator prototype must be considered in determining the calculation of control system.

The electric valve has a voltage not more than 12 V in order to ensure that it can be connected and controlled by the Arduino.

The programming control system for the resistance parameters need to be checked experimentally due to the fact that the measuring of the resistance airflow requires the measuring of simultaneous changes in the pressure and volume in the air bag lung simulator. There are many factors which may affect the resistance flow rate of the gas including:

- The variation length and diameter of the endotracheal (ETT) tube.
- The variation of the pressure input and output.
- The content and type of gases introduced into the lung simulator.

In addition, the feedback and adaptation of the ventilator towards the lung simulator prototype must be considered in determining the specific calculation of the resistance values.
6.7. LEAKAGE / Mechanism

Air leakage is one of the major problems associated with the leakage of gas during assisted invasive or non-invasive ventilation. It causes the reduction of air being introduced into the lung and interferes with the ventilator’s capability to detect the changes of spontaneous ventilation. Usually, the leaks are going to be minimized as much as possible in clinical practice. In this case, the manipulation of the air leakage is going to be presented in percentage unit and this has been approved by the doctors.

6.7.1. MECHANISM

For the leakage, the same method will be used, in which a second electric valve comes in need. This time, a normally closed two ways proportional electro valve is used as the leakage should be zero in a normal condition. The inlet of the leakage proportional valve is connected with the resistance valve connection, while the outlet port is connected to the outer environment allowing air to be expelled. The following diagram depicts the basic components of a normally closed 2 way valve.

The operation principle of the two-way normally closed solenoid valve:
The air or gas flow enters the solenoid valve through the inlet port. In order for it to be able to reach and exit through the outlet port, the air must flow through the orifice. The orifice which control the air flow is closed and opened by the plunger.
- De-energized  →  When the valve is switched off, the plunger stay at its initial position in which the spring presses the plunger tip against the opening of the orifice and impede air flow.

- Energized  →  When the valve is switched on, the plunger is lifted up by an electromagnetic field created by the coil and the air is allowed to flow through the orifice and the outlet port. The air is released.

### 6.7.2. Control System

In general, the same mechanism and control system is used for the leakage control system. The leakage valve is connected to a programmed Arduino microcontroller. At the same time, the lung simulator is equipped with Bluetooth system in order for it to be able to be controlled wirelessly through an application in a mobile device.

The usage of proportional electro-valve provides numerous options of percentage of leakage to be simulated. It is manipulated by varying the input current, as a result the valve’s flow rate can be adjusted accurately and precisely in a wide range of values. In addition, the proportional valve helps to improve the sensitivity of leakage parameter and enables simulation of various clinical scenarios. The maximum voltage of the electro-valve used is not more than 12 V in order to ensure that it is compatible and can be connected to the Arduino microcontroller.

The programming of the Arduino control system and the percentage of leakage result produced in the mobile application has to be tested experimentally in order to synchronize the feedback of the ventilator with the changing of lung simulator parameters.
6.8. PRODUCT/ Use sequence

1. Add the holders to the lung simulator
2. Select between the neonatal or the paediatric bag
3. Hang the lung simulator on the side of the ventilator
4. Connect the lung simulator with the air source
5. Connect the lung simulator to the power source
   Push the on/off button to turn on the device
6. Open the app in your phone or tablet to start the simulation
7. Simulation begins:
   The doctor can change the parameters in the lung simulator
   The students analyze and interpret this feedback in the ventilator
8. Simulation finish:
   The doctor turn off the app and give the students some feedback about the simulation
9. Disconnect the lung simulator from the power source
   Push the on/off button to turn off the device

Figure 68: Sequence of use
FEATURES OF THE PROTOTYPES

To successfully develop prototypes it is required conceive the construction on a different way to manufacture or fabricate. The first and most important it is that a prototype is not a final product.

DIFFERENCE BETWEEN PROTOTYPE AND MANUFACTURED PRODUCT

Prototyping and manufacturing are different activities. The products manufactured massively get their economy of scale by selling thousands of products, also the time and cost of manufacturing various types of machines and install them in a production line is a huge capital investment. The prototypes are used to reduce the risk associated with this level of investment.

As the prototypes are only produced in small numbers they do not require machinery to be built and they can be made in a completely different way. In the early stages of a project the attention is not on the manufacture, but in resolving the basic settings and how the product is used. As the designer comes to production, it is necessary to prototype all components before investing in a large-scale production.

The first step in the creation of the prototype was to figure 3d/2d through planes.

Laser cut is used in order to complete the details of the prototype. Acrylic colors are used.
With the 2D drawings, the mold is constructed with foam which is then is sanded and hardened with white glue.

Once the mold is created, the fiber-glass resin is placed.

After it is dried for 6 hours, the housing is sanded.

Taking the final piece will include laser cut details.
In order to control the lung simulator remotely it has been chosen to use a tablet or Smartphone through an application considering that the lung simulator has been designed to be controlled through ARDUINO.

### 6.10. ARDUINO

**What?**

An Arduino is an open-source electronics platform, based on easy to use hardware and software. It is a small power-circuit board, with connection point brought to the outside. On the circuit board there is a microcontroller that controls all the inputs and outputs.

For the prototype, an Arduino mega 2560 is used. It has a ATmega2560 microcontroller. The microcontroller has 54 digital input/output pins, 16 analog inputs, 4UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, a ICSP header (In-Circuit Serial Programming, the ability to be programmed while installed in a complete system instead of programmed before installed in the system), and a reset button.\(^{(26)}\)
How does it work?

Arduino works by uploading a program to the microcontroller and connect the visual inputs and outputs to let the programmed comments work. The program that has to be uploaded in the Arduino is written in c-language. The Arduino operates with an external power supply, this can be an USB connection or a AC-to-DC adapter, of 6 to 20V. If the supply is less than 7V the 5V pin may supply less than 5V and the board may be unstable; at more than 12V the voltage regulator may overheat and damage the board. In order to have the best working conditions it is recommended to work with a range from 7 to 12 volts.

Advantages

- Easy program language
- Pre-programmed libraries
- Easy to connect components to board
- Different size of board
- Many components in the market
- You can use it in windows or linux
- Interface with other softwares

6.10.2. APPLICATION DEVELOPMENT

Because the lung simulator has to be remotely controlled, it is handy to use an application, due to the popularity of the Smartphones and tablets. An online application creator, named Appinventor, was used to create it.
The application is easy to use, even people lacking knowledge about medicine part can use it. So when the doctor asks somebody else to change the settings it has to be possible.

On the start screen baby of child option appear as choices.

Once selecting one of the two choices, a new screen is opening. The screen contains an overview of all changeable parameters, a start and a stop button.

Each parameter has its own adjustment screen. The parameter changing controls the Arduino via Bluetooth in order to control the actual prototype components. The start and stop buttons are present on the parameter screens too.
Choose the patient

Baby
Child

Changeable parameters

Change resistance
Change compliance
Change air leakage
Change spontaneous breathing

Change the value of the chosen parameter
Table 11: Diagram
MANUFACTURING
A series of materials has been chosen for the designed prototype. In order to understand the material choices, the following picture shows the component breakdown of the prototype.

![Component breakdown of the lung simulator](image)

**Table 12: Main components**

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air bag</td>
</tr>
<tr>
<td>2</td>
<td>Cylinder tube</td>
</tr>
<tr>
<td>3</td>
<td>Air way T-tube</td>
</tr>
<tr>
<td>4</td>
<td>Cover disk</td>
</tr>
<tr>
<td>5</td>
<td>The case - Top part</td>
</tr>
<tr>
<td>5</td>
<td>The case - Down part</td>
</tr>
<tr>
<td>6</td>
<td>Motor</td>
</tr>
<tr>
<td>7</td>
<td>Solenoid Electro valves</td>
</tr>
<tr>
<td>8</td>
<td>LEDs</td>
</tr>
<tr>
<td>9</td>
<td>Arduino</td>
</tr>
</tbody>
</table>
7.1.1. - THE AIR BAG

MATERIAL:
NATURAL RUBBER

Natural rubber consists of polymers of the organic compound isoprene with minor impurities of other organic compounds water. It is harvested from rubber trees in the form of latex. Latex is a sticky milky colloid drawn from the trees which is then refined into rubber for commercial processing which is used widely in many applications and products.

The air bag for the prototype will be made of natural rubber because of the advantages that gives to our product to be eco friendly and have the right properties to accomplish the task.\[27\]

PROPERTIES

The properties of natural rubber are: large stretch capacity, high resilience, high tensile strength and very elastic which make it the most suitable material that can simulate the behavior of the real lung. The air bag can expand and contract due to the elasticity property of the material with specific elastic limit.

ECO PROPERTIES

A virgin or one hundred percent natural rubber is environmentally friendly when it is manufactured into different products. It comes from the rubber tree which also good at removing carbon dioxide from the air. Another form of environmentally friendly rubber is recycled rubber. This is rubber that would have otherwise gone to landfill, creating excess waste and pollution. Rubber that is no longer needed for its original purpose is recycled into another product. The most commonly recycled rubber object is tires but tennis shoes, rubber beach balls, and hot water bottles, amongst other times can all be recycled. When the recycled rubber product has reached the end of its life span, it can be recycled yet again into another product.\[27\]

MANUFACTURING PROCESS

In a raw state, natural and synthetic rubber becomes sticky when hot and brittle when cold. The vulcanization process which modifies rubber so that these changes will not occur, is needed. This process helps to increase rubber's elasticity and its resistance to heat, cold, abrasion, and oxidation. It also makes rubber relatively airtight and resistant to deterioration by sunlight.
7.1.2. - CYLINDER TUBE

MATERIAL:
THERMOPLASTIC ELASTOMER

The cylinder tube in the prototype is the bag container which can be seen in the figure. It should have durable elastic properties and it should also be resistant to the internal higher air pressures that are produced during its compression. The internal pressure must push the air out of the air bag instead of bending the cylinder tube. The tube must also have a good manufacture quality because it must sustain the inside vacuum (created by isolating it from the outside in middle position, at atmospheric pressure). Thermoplastic Polyurethane (TPU) is the material that can provide the required properties for this component.

7.1.3. - AIR WAY TUBE

MATERIAL:
THERMOPLASTIC ELASTOMER

Thermoplastic elastomer (TPE) Thermoplastic elastomers are a class of copolymers, meaning a physical mix of polymers, usually plastic and rubber, and have both thermoplastic and elastic properties. They are generally low modulus, flexible materials that can be stretched repeatedly to at least twice their original length at room temperature with an ability to return to their approximate original length when stress is released.\[28\]

There are six generic classes of commercial TPEs:

1- Styrenic block copolymers (TPE-s)
2- Polyolefin blends (TPE-o)
3- Elastomeric alloys (TPE-v or TPV)
4- Thermoplastic polyurethanes (TPU)
5- Thermoplastic copolyester
6- Thermoplastic polyamides

The product cylinder tubes are designed to be made out of TPE (Polyurethane TPU), as they have to assure a certain level of flexibility and have to be molded with the air bag and the cover disk. Besides, the airway T-Tube is made of TPE (Polyurethane tpPUR). Both of the components must be able to withstand certain level of elastic limit when it is being stretched and pressure exerted.

The airway tubes are the ones that are connected to the air bag, valves and assure the connection to the hospital’s ventilating equipment. They do not need any special properties and are generally made of polyurethane (tpPUR). The properties for polyurethane can be seen in the polyurethane properties table 13.\[29\]
PROPERTIES

The physical properties of polyurethane are considerable. Polyurethane performs well for hardness, relies on the prepolymer’s molecular structure can be manufactured from 20 SHORE A to 85 SHORE D, tensile strength allowing for very good elongation and recovery properties, impact resistance, abrasion resistance and tear strength. The table shows the physical properties of polyurethane.

<table>
<thead>
<tr>
<th>Property</th>
<th>Polyester TPU</th>
<th>Polyether TPU</th>
<th>Effect of Increasing hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasion Resistance</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Decreases slightly</td>
</tr>
<tr>
<td>Low Temperature Flexibility</td>
<td>Very good</td>
<td>Excellent</td>
<td>Decreases (stiffer at low temperatures)</td>
</tr>
<tr>
<td>Flex Life</td>
<td>Excellent</td>
<td>Excellent</td>
<td>No effect</td>
</tr>
<tr>
<td>Tear Strength</td>
<td>Excellent</td>
<td>Very Good - Excellent</td>
<td>Increases</td>
</tr>
<tr>
<td>Cut resistance, cut propagation</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Improves</td>
</tr>
<tr>
<td>Compression Set</td>
<td>Fair, improves by annealing</td>
<td>Fair, improves by annealing</td>
<td>Increases moderately</td>
</tr>
<tr>
<td>Resilience</td>
<td>Very Good</td>
<td>Good - Very Good</td>
<td>Increases, but stiffer materials</td>
</tr>
<tr>
<td>Long term High Temperature Aging</td>
<td>Good - Very Good</td>
<td>Poor to Fair</td>
<td>Improves</td>
</tr>
<tr>
<td>Hydrolysis Resistance</td>
<td>Poor to Good</td>
<td>Excellent</td>
<td>Improves</td>
</tr>
<tr>
<td>Chemical Resistance (primarily fuels, oils)</td>
<td>Good - Very Good</td>
<td>Good</td>
<td>Improves</td>
</tr>
<tr>
<td>Microbial Resistance</td>
<td>Poor to Good</td>
<td>Very Good - Excellent</td>
<td>Improves</td>
</tr>
</tbody>
</table>

Table 13: Polyurethane properties

ECO PROPERTIES

Thermoplastic elastomers are recyclable as they can be molded, extruded and reused such as plastics. Due to uncured molecular chains, it is possible to melt down the thermoplastic elastomers again and again. This characteristic allows it to lead back the thermoplastic elastomers into its manufacturing process. Therefore, material is saved and the environment preserved. [38]

MANUFACTURING PROCESS

PLASTIC EXTRUSION MOLDING PROCESS

A machine used to extrude materials is very similar to the injection moulding machine. A motor turns a thread which feeds granules of plastic through a heater. The granules melt into a liquid which is forced through a die, forming a long 'tube like' shape. The extrusion is then cooled and forms a solid shape. The shape of the die determines the shape of the tube. [20]
7.1.4. - COVER DISK

**MATERIAL: POLYETHYLENE**

The cover disks are the components which are glued to the cylinder tube with a high quality adhesive. One has the role to push and pull the air from the cylinder tube and is in direct contact with the linear actuator and other has the role to fix the cylinder from moving back and forward, in order to create different internal pressures, and also to provide an exit for the air inside the air bag. The cover disk that provides the air flow path for the air bag must be glued perfectly with both the air bag and the cylinder tube in order to maintain the vacuum effectively and for a long time. The right material for those is Polyethylene. This material provides both resistance and gluing capabilities.

7.1.5. - THE CASE

**MATERIAL: POLYETHYLENE**

Polyethylene is the most produced plastic in the world, with which everyone daily comes into contact. From its early days it has been considered a real asset in the world of the materials, although at first its value was only proven as insulation of electrical wiring. At present the power of polyethylene is its discrete reliability, its obvious solidity and its almost unlimited uses. We are so used to this modern material, it has become something common and everyday, and we tend to take it for granted.

The raw material - from naphtha to polyethylene: Naphtha is extracted from crude oil. Naphtha is another word for petroleum. By strongly heating up ("crack") the naphtha, ethylene is released. In a factory this ethylene is transformed into polyethylene. The word polyethylene means: "a lot of ethylene parts". These invisible tiny ethylene parts form the building blocks for polyethylene during the production. If we could look into the material during this process, we would see that these building blocks thread together into strings. Once these strings are ready, they look like branches.

The prototype is designed to used High Density Polyethylene (HDPE) for the casing and for the cover disks. However it should be manufactured out of just 60% recycled material and use 40% virgin material because the casing has to offer protection for its components and the covers must be molded perfectly with the container of the bag to be able to maintain long lasting vacuum. [31]
The case is the whole part that offers a pleasant aspect of the product to the user’s eyes, holds the components together and also protects them from external damage (for example in the case of accidental dropping). The case is equipped with hangs so the lung simulator could be hanged to the ventilators in the hospital, has inside clips offering the possibility of changing the bags from pediatric to neonatal. It is also used as a movement guide for the cylinder tube so it doesn’t bend instead of varying the internal pressures. HDPE (High Density Polyethylene) is the right material for the casing because it offers a high resistance of the casing. Protecting the internal components is a requirement as they could be easily damaged by accidental dropping. HDPE properties can be seen in the Polyethylene Properties Table 14.

**ECO PROPERTIES**

Polyethylene is an oil based product. It could be easily considered that this cuts it off the ecological branch of materials. However it can be considered ecological based on the following facts:

1- The manufacturing requires a very small amount of additional carbon based energy
2- It is easily melted, formed and cooled with no major mechanical efforts
3- It is completely recyclable
4- It can be recycled several times (more times than paper in which the fiber becomes weak)

**MANUFACTURING PROCESS**

The raw material: where do the pellets come from?
The ethylene enters the factory as a gas. When the gas is transformed into polyethylene it looks like a warm, fluid pulp. Before it solidifies, the pulp is pushed through a plate with small holes in a constant stream. The solidifying polyethylene strings that come out at the other end are immediately cut into small pieces by a rotating knife. The result is a mass of white, transparent granules that look a lot like coarse hail. These granules will go to companies as raw material, where they are melted and processed into all kinds of products. [31]
PLASTIC INJECTION MOLDING PROCESS

1. Granules of plastic pellets (note the plastics listed above) are poured or fed into a hopper which stores it until it is needed.

2. A heater heats up the tube and when it reaches a high temperature a screw thread starts turning.

3. A motor turns a thread which pushes the granules along the heater section which melts then into a liquid. The liquid is forced into a mould where it cools into the shape.

4. The mould then opens and the unit is removed.

Figure 84: Injection molding process

Table 14: Polyethylene properties

Figure 85: Open case
7.1.6. - MOTOR

LINEAR ACTUATOR

The prototype requires a linear actuator, fast enough to simulate the breath of a patient and strong enough to be able to maintain the speed for different compliance and resistance scenarios. The actuator must also be produced of quality materials, as it needs to keep up with the long lasting life of the prototype.

The linear actuators can be used instead of hydraulic or pneumatic systems. They are driven by high torque brushed DC gear motors which are coupled to an ACME screw to create a linear drive. The screw provides efficient linear thrust that can support both pushing and pulling loads. Each actuator is equipped with a potentiometer which can be used for positioning feedback. This feature is very handful as the lung simulator prototype uses an Arduino and is controlled remotely by an application. It has to simulate different conditions by the actuator’s positioning. It has been decided that the following actuator would be the best choice for the prototype.

PROPERTIES

ServoCity 25 lbs. thrust linear actuator
The all aluminium construction ensures the tremendous durability and reliability.
Detailed specifications
Operating Voltage: 6.0-12 Volts DC
Operating Temp. Range: -26 to +65°C -14.8 to +149°F
Operating Speed (12V): 5.08 cm/s at No load
Operating Speed (12V): 3.47 cm/s at Max load
Dynamic Thrust (12V): 11.33 kg Thrust
Static Load: 226.79 kg
Current Drain (12V): 800mA operating No load
Current drain (12V): 3.8A operating full load
Current drain (12V): 15A at stall
(Warning: Damage can occur at stall)
Motor Type: 3 Pole Ferrite
Potentiometer: I0K
Gear Ratio: 5:1 Ratio
Gear Type: 4 Metal Gears
Connector Wire Length: 60.96 cm
Recommended Fuse: 5A inline
IP Grade: IP 65 - total dust protection, water resistant
Duty Cycle: 25% (25% on, 75% off)
Housing Material: Zinc Alloy
Lead Screw: 3mm pitch, single thread
7.1.7. - SOLENOID ELECTRO VALVES

As mentioned before in the report, proportional electric valves are needed to control the air flow through the ventilation tubes in order to simulate the resistance and the leakage of the lungs. To achieve this small pressure valves (below 2 bars) are needed that can offer an accurate control over the air flow. Also two different types of valves are needed for the prototype, one normally closed and one normally opened. This has been also explained before in the report.

Electrical properties are important as the prototype is designed to be as ecological as possible and power consumption should not be too high. The Arduino connection is requiring specific voltages too, and such, 12V valves are ideal. The dimension of the valves is an important factor too, as the prototype has to be portable.

Considering all those aspects the following valves have been chosen for the prototype. The most important aspects of their parameters will be shown in the following part. [40]

FEATURES

· 2-way or 3-way, 2 position valve (NO, NC & Distributor)
· Offer a discrete valve design with up to 260 million life cycle rating
· Available in manifold mounting
· Provide a range of electrical coil options, including PC mountable, spade lugs, or wire leads
· Powerful enough for a range of uses that require high flow
· RoHS compliant
· PRO services

MEDIA COMPATIBILITY

Air, argon, helium, hydrogen, methane, nitrogen, oxygen & other nonreacting gasses

ELECTRICAL PROPERTIES

Power: 0.5/1/2 W
Voltage: 5/12/24 VDC
The electrical properties show that operating the valves do not require a high amount of power and the voltages allow the connection to the Arduino.

The nearby graph is showing the flow curves of the valves. The medical requirements for the pressures are between 0 and 1 [bar]. The green curve is the most appropriate one for the prototype.

The following illustrations clearly show the differences between 2 way normally closed and 2 way normally opened valves, which are needed in the prototype.

Dimensions of the valves

[38]
7.1.8. - LEDS

RGB LEDs

An RGB LED is a small light diode capable of emitting light of any color (based on combining R=red, G=green or B=blue light). The advantage of using LEDs instead of normal bulbs as light sources, consists in a long lasting life and a low power consumption.

RGB LEDs can be controlled with the Arduino in any needed way. For example they can be used just to show that the power is on, or that the device is turned on. They can point multiple working stances. In the case of the lung simulator prototype, LEDs are used to show the users if the device is ON or OFF. Their functionality can be reprogrammed via the Arduino interface.\(^{[37]}\)
8.1. ECO-AUDIT / Analysis

The differences of energy consumption and carbon footprint between virgin, recycled materials and different end of life (EoL).

![Energy Consumption Chart](chart1)

**Table 16: Differences of Energy Consumption**

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacture</th>
<th>Transport</th>
<th>Use</th>
<th>Disposal</th>
<th>EoL potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Lung Simulator (virgin + landfill and combust)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Lung Simulator (virgin + recycle and re-manufacture)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Lung Simulator (recycled content + recycle and re-manufacture)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![CO2 Footprint Chart](chart2)

**Table 17: Differences of Carbon Footprint**

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacture</th>
<th>Transport</th>
<th>Use</th>
<th>Disposal</th>
<th>EoL potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Lung Simulator (virgin + landfill and combust)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Lung Simulator (virgin + recycle and re-manufacture)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Lung Simulator (recycled content + recycle and re-manufacture)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Based on the Eco-Audit analysis, we can conclude that the most energy consumption is through the usage of the lung simulator. A very huge different percentage is produced between the material and usage category in terms of energy consumption and CO2 footprint. In this case, we are not able to change or manipulate the usage consumption since it is based on the usage requirement and needs of the hospital.

In order to reduce the environmental impact of the lung simulator production, option C was chosen, which is (the materials with certain percentage of recycled content and re-manufacture/recycle) as the best option. Based on the graph, we could see that a very slight differences between option A, B and C in terms of energy consumption and carbon footprint for the materials as well as the manufacture section.

On the other hand, for the ‘End of Life (EoL)’ section, option B and C provides the best solution in order to ensure the most environmental friendly life cycle. It is because if we look in long terms effect, recycling helps to provide the best way to extract value from waste and return materials to the supply-stream, preserving material stock. It helps to prevent problem of smelly or an eye-sore landfill as well as combustion of toxic materials which are hazardous to the environment and life being.

Option C also promotes the usage of recycled content in the production of the material at the same time producing an eco-friendly product. Therefore, the detailed analysis report option C for the Eco-Audit report is going to be further discussed in the next section.

8.2. DETAILED REPORT

C. Lung Simulator (recycled content+ recycle and re-manufacture)

PRODUCT NAME

C. Lung Simulator (recycled content+ recycle and re-manufacture)

PRODUCT LIFE

12 years
8.2.1. Energy and CO2 Footprint Summary:

<table>
<thead>
<tr>
<th>PHASE</th>
<th>ENERGY (MJ)</th>
<th>ENERGY (%)</th>
<th>CO2 (KG)</th>
<th>CO2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>591</td>
<td>14.7</td>
<td>35.2</td>
<td>15.3</td>
</tr>
<tr>
<td>Manufacture</td>
<td>41.2</td>
<td>1.0</td>
<td>3.12</td>
<td>1.4</td>
</tr>
<tr>
<td>Transport</td>
<td>0.0774</td>
<td>0.0</td>
<td>0.0055</td>
<td>0.0</td>
</tr>
<tr>
<td>Use</td>
<td>3.39e+03</td>
<td>84.2</td>
<td>192</td>
<td>83.3</td>
</tr>
<tr>
<td>Disposal</td>
<td>1.45</td>
<td>0.0</td>
<td>0.101</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total (For Firsts Life)</strong></td>
<td><strong>4.02e+03</strong></td>
<td><strong>100</strong></td>
<td><strong>231</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td><strong>End of Life Potential</strong></td>
<td><strong>-505</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

-505

Table 18: Energy and CO2 foot print summary.
### 8.2.2. Energy Analysis:

**Equivalent Annual Environmental Burden (averaged over 12 year product life):**

335 ENERGY (MJ / YEAR)

### Detailed Breakdown of Individual Life Phases

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
<th>RECYCLE CONTENT* (%)</th>
<th>PART MASS (KG)</th>
<th>QTY</th>
<th>TOTAL MASS (KG)</th>
<th>ENERGY (MJ)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR BAG</td>
<td>Natural rubber (NR)</td>
<td>Virgin (0%)</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>3.4</td>
<td>0.6</td>
</tr>
<tr>
<td>CYLINDER TUBE</td>
<td>Polyurethane</td>
<td>Virgin (0%)</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td>17</td>
<td>2.9</td>
</tr>
<tr>
<td>COVER DISKS</td>
<td>Polyethylene (PE)</td>
<td>60.0%</td>
<td>0.4</td>
<td>2</td>
<td>0.8</td>
<td>50</td>
<td>8.4</td>
</tr>
<tr>
<td>THE CASE</td>
<td>Polyethylene (PE)</td>
<td>60.0%</td>
<td>0.6</td>
<td>1</td>
<td>0.6</td>
<td>37</td>
<td>6.3</td>
</tr>
<tr>
<td>AIRWAY T-TUBE</td>
<td>Polyurethane (tpPUR)</td>
<td>100.0%</td>
<td>0.12</td>
<td>1</td>
<td>0.12</td>
<td>4.6</td>
<td>0.8</td>
</tr>
<tr>
<td>BATTERY</td>
<td>Li-ion AA cell battery</td>
<td>100.0%</td>
<td>0.25</td>
<td>1</td>
<td>0.25</td>
<td>50</td>
<td>8.4</td>
</tr>
<tr>
<td>WIRING</td>
<td>Copper</td>
<td>70.0%</td>
<td>0.2</td>
<td>1</td>
<td>0.02</td>
<td>0.55</td>
<td>0.1</td>
</tr>
<tr>
<td>LEDS</td>
<td>Diodes and LEDs</td>
<td>Virgin (0%)</td>
<td>0.008</td>
<td>6</td>
<td>0.048</td>
<td>2.2e+02</td>
<td>37.7</td>
</tr>
<tr>
<td>ARDUINO</td>
<td>Integrated circuit, small</td>
<td>Virgin (0%)</td>
<td>0.075</td>
<td>1</td>
<td>0.075</td>
<td>1.3e+02</td>
<td>22.7</td>
</tr>
<tr>
<td>MOTOR</td>
<td>Cast Al-alloys</td>
<td>Virgin (0%)</td>
<td>0.15</td>
<td>1</td>
<td>0.15</td>
<td>30</td>
<td>5.1</td>
</tr>
<tr>
<td>SOLENOID ELECTROVALVES</td>
<td>Age-hardening wrought Al-alloys</td>
<td>Virgin (0%)</td>
<td>0.1</td>
<td>2</td>
<td>0.2</td>
<td>42</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>2.5</td>
<td>5.9e+02</td>
<td>100</td>
</tr>
</tbody>
</table>

*Table 19: Life phases*

### Manufacture:

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>PROCESS</th>
<th>AMOUNT PROCESSED</th>
<th>ENERGY (MJ)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR BAG</td>
<td>Polymer molding</td>
<td>0.05 kg</td>
<td>0.8</td>
<td>2.0</td>
</tr>
<tr>
<td>CYLINDER TUBE</td>
<td>Polymer molding</td>
<td>0.2 kg</td>
<td>4.6</td>
<td>11.2</td>
</tr>
<tr>
<td>COVER DISKS</td>
<td>Polymer molding</td>
<td>0.8 kg</td>
<td>17</td>
<td>42.5</td>
</tr>
<tr>
<td>THE CASE</td>
<td>Polymer molding</td>
<td>0.6 kg</td>
<td>13</td>
<td>31.9</td>
</tr>
<tr>
<td>AIRWAY T-TUBE</td>
<td>Polymer molding</td>
<td>0.12 kg</td>
<td>2.3</td>
<td>5.5</td>
</tr>
<tr>
<td>MOTOR</td>
<td>Casting</td>
<td>0.15 kg</td>
<td>1.7</td>
<td>4.2</td>
</tr>
<tr>
<td>SOLENOID ELECTROVALVES</td>
<td>Rough rolling, forging</td>
<td>0.2 kg</td>
<td>1.1</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td>41</td>
<td>100</td>
</tr>
</tbody>
</table>

*Table 20: manufacture*
## Breakdown by Transport Stage:

<table>
<thead>
<tr>
<th>Stage Name</th>
<th>Transport Type</th>
<th>Distance (KM)</th>
<th>Energy (MJ)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Manufacturer to Hospital</td>
<td>Light goods vehicle</td>
<td>22</td>
<td>0.077</td>
<td>100.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>22</strong></td>
<td><strong>0.077</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

Table 21: Transport stage

## Breakdown by Transport Stage:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (KG)</th>
<th>Energy (MJ)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Bag</td>
<td>0.05</td>
<td>0.0015</td>
<td>2.0</td>
</tr>
<tr>
<td>Cylinder Tube</td>
<td>0.2</td>
<td>0.0062</td>
<td>8.0</td>
</tr>
<tr>
<td>Cover Disks</td>
<td>0.8</td>
<td>0.025</td>
<td>31.8</td>
</tr>
<tr>
<td>The Case</td>
<td>0.6</td>
<td>0.018</td>
<td>23.9</td>
</tr>
<tr>
<td>Airway T-tube</td>
<td>0.12</td>
<td>0.0037</td>
<td>4.8</td>
</tr>
<tr>
<td>LEDs</td>
<td>0.048</td>
<td>0.0015</td>
<td>1.9</td>
</tr>
<tr>
<td>Arduino</td>
<td>0.075</td>
<td>0.0023</td>
<td>3.0</td>
</tr>
<tr>
<td>Motor</td>
<td>0.15</td>
<td>0.0046</td>
<td>6.0</td>
</tr>
<tr>
<td>Solenoid Electrovalves</td>
<td>0.02</td>
<td>0.0062</td>
<td>8.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.5</strong></td>
<td><strong>0.077</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 21: Transport stage
## USE (STATIC MODE):

<table>
<thead>
<tr>
<th>Energy Input and Output Type</th>
<th>Electric to Mechanical (Electric Motors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use Location</td>
<td>Spain</td>
</tr>
<tr>
<td>Power Rating (W)</td>
<td>50</td>
</tr>
<tr>
<td>Usage (Hours Per Day)</td>
<td>4</td>
</tr>
<tr>
<td>Usage (Days Per Year)</td>
<td>1.8e+02</td>
</tr>
<tr>
<td>Product Life (Years)</td>
<td>12</td>
</tr>
</tbody>
</table>

### DISPOSAL:

<table>
<thead>
<tr>
<th>Component</th>
<th>End of Life Option</th>
<th>Energy (MJ)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Bag</td>
<td>Re-manufacture</td>
<td>0.01</td>
<td>0.7</td>
</tr>
<tr>
<td>Cylinder Tube</td>
<td>Re-manufacture</td>
<td>0.04</td>
<td>0.28</td>
</tr>
<tr>
<td>Cover Disks</td>
<td>Recycle</td>
<td>0.56</td>
<td>38.7</td>
</tr>
<tr>
<td>The Case</td>
<td>Recycle</td>
<td>0.42</td>
<td>29.0</td>
</tr>
<tr>
<td>Airway T-Tube</td>
<td>Recycle</td>
<td>0.084</td>
<td>5.8</td>
</tr>
<tr>
<td>LEDs</td>
<td>Re-manufacture</td>
<td>0.0096</td>
<td>0.7</td>
</tr>
<tr>
<td>Arduino</td>
<td>Re-manufacture</td>
<td>0.015</td>
<td>1.0</td>
</tr>
<tr>
<td>Motor</td>
<td>Recycle</td>
<td>0.11</td>
<td>7.3</td>
</tr>
<tr>
<td>Solenoid Electrovalves</td>
<td>Recycle</td>
<td>0.14</td>
<td>9.7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.4</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 23: Use static mode

Table 24: Use disposal
## Relative Contribution of Static and Mobile Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy (MJ)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>3.4e+03</td>
<td>100</td>
</tr>
<tr>
<td>Mobile</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3.4e+03</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 25: Static and mobile modes

## EOL Potential:

### Component | End of Life Option | Energy (MJ) | %  |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Bag</td>
<td>Re-manufacture</td>
<td>-3.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Cylinder Tube</td>
<td>Re-manufacture</td>
<td>-17</td>
<td>3.3</td>
</tr>
<tr>
<td>Cover Disks</td>
<td>Recycle</td>
<td>-10</td>
<td>2.0</td>
</tr>
<tr>
<td>The Case</td>
<td>Recycle</td>
<td>-7.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Airway T-Tube</td>
<td>Recycle</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>LEDs</td>
<td>Re-manufacture</td>
<td>-2.2e+02</td>
<td>44.1</td>
</tr>
<tr>
<td>Arduino</td>
<td>Re-manufacture</td>
<td>-1.3e+02</td>
<td>26.5</td>
</tr>
<tr>
<td>Motor</td>
<td>Recycle</td>
<td>-26</td>
<td>5.2</td>
</tr>
<tr>
<td>Solenoid Electrovalves</td>
<td>Recycle</td>
<td>-35</td>
<td>6.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>-5e+02</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 26: Eol potential
### 8.2.3. CO2 Footprint Analysis

**Equivalent Annual Environmental Burden (Averaged Over 12 Year Product Life):**

19.2 CO2 (kg/year)

---

#### Detailed Breakdown of Individual Life Phases

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
<th>RECYCLE CONTENT* (%)</th>
<th>PART MASS (KG)</th>
<th>QTY</th>
<th>TOTAL MASS (KG)</th>
<th>CO2 FOOTPRINT (KG)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR BAG</td>
<td>Natural rubber (NR)</td>
<td>Virgin (0%)</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>CYLINDER TUBE</td>
<td>Polyurethane</td>
<td>Virgin (0%)</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td>0.74</td>
<td>2.1</td>
</tr>
<tr>
<td>COVER DISKS</td>
<td>Polyethylene (PE)</td>
<td>60.0%</td>
<td>0.4</td>
<td>2</td>
<td>0.8</td>
<td>2.8</td>
<td>7.8</td>
</tr>
<tr>
<td>THE CASE</td>
<td>Polyethylene (PE)</td>
<td>60.0%</td>
<td>0.6</td>
<td>1</td>
<td>0.6</td>
<td>2.1</td>
<td>5.9</td>
</tr>
<tr>
<td>AIRWAY T-TUBE</td>
<td>Polyurethane (tpPUR)</td>
<td>100.0%</td>
<td>0.12</td>
<td>1</td>
<td>0.12</td>
<td>0.36</td>
<td>1.0</td>
</tr>
<tr>
<td>LEDS</td>
<td>Diodes and LEDs</td>
<td>Virgin (0%)</td>
<td>0.008</td>
<td>6</td>
<td>0.048</td>
<td>11</td>
<td>31.2</td>
</tr>
<tr>
<td>ARDUINO</td>
<td>Integrated circuit, small</td>
<td>Virgin (0%)</td>
<td>0.075</td>
<td>1</td>
<td>0.075</td>
<td>10</td>
<td>28.5</td>
</tr>
<tr>
<td>MOTOR</td>
<td>Cast Al-alloys</td>
<td>Virgin (0%)</td>
<td>0.15</td>
<td>1</td>
<td>0.15</td>
<td>1.8</td>
<td>5.1</td>
</tr>
<tr>
<td>SOLENOID ELECTROVALVES</td>
<td>Age-hardening wrought Al-alloys</td>
<td>Virgin (0%)</td>
<td>0.1</td>
<td>2</td>
<td>0.2</td>
<td>2.6</td>
<td>7.3</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>18</td>
<td></td>
<td>2.5</td>
<td>35</td>
<td>100</td>
</tr>
</tbody>
</table>

*Table 27: Breakdown Individual Life Phases*

**Manufacture:**

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>PROCESS</th>
<th>AMOUNT PROCESSED</th>
<th>CO2 FOOTPRINT (KG)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR BAG</td>
<td>Polymer molding</td>
<td>0.05 kg</td>
<td>0.064</td>
<td>2.1</td>
</tr>
<tr>
<td>CYLINDER TUBE</td>
<td>Polymer molding</td>
<td>0.2 kg</td>
<td>0.37</td>
<td>11.8</td>
</tr>
<tr>
<td>COVER DISKS</td>
<td>Polymer molding</td>
<td>0.8 kg</td>
<td>1.3</td>
<td>42.1</td>
</tr>
<tr>
<td>THE CASE</td>
<td>Polymer molding</td>
<td>0.6 kg</td>
<td>0.99</td>
<td>31.6</td>
</tr>
<tr>
<td>AIRWAY T-TUBE</td>
<td>Polymer molding</td>
<td>0.12 kg</td>
<td>0.17</td>
<td>5.4</td>
</tr>
<tr>
<td>SOLENOID ELECTROVALVES</td>
<td>Rough rolling, forging</td>
<td>0.2 kg</td>
<td>0.083</td>
<td>2.6</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>3.1</td>
<td>100</td>
</tr>
</tbody>
</table>

*Table 28: Manufacturing (CO2)*
### Breakdown by Transport Stage:

<table>
<thead>
<tr>
<th>Stage Name</th>
<th>Transport Type</th>
<th>Distance (km)</th>
<th>CO2 Footprint (kg)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Manufacturer to Hospital</td>
<td>Light goods vehicle</td>
<td>22</td>
<td>0.0055</td>
<td>100.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>22</td>
<td>0.0055</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 29: Transport (CO2)

### Breakdown by Components:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
<th>CO2 Footprint (kg)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Bag</td>
<td>0.05</td>
<td>0.00011</td>
<td>2.0</td>
</tr>
<tr>
<td>Cylinder Tube</td>
<td>0.2</td>
<td>0.00044</td>
<td>8.0</td>
</tr>
<tr>
<td>Cover Disks</td>
<td>0.8</td>
<td>0.0017</td>
<td>31.8</td>
</tr>
<tr>
<td>The Case</td>
<td>0.6</td>
<td>0.0013</td>
<td>23.9</td>
</tr>
<tr>
<td>Airway T-Tube</td>
<td>0.12</td>
<td>0.00026</td>
<td>4.8</td>
</tr>
<tr>
<td>Battery</td>
<td>0.25</td>
<td>0.00055</td>
<td>9.9</td>
</tr>
<tr>
<td>Arduino</td>
<td>0.075</td>
<td>0.00016</td>
<td>3.0</td>
</tr>
<tr>
<td>Motor</td>
<td>0.15</td>
<td>0.00033</td>
<td>6.0</td>
</tr>
<tr>
<td>Solenoid Electrovalves</td>
<td>0.02</td>
<td>0.00044</td>
<td>8.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2.5</td>
<td>0.0055</td>
<td>100</td>
</tr>
</tbody>
</table>

### Relative Contribution of Static and Mobile Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>CO2 Footprint (kg)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>1.9e+02</td>
<td>100</td>
</tr>
<tr>
<td>Mobile</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.9e+02</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 30: Static and Mobile Modes (CO2)
### Use (Static Mode):

<table>
<thead>
<tr>
<th>ENERGY INPUT AND OUTPUT TYPE</th>
<th>ELECTRIC TO MECHANICAL (ELECTRIC MOTORS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USE LOCATION</td>
<td>Spain</td>
</tr>
<tr>
<td>POWER RATING (W)</td>
<td>50</td>
</tr>
<tr>
<td>USAGE (HOURS PER DAY)</td>
<td>4</td>
</tr>
<tr>
<td>USAGE (DAYS PER YEAR)</td>
<td>$1.8 \times 10^2$</td>
</tr>
<tr>
<td>PRODUCT LIFE (YEARS)</td>
<td>12</td>
</tr>
</tbody>
</table>

### Disposal:

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>END OF LIFE OPTION</th>
<th>CO2 FOOTPRINT (KG)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR BAG</td>
<td>Re-manufacture</td>
<td>0.0007</td>
<td>0.7</td>
</tr>
<tr>
<td>CYLINDER TUBE</td>
<td>Re-manufacture</td>
<td>0.0028</td>
<td>0.28</td>
</tr>
<tr>
<td>COVER DISKS</td>
<td>Recycle</td>
<td>0.039</td>
<td>38.7</td>
</tr>
<tr>
<td>THE CASE</td>
<td>Recycle</td>
<td>0.029</td>
<td>29.0</td>
</tr>
<tr>
<td>AIRWAY T-TUBE</td>
<td>Recycle</td>
<td>0.0059</td>
<td>5.8</td>
</tr>
<tr>
<td>LEDS</td>
<td>Re-manufacture</td>
<td>0.00067</td>
<td>0.7</td>
</tr>
<tr>
<td>ARDUINO</td>
<td>Re-manufacture</td>
<td>0.0011</td>
<td>1.0</td>
</tr>
<tr>
<td>MOTOR</td>
<td>Recycle</td>
<td>0.0074</td>
<td>7.3</td>
</tr>
<tr>
<td>SOLENOID ELECTROVALVES</td>
<td>Recycle</td>
<td>0.0098</td>
<td>9.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>0.1</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 31: Use (CO2)

Table 32: Disposal (CO2)
## Relative Contribution of Static and Mobile Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>CO2 Footprint (KG)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>1.9e+02</td>
<td>100</td>
</tr>
<tr>
<td>Mobile</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.9e+02</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 33: Static and mobile modes (CO2)

## Disposal:

<table>
<thead>
<tr>
<th>Component</th>
<th>End of Life Option</th>
<th>CO2 Footprint (KG)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Bag</td>
<td>Re-manufacture</td>
<td>0.0007</td>
<td>0.7</td>
</tr>
<tr>
<td>Cylinder Tube</td>
<td>Re-manufacture</td>
<td>0.0028</td>
<td>0.28</td>
</tr>
<tr>
<td>Cover Disks</td>
<td>Recycle</td>
<td>0.039</td>
<td>38.7</td>
</tr>
<tr>
<td>The Case</td>
<td>Recycle</td>
<td>0.029</td>
<td>29.0</td>
</tr>
<tr>
<td>Airway T-Tube</td>
<td>Recycle</td>
<td>0.0059</td>
<td>5.8</td>
</tr>
<tr>
<td>Battery</td>
<td>Re-manufacture</td>
<td>0.0035</td>
<td>3.5</td>
</tr>
<tr>
<td>Wiring</td>
<td>Recycle</td>
<td>0.00098</td>
<td>1.0</td>
</tr>
<tr>
<td>LEDs</td>
<td>Re-manufacture</td>
<td>0.00067</td>
<td>0.7</td>
</tr>
<tr>
<td>Arduino</td>
<td>Re-manufacture</td>
<td>0.0011</td>
<td>1.0</td>
</tr>
<tr>
<td>Motor</td>
<td>Recycle</td>
<td>0.0074</td>
<td>7.3</td>
</tr>
<tr>
<td>Solenoid Electrovalves</td>
<td>Recycle</td>
<td>0.0098</td>
<td>9.7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.1</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 34: Disposal (CO2)
### EOL Potential:

<table>
<thead>
<tr>
<th>Component</th>
<th>End of Life Option</th>
<th>CO2 Footprint (kg)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR BAG</td>
<td>Re-manufacture</td>
<td>-0.093</td>
<td>0.3</td>
</tr>
<tr>
<td>CYLINDER TUBE</td>
<td>Re-manufacture</td>
<td>-0.7</td>
<td>2.5</td>
</tr>
<tr>
<td>COVER DISKS</td>
<td>Recycle</td>
<td>0.36</td>
<td>-1.3</td>
</tr>
<tr>
<td>THE CASE</td>
<td>Recycle</td>
<td>0.27</td>
<td>-0.9</td>
</tr>
<tr>
<td>AIRWAY T-TUBE</td>
<td>Recycle</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BATTERY</td>
<td>Re-manufacture</td>
<td>-3.7</td>
<td>13.0</td>
</tr>
<tr>
<td>WIRING</td>
<td>Recycle</td>
<td>-0.016</td>
<td>0.1</td>
</tr>
<tr>
<td>LEDS</td>
<td>Re-manufacture</td>
<td>-11</td>
<td>38.1</td>
</tr>
<tr>
<td>ARDUINO</td>
<td>Re-manufacture</td>
<td>-10</td>
<td>35.3</td>
</tr>
<tr>
<td>MOTOR</td>
<td>Recycle</td>
<td>-1.5</td>
<td>5.2</td>
</tr>
<tr>
<td>SOLENOID ELECTROVALVES</td>
<td>Recycle</td>
<td>-2</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>-28</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

*Table 35: Eol potential (CO2)*
8.3. CONCLUSIONS

Analysis and Conclusion Based on the Eco-Audit analysis,

We can conclude that the most energy consumption is through the usage of the lung simulator. A very huge different percentage is produced between the material and usage category in terms of energy consumption and CO2 footprint. In this case, we are not able to change or manipulate the usage consumption since it is based on the usage requirement and needs of the hospital. On the other hand, the transportation as well as disposal category have the least percentages of energy consumption and CO2 footprint. As for the location of the manufacturer, it is going to be located in area El Prat de Llobregat.

This has been decided by taking into account the logistic factors as well as transportation and manufacturing cost. The location of the factory manufacturer is located near to the Barcelona city center, which is twenty kilometers from the Hospital San Joan de Deu Barcelona which is our main client for the time being. It is also good for the long term plan as the demand of the production increase, it may require an exportation of the product to other countries. It is the most strategic location as it is located very near to the industrial port and therefore it helps to reduce the energy consumption as well as the cost for the transportation.

The selection of materials, manufacturing and end of life cycle of the product has been made by considering all factors that may affect the performance of the lung simulator, at the same time taking into account the environmental impact. For example, polyurethane (tpUR) has been chosen as the material for the airway T-tube connecting the valves instead of PVC. It is because, as it is widely known, that PVC is difficult to recycle and has been reported as the least recycled of all plastics. It has some environmental issues and health concerns regarding the usage and disposal of the PVC. All of the components are also going to be recycle and re-manufacture in order to provide a good life cycle of the product and reducing the amount of the disposal. It is also essential for us to balance out the end-of-life potential together with the amount of energy consumption as it is highly believed that the material choice that best suits end-of-life sometimes may not minimize the energy usage and in fact may increase it.

To draw the line, the designed prototype is intended to be as much ecological as possible. As strict requirements come with the project goals and with the functionalities of the prototype, the design process could not exclude using some virgin materials, to assure the durability and maintaining specific properties for a longer time. However this can be considered as an ecological aspect too, because a longer life of the product would require less maintenance or component replacing which could cause new waste of energy. The ecological goals that had to be achieved for the prototype were successfully accomplished.
9 PRODUCT DEVELOPMENT
LUNG SIMULATOR
Develop a lung simulator that provides pre-defined common clinical scenarios. Compared with simulators that are now available on the market the designed lung simulator offers remotely controlled simulations of the main problems in Neonatal and pediatric lung capabilities, such as: air leakage, air resistance, bag compliance and spontaneous breathing generation, allowing to improve hospital’s educational needs and increasing the knowledge acquired by students through simulated realistic clinical scenarios.

The device is lightweight so it is portable and transportable through hospital’s space. Compared to existing products with the same features the lung simulator costs less but without neglecting the quality of the product. The lung simulator is innovative in design and ergonomics with an easy wireless control, high precision and reliability.

The designed lung simulator is developed with great educational advantages, since being wireless can perform the simulation of different lung problems without students cheating, so it provides a closer to reality environment.

The design of the lung simulator belongs to the team (EPS/IDPS), has a medical educational sense and has a sustainable liability since it’s manufacturing process. The product is manufactured with high quality materials and durability which are available on the market to any customers.

The product design is attractive and modern and also brings benefits to hospitals to improve teaching future doctors. This prototype can compete with products currently on the market since all parameters can be controlled remotely while having a low cost, compared with existing products with the same characteristics which are not ergonomic and easy to operate.

Having an own designs that could innovate the market in medical education and training with a durable life time and manufactured with quality materials could become a challenge for the future competitors.
9.3. USER / Who?

The market rate which the product is seeking to focus on, is the one of doctors and professors with research purposes who will be able to show the students, through the product, different scenarios in which a lung can be found. After seeing these scenarios the students should be able to diagnose the patient.

In a growing market of a vision that point to an overall increase in medical technology market by 5% annually between 2013 and 2020, reaching global sales of 514,000 million dollars in 2020, it is believed that the product could reach high sales. Medical education and training is a field which will always be needed.

Forecasts indicate that medical technology will continue to expand its position benefiting the lung simulator, as this may be manufactured by different companies interested in the field of research and product development of medical education.

**Users that we are looking with this product include:**

01. Doctors and teachers with research purposes

02. Hospitals: Purchase of specialized products

03. Medical education schools

04. Sponsors sense of social responsibility

05. Conscious business of health care

06. With interest in medicine or in medical education

**Make the product eco-friendly reducing the impact of its life-cycle.**
9.4. AREA OF INNOVATION / Why is it different?

The product renews the traditional simulation process incorporating the design and technology (wireless) as a basis for innovation, giving it a contemporary feel that is according to the needs and likes of the market.

High commitment for manufacturing can be found in the lung simulator, reducing CO2 emissions, recycling raw materials and using recycled materials in a way that does not affect the quality.

In a very important way, this lung simulator is proposing a change in current habits of laboratories and doctors in the area of education, because nowadays most of the simulations are performed manually and this is imprecise and does not give the opportunity to students to interact in a real field. Only the most presiguados hospitals have updated equipment to perform these simulations.

In terms of design, the product offers a solution that fit the needs and lifestyles of its users and customers, instead of being a tool to which the person must adapt. It is a better solution to costumers. As any electrical and mechanical device, the lung simulator might need repairs or maintenance due to accidental dropping, wrong usage or manufacturing errors. Those cases should be rare to almost non existent, but if needed, the product is designed by components being easily assembled and disassambled. Any kind of part replacement or repair is cheap if the product is out of its warranty time.

**ALSO ADD VALUE TO OUR PRODUCT IN DIFFERENT ASPECTS SUCH AS:**

01 USE MATERIALS OF THE HIGHEST QUALITY

02 WE CREATE NEW TEACHING HABITS INCORPORATING THE RIGHT TECHNOLOGY

03 PRODUCT WITH A CHARACTER 100% FUNCTIONAL WITH AN ESTHETIC VALUE

04 RESPOND TO THE NEEDS OF A GROWING MARKET

05 GIVE THE POSSIBILITY OF A WIRELESS SIMULATION IN A REAL ENVIRONMENT

06 GENERATE DESIGN SOLUTIONS FOR OUR CUSTOMERS,

In terms of design, the product offers a solution that fit the needs and lifestyles of its users and customers, instead of being a tool to which the person must adapt. It is a better solution to costumers. As any electrical and mechanical device, the lung simulator might need repairs or maintenance due to accidental dropping, wrong usage or manufacturing errors. Those cases should be rare to almost non existent, but if needed, the product is designed by components being easily assembled and disassambled. Any kind of part replacement or repair is cheap if the product is out of its warranty time.

*In this sense, we create an:*

**EXPERIENCE**

selling and not just a product marketing.
Active supplier with manufacturing facilities needed for the manufacture of the product in question. Active provider network that handles distribution to different customers interested. Active provider to take care of the systems of different outlets, can be talking directly with the company (the team) or on the online sales system.

The intellectual resources will be the lung simulator brand sponsored by the Children's Hospital Sant Joan de Deu. Obtaining patent and intellectual property of the product.

The business model is based on having the human resource inasmuch the company depends heavily on a creative sense and knowledge of the team of engineers and designers.

The business model requires financial resources and/or financial guarantees, cash and credit lines to carry out the production, distribution and product sales.
One of the main goals of the project is to produce an economical lung simulator which is at the same time equipped with complete manipulator parameters in order to simulate various clinical scenarios via Bluetooth.

However, based on the project agreement between both parties, the lung simulator UPC team and the hospital doctors, it has been agreed upon, that the project is research intended, and working on the marketing, transporting, packaging, manufacturing and sale of the product is not compulsory.

However, as one of the goals was to make an affordable prototype which could clearly compete with the already available lung simulators on the market, it has been calculated in the table below, the average cost which consists of the total summation of the components parts and materials which are going to be used in the new lung simulator product. (The prices for the materials are calculated based on the current - June 2015 - sale price of the raw materials in the market excluding the processing and manufacturing price factors)

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>UNIT</th>
<th>MATERIAL / TYPES</th>
<th>PRICE PER UNIT (€)</th>
<th>TOTAL PRICE (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Motor</td>
<td>1</td>
<td>25 lbs-HAD 2 step</td>
<td>129.99/unit</td>
<td>129.99</td>
</tr>
<tr>
<td>Whole case</td>
<td>1</td>
<td>Polyethylene (PE)</td>
<td>0.70/kg</td>
<td>1.70</td>
</tr>
<tr>
<td>LED</td>
<td>5</td>
<td>RGB LED 5mm</td>
<td>0.20/unit</td>
<td>1.00</td>
</tr>
<tr>
<td>Air bags</td>
<td>2</td>
<td>Latex rubber</td>
<td>1.24/kg</td>
<td>0.35</td>
</tr>
<tr>
<td>Cover disk</td>
<td>4</td>
<td>Polyethylene (PE)</td>
<td>0.70/kg</td>
<td>0.80</td>
</tr>
<tr>
<td>Cover dish connection</td>
<td>1</td>
<td>Polyethylene (PE)</td>
<td>0.70/kg</td>
<td>0.30</td>
</tr>
<tr>
<td>Connection tubes</td>
<td>2</td>
<td>Polyurethane</td>
<td>0.99/kg</td>
<td>0.20</td>
</tr>
<tr>
<td>Solenoid electro valves</td>
<td>2</td>
<td>Standard</td>
<td>89.23/unit</td>
<td>178.46</td>
</tr>
<tr>
<td>Arduino</td>
<td>1</td>
<td>Mega 2560</td>
<td>25.00/unit</td>
<td>25.00</td>
</tr>
<tr>
<td>Cylinder tubes</td>
<td>2</td>
<td>Polyurethane</td>
<td>0.99/kg</td>
<td>0.60</td>
</tr>
<tr>
<td>Entrance tube</td>
<td>1</td>
<td>Polyurethane</td>
<td>0.70/kg</td>
<td>0.50</td>
</tr>
<tr>
<td>Bluetooth receiver</td>
<td>1</td>
<td>HC-06 bluetooth module</td>
<td>15.00/unit</td>
<td>15.00</td>
</tr>
<tr>
<td>TOTAL COST</td>
<td></td>
<td></td>
<td></td>
<td>353.90</td>
</tr>
</tbody>
</table>

Table 36: Sale price

Based on calculation presented above, it can be concluded that the total average material cost for the lung simulator product is about 353.90 Euro. The raw cost can be considered as economical and within the affordable price range compared to the price of existing lung simulators available in the market.
9.8. SWOT ANALYSIS / Evaluate the project

**STRENGTHS**
- Wireless control
- Easy to operate
- Intuitive software
- Multiple patient scenarios
- Accurate control
- Adjustable (neonatal & pediatric)

**WEAKNESSES**
- Limited budget
- Lack of programming background
- Short period of time

**OPPORTUNITIES**
- Renew the traditional simulation process
- Give the possibility of a wireless simulation in a real environment
- First product on the market that includes all the parameters features controlled remotely

**THREATS**
- New and existing regulations
- New and existing competitors
- New technologies that in a future make the product obsolete
10.1. CONCLUSION

The designed lung simulator is an innovation in medical training as it is accomplishing all the main required features, such as leakage simulation, resistance simulation, compliance simulation, spontaneous breathing simulation, remote control and portability.

It is designed to be a durable and reliable product, and also to be eco-friendly. The manufacturing does not require any energy wasting or chemical process and the usage is not energy intensive. It is also easy to manipulate and use, as it provides also an Android application to be remotely controlled. The internal mechanism is easy to manipulate as the system responsible for changing pediatric and neonatal bags is a clip based system.

The prototype is also affordable compared to its competitors on the market. All the available lung simulators which include those functionalities are expensive, hard to operate or weight too much to be portable around training environments.

The main advantage of the prototype is that it provides a lot of room for even more improvement and development while it is already offering competitive features for the lung simulators market.

10.2. RECOMMENDATION FOR FURTHER RESEARCH

As for any existing product and prototype, there is also a lot of room for improvement. The lung simulator could also have the following improved:

- Creating a direct relationship between the application sliders and the medical parameters
- Testing the prototype in the medical training environment and adapt the generated parameters to the medical equipment available in the hospital
- Research other possible manufacturing materials for its components to eventually manufacture it even more light, cheap and ecological
- Improve the Arduino programming to make it simulate accurately the medical parameters
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11.5. GLOSSARY

Air sac ➔ A sac containing air or alveolus
Airway ➔ A passageway by which air passes from the nose or mouth to the air sacs of the lungs
Adenoid ➔ An enlarged mass of lymphoid tissue in the upper pharynx, often obstructing breathing through the nasal passages
Anatomy ➔ The branch of science concerned with the bodily structure of humans, animals, and other living organisms, especially as revealed by dissection and the separation of parts:
Apex ➔ The top or highest part of something, especially one forming a point
Bronchi ➔ Any one of the system of tubes which make up the main branches of the windpipe through which air passes in and out of the lungs
Congenital ➔ Of a disease or physical abnormality present from birth; Of a person having a particular trait from birth or by firmly established habit:
Cords ➔ An anatomical structure resembling a length of cord.
ECG ➔ Electrocardiography; is the process of recording the electrical activity of the heart over a period of time using electrodes placed on a patient's body.
Endotracheal tube (ETT) ➔ A catheter that is inserted into the trachea for the primary purpose of establishing and maintaining a patent airway and to ensure the adequate exchange of oxygen and carbon dioxide.
Exhalation ———— E The process or action of exhaling; An expiration of air from the lungs.

Extubation ———— The removal of a tube from an organ, structure, or orifice; specifically, the removal of the tube after intubation of the larynx or trachea.

Infant ———— A child during the earliest period of its life, especially before he or she can walk; baby.

Inflammatory ———— Caused by inflammation; redness, swelling, pain, tenderness, heat, and disturbed function of an area of the body, especially as a reaction of tissues to injurious agents.

Inhalation ———— An act of inhaling; to breath in.

Invasive ———— Requiring the entry of a needle, catheter, or other instrument into a part of the body, especially in a diagnostic procedure, as a biopsy.

Lingula ———— One of the segments of the left lung with a tongue-shape.

Manikin or mannequin ——— A model of the human body for teaching anatomy, demonstrating surgical operations.

Meconium aspiration ——— A situation happen before, during, or after labor and delivery when a newborn inhales (or aspirates) a mixture of meconium and amniotic fluid (the fluid in which the baby floats inside the amniotic sac).

Mucus ———— A viscous, slimy mixture of mucins, water, electrolytes, epithelial cells, and leukocytes that is secreted by glands lining the nasal, esophageal, and other body cavities and serves primarily to protect and lubricate surfaces.

Nasal cavity ———— The cavity on either side of the nasal septum, extending from the nares to the pharynx, and lying between the floor of the cranium and the roof of the mouth.

Nasal cannula ———— A device used to deliver supplemental oxygen or airflow to a patient or person in need of respiratory help. This device consists of a lightweight tube which on one end splits into two prongs which are placed in the nostrils and from which a mixture of air and oxygen flows.

Neonatal ———— Relating to newborn children

Non-invasive ———— Of medical procedures not involving the introduction of instruments into the body

Paediatric ———— The branch of medicine concerned with the development, care, and diseases of babies and children.

Peripheral ———— Relating to or situated on the edge or periphery of something

Physiology ———— The branch of biology dealing with the functions and activities of living organisms and their parts, including all physical and chemical processes.

Plethysmography ——— A device for measuring and recording changes in the volume of the body or of a body part or organ.
Pneumonia

Lung inflammation caused by bacterial or viral infection, in which the air sacs fill with pus and may become solid. Inflammation may affect both lungs (double pneumonia) or only one (single pneumonia).

Respiratory

Pertaining for respiration; the act of respiring; inhalation and exhalation of air; breathing.

Spirometry

An instrument for measuring the air capacity of the lungs.

Sub-glottic edema

A swelling caused by fluid accumulation in the soft tissues of the larynx. The condition, usually inflammatory, may result from infection, injury, or inhalation of toxic gases.

Thorax

The part of the trunk in humans and higher vertebrates between the neck and the abdomen, containing the cavity, enclosed by the ribs, sternum, and certain vertebrae, in which the heart, lungs, etc., are situated; chest.

Thoracic cavity

The space within the walls of the chest, bounded below by the diaphragm and above by the neck, and containing the heart and the lungs.

Tonsil

A prominent oval mass of lymphoid tissue on each side of the throat.

Tracheobronchial

Pertaining to the trachea and bronchi.

Tracheostomy

An incision in the windpipe made to relieve an obstruction to breathing.

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12 PLANS
Every chamfer is 1x45°, unless indicated differently.
All fillets are R0.5, unless specified differently.
Every fillet is R1, unless specified differently.