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FACULTY OF BIOMEDICAL ENGINEERING

Department of Biomedical Technology

Comparison of neonatal resuscitation systems

Bachelor Thesis

Study program: Biomedical and Clinical Technology
Study branch: Biomedical Technician

Bachelor thesis supervisor: doc. Ing. Petr Kudrna, Ph.D.

Marina Radić

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BACHELOR'S THESIS ASSIGNMENT

I. PERSONAL AND STUDY DETAILS

Student's name:	**Radić Marina**	Personal ID number:	**491765**
Faculty:	**Faculty of Biomedical Engineering**		
Department:	**Department of Biomedical Technology**		
Study program:	**Biomedical and Clinical Technology**		
Branch of study:	**Biomedical Technician**		

II. BACHELOR'S THESIS DETAILS

Bachelor's thesis title in English:

Comparison of neonatal resuscitation systems

Bachelor's thesis title in Czech:

Porovnání novorozeneckých resuscitačních systémů

Guidelines:

Design, implement and evaluate a laboratory experiment to compare resuscitation systems for newborns. Focus on assessing pressure phenomena and the humidification rate of the ventilation mixture. Make a comparison of at least 2 systems used in clinical practice. Suggest recommendations to users of these resuscitation systems concerning their operation in clinical practice.

Bibliography / sources:

[1] Tricia L. Gomella, Neonatology: management, procedures, on-call problems, diseases and drugs, ed. Sixth Edition, McGraw Hill Professional, 2009, ISBN 78-0-07-154431-3
[2] Donaldsson, S., Drevhammar, T., Taittonen, L., Klemming, S., & Jonsson, B., Initial stabilisation of preterm infants: A new resuscitation system with low imposed work of breathing for use with face mask or nasal prongs, Archives of Disease in Childhood-Fetal and Neonatal Edition, ročník 102, číslo 3, 2017
[3] Andrew D. Shearmana, David Houa, Kimble R. Dunsterc, Luke Jardinea, Heating of gases during neonatal resuscitation: A bench study, Resuscitation, číslo 83, 2012, 369–373 s.

Name of bachelor's thesis supervisor:

doc. Ing. Petr Kudrna, Ph.D.

Name of bachelor's thesis consultant:

Date of bachelor's thesis assignment: **14.02.2023**
Assignment valid until: **20.09.2024**

doc. Ing. Martin Rožánek, Ph.D.
Head of department

prof. MUDr. Jozef Rosina, Ph.D., MBA
Dean

DECLARATION

I hereby declare that I have completed this thesis having the topic “Comparison of neonatal resuscitation systems” independently, and that I have attached an exhaustive list of citations of the employed sources.

I do not have a compelling reason against the use of the thesis within the meaning of Section 60 of the Act No.121 / 2000 Sb., on copyright, rights related to copyright and amending some laws (the Copyright Act).

In Kladno 18.05.2023 …..……..……...

Marina Radić

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First and foremost, I would like to thank my thesis supervisor doc. Ing. Petr Kudrna, Ph.D., for the invaluable patience, for the knowledge he provided me with, and for the incredible advices. Above all, I would like to thank you for your great motivation, which was the main reason for the successful completion of this thesis.

Special thanks to my mother, father, and brother, and all my friends, for supporting me during my studies and making me the person I am today.

ABSTRACT

Comparison of neonatal resuscitation systems:

Continuous improvement in medical technology is vital to improve neonatal resuscitation outcomes and save lives of infants. Although the resuscitation bag represents a significant breakthrough in resuscitation, the invention of a T-piece resuscitator has overshadowed its use. The traditional TPR Neopuff and the modern TPR rPAP are two of the most commonly used resuscitation systems with distinctive functions. This thesis aims to investigate pressure phenomena and compare the resuscitation systems mentioned above in terms of the delivery of heated humidified gas. Data were collected from an experiment that simulates a practical clinical setting for infant resuscitation and subsequently used to analyse the time parameters of the pressure increase. The findings reveal that rPAP performs better in terms of pressure phenomena, whereas only Neopuff can be used for heated humidified resuscitation with an adequate time duration.

Key words

Neonatal resuscitation, T-piece resuscitator, heated humidified gas

Table of Contents

List of symbols and abbreviations

List of symbols

Symbol	Unit	Importance
PEEP	cmH_2O	Positive end-expiratory pressure
CPAP	cmH_2O	Continuous positive airway pressure
PIP	cmH_2O	Peak inspiratory pressure
O_2	-	Oxygen
CO_2	-	Carbon dioxide
FiO_2	%	Fraction of oxygen
PaO_2	mmHg	Arterial oxygen partial pressure
$PaCO_2$	mmHg	Arterial carbon dioxide partial pressure
pH	-	Potential of hydrogen
SpO_2	%	Oxygen saturation
V_T	ml/kg	Tidal volume
RR	breaths per minute (bpm)	Respiratory rate
HR	beats per minute (BPM)	Heart rate
R_e	-	Reynolds number
r	m	Radius of ETT
v	m/s	Velocity of the flow
n	kg/m·s	Viscosity of the flow
d	kg/m3	Density of the flow
q	l/min	Flow
c	ml/cmH_2O	Lung compliance
C_{int}	ml/cmH_2O	Internal compliance
C_{ex}	ml/cmH_2O	External compliance
T	°C	Temperature
H	%	Humidity
R_t	$cmH_2O/l/s$	ETT resistance
R_a	$cmH_2O/l/s$	Airway resistance
P_{alv}	cmH_2O	Alveolar pressure
P_{etr}	cmH_2O	ETT pressure
P_y, P_t	cmH_2O	Pressure in the Y-piece/T-piece
V_{lung}	l	Cylinder volume
TC, τ	s	Time constant
T_{alv}, τ_{alv}	s	Alveolar pressure inspiratory time constant
T_t, τ_t	s	T-piece pressure inspiratory time constant
RT	s	Rise time
R_{alv}	s	Alveolar pressure inspiratory rise time
R_t	s	T-piece pressure inspiratory rise time

List of abbreviations

Abbreviation	Importance
PPV	Positive pressure ventilation
FRC	Functional residual capacity
WOB	Work of breathing
iWOB	Inspiratory work of breathing
ETT	Endotracheal tube
VC	Ventilation circuit
BVM	Bag valve mask
AMBU	Artificial manual breathing unit
TPR	T-piece resuscitator
PID	Proportional-integral-derivative
H0	Null hypothesis
H1	Alternative hypothesis

1 Introduction

Approximately 110 000 babies are born in the Czech Republic each year, of which about 8 000 are born prematurely. Prematurity is one of the leading threats to infant life, as undeveloped lungs cause respiratory problems and urgent medical intervention is required. The Czech Republic has proven to be one of the leaders in newborn care, as evidenced by the declining number of newborn deaths since the 1990s [1].

Newborn resuscitation is a critical aspect of neonatal care, providing support to infants who have difficut breathing or are not breathing on their own. The selection of appropriate resuscitation equipment is crucial to ensure adequate oxygenation and ventilation and reduce the risk of complications. Pressure phenomena such as barotrauma and volutrauma can cause lung damage in newborns, while inadequate humidification can cause irritation of the airways and dehydration [2].

The first device developed for neonatal resuscitation and stabilisation is known as a self-inflating bag. It was founded in the middle of the twentieth century and represents a substantial breakthrough in saving lives for preterm infants. As it is manually manipulated, its performance quality cannot be guaranteed. The imperfection of this device also lies in the fact that the pressure that delivers gas to a patient cannot be controlled [3].

Advancement in technology has led to the development of T-piece resuscitators that provide controlled positive pressure ventilation with the possibility of delivering heated humidified gas in contrast to traditional cold dry gas delivery. These devices are used in combination with devices that help manipulate the characteristics of the gas, such as a blender, flowmeter, and humidifier [4].

The two most widely used resuscitation systems in clinical practise are the rPAP and NEOPUFF systems. NEOPUFF represents a conventional resuscitator, while rPAP is marked as innovative, as it is known to produce low iWOB in newborns. Studies have shown the differences of these devices with regard to pressure phenomena and the delivery of heated humidified gas, but further research is necessary to determine which of these two is more convenient for practical use in delivery rooms.

To save as many new lives as possible and provide the necessary medical help, it is essential to investigate the area of resuscitation possibilities and continuously improve this part of neonatal care. By comparing the performance of the rPAP and NEOPUFF systems, we hope to provide valuable information to neonatal healthcare providers on the selection and use of these resuscitation systems in clinical practise.

2 Overview of the current state of the art

In this part of the thesis, the importance of resuscitation in newborn infant care will be explained, starting with the complexity of newborn lungs and continuing with a variety of resuscitation devices and their possibilities. In the final part of this section, knowledge of the two most commonly used resuscitation devices will be compared and later used in combination with research in this field.

2.1 Birth complications

The first few minutes of a baby's existence are crucial for its future well-being and health stability. Neonatal care in the Czech Republic has improved substantially during the previous century, largely due to rapid adaptation to new medical technologies. To ensure the advancement of medical technology, it is essential to understand the intricate nature of neonatal respiratory systems, as well as the challenges that arise during the transition from intrauterine to extrauterine existence.

2.1.1 Respiratory system of newborns

Lung development is a process from conception to birth, beginning with the formation of organs, including the lungs. The respiratory system then develops in the form of new tissues, enlargement of the airways, and perfection of the blood vessels. The last phase begins in the 24th week of gestation and is called the saccular period. This period is important for the formation and development of lung villi, which are essential for breathing. The postnatal period also plays an important role in lung development, as babies are different from adult lungs. Figure 2.1 shows the structure of the neonatal lungs [5].

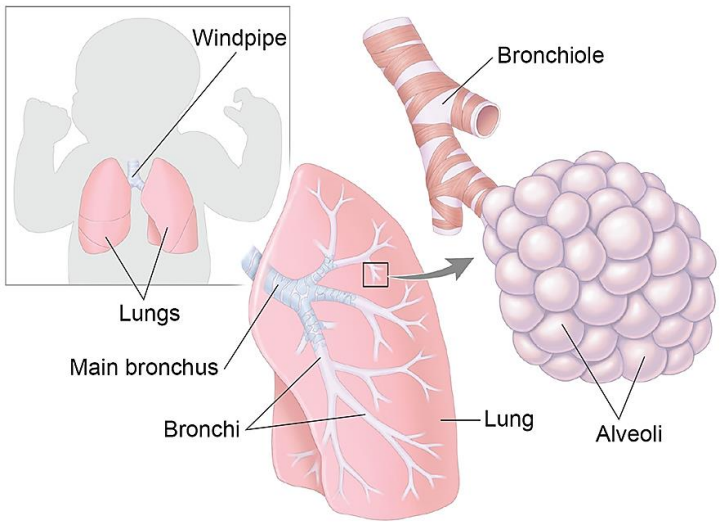


Figure 2.1: Components of the respiratory system of a newborn. Taken from [6].

During pregnancy, the foetus receives all the necessary components for survival, such as oxygen , nutrients, and carbon dioxide excretion. After birth, the body has to adapt to different conditions to promote further development and initiate extrauterine gas exchange. Immature lungs are difficult to develop due to their lack of airway diameter, oxygen consumption, and inefficient respiratory muscles. This can lead to respiratory problems such as respiratory distress syndrome, congenital and surgical anomalies, delayed adaptation to extrauterine life, and pulmonary infections [7].

The fluid that covers the inner lining of normal lung chambers, called pulmonary surfactant, is an important factor in lung failure, as it replaces the foetal lung fluid and plays a role in reducing surface tension in small airways and alveoli. The surfactant begins its development in the lungs around the 20^{th} week of pregnancy and is composed of phospholipids and neutral lipids, while proteins make up only 10 % of the total substance [7].

Main cause of complications

Prematurity is the leading cause of mortality among newborns, accounting for 27 % of all infant deaths worldwide. Neonatal asphyxia is an underlying problem that accounts for 20.9 % of neonatal deaths.[8] The inability to initiate and maintain breathing at birth is known as birth asphyxia. Several factors can cause asphyxia, including heart failure, foetal anemia, and maternal asphyxia [9].

2.1.2 Resuscitation guidelines

Following the resuscitation guidelines is advised after discovering issues with a newborn. They cover a wide range of baby resuscitation difficulties, including newborn evaluation, respiratory assistance, and proper oxygenation and circulation. They make specific suggestions for high-risk newborns, such as those born prematurely or with serious medical conditions [10].

Four criteria can be used to quickly identify neonates who do not require resuscitation: full-term gestation, clear amniotic fluid, breathing or crying, and adequate muscular tone. If the answer to any of these questions is yes, the newborn should receive one or more of the four types of action listed below in order: early steps in stabilisation, ventilation, chest compression, epinephrine administration and/or volume expansion [10].

Depending on the severity of the newborn's breathing issues, there are many techniques for providing respiratory assistance. Gentle stimulation may be adequate to induce breathing if the baby is not breathing,, but has normal heart rate and muscular tone. This might include caressing the newborn's back, gently tapping the feet, or flicking the soles of the feet [10].

Positive pressure ventilation (PPV) may be required if the infant is not breathing effectively or has a low heart rate and muscular tone. Using a mask or endotracheal tube, controlled air or oxygen flow is delivered to the newborn's lungs. Supplemental oxygen may be administered through a nasal cannula, oxygen mask, or inhaler if the infant has low levels of oxygen saturation [10].

2.1.3 Ventilation parameters

During the first minutes of life, proper ventilation is critical for preterm infants. The lungs must quickly adapt to the new environment and establish functional residual capacity (FRC) during the transition from intrauterine to extrauterine life. FRC is the amount of air left in the lungs at the end of a normal expiration, which is necessary for gas exchange and lung function [11].

To establish the FRC, adequate pressure values are required during ventilation. A pressure gradient is necessary to overcome airflow resistance and move lung fluid distally through the airways. Opening pressure is then needed to overcome surface tension and open the alveoli. This first lung recruitment manoeuvre is a prerequisite for the surfactant to reach a large proportion of alveoli, begin its action, and promote a more uniform lung volume. The use of positive end-expiratory pressure (*PEEP*) or continuous positive airway pressure (*CPAP*) of at least 4–6 cmH_2O is recommended to evoke expansion of the lungs and establish early FRC. Along with *PEEP*, another important pressure value is the peak inspiratory pressure (*PIP*), which is the highest pressure during the respiratory cycle [11, 12].

Infant oxygenation is greatly influenced by the selected fraction of oxygen (FiO_2). This parameter represents the oxygen concentration in the gas administered to a apatient and can range from 21–100%. This parameter directly affects the partial pressures of oxygen, which have a profound influence on the appearance of hypoxemia, a major factor contributing to birth complications [13].

Continuous monitoring of blood gases is also essential to optimise oxygenation and ventilation in the neonatal patient. The partial arterial oxygen pressure (PaO_2) should be maintained within the range of 50–80 mmHg, while the arterial carbon dioxide pressure ($PaCO_2$) should be maintained within 40–55 mmHg. Furthermore, it is important to maintain a *pH* level greater than 7.5, while the optimal oxygen saturation SpO_2 should be greater than 95 % [14].

Work of breathing

Work of breathing (WOB) stands for the amount of energy required by the respiratory muscles for optimal ventilation. It can be looked at as total work, as well as inspiratory or expiratory WOB. 'Inspiratory work of breathing' is abbreviated iWOB. It is the amount of energy required for an infant to inhale a certain volume of air, taking into account the resistance and compliance of the respiratory system. iWOB is calculated by measuring

the pressure needed to overcome the resistance of the airways and the elasticity of the lungs and chest wall during inspiration [15].

WOB is determined by compliance and resistance, which represent the characteristics of pressure and volume [15]. This pressure-volume loop during one respiratory cycle is graphically presented in Figure 2.2.

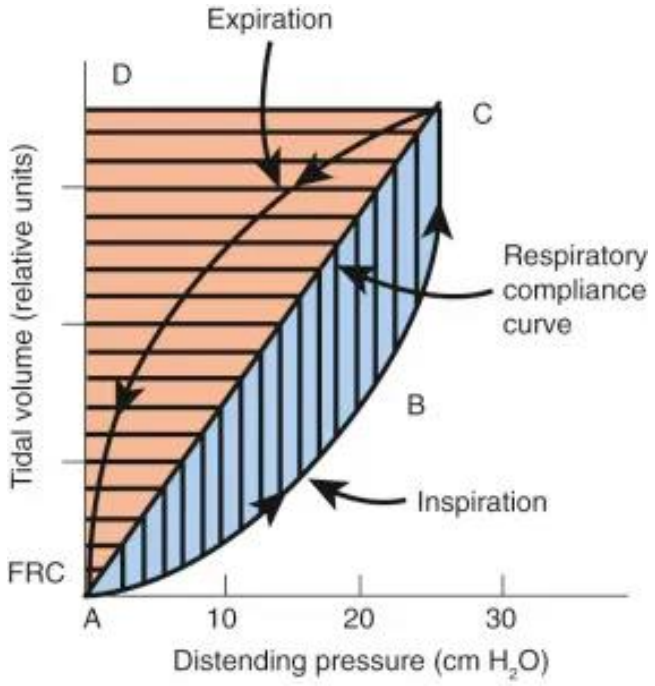


Figure 2.2: Graphical presentation of breathing work. Taken from [16].

2.2 Resuscitation equipment

This part of the thesis provides information on the most commonly used interfaces for neonatal resuscitation and stabilisation. Depending on the clinical situation and the available equipment, positive pressure ventilation (PPV) can be achieved using a variety of methods. In neonatal resuscitation, PPV can be administered by means of a self-inflating bag or a flow-inflating bag attached to a face mask. Another widely used interface is an endotracheal tube (ETT) inserted into the infant's airway, allowing for more precise control of ventilation parameters. Adjustment of the patient interface is not entirely possible when dealing with newborns and, for this reason, emphasis is placed on adjusting the pressure level during neonatal ventilation [17].

2.2.1 Resuscitation mask

Noninvasive ventilation masks are critical for providing respiratory support to preterm infants during the birth transition. This method allows babies to breathe naturally and contribute to their own pulmonary ventilation, while providing additional respiratory

support if necessary. However, during audits of newborn stabilisation and resuscitation procedures, it has been found that the use of masks immediately after birth can negatively affect preterm infant breathing [18].

Resuscitation masks from Fisher & Paykel Healthcare can be used with a self-inflating bag, a flow-inflating bag, or a T-piece circuit [19]. According to research, 35-millimeter diameter masks are the best for infants under 29 weeks of gestation, while 42-millimeter masks are best for infants between 27 and 33 weeks of gestation [20]. Figure 2.3 shows an example of resuscitation masks.

Figure 2.3: Range of resuscitation masks for infants from Fisher & Paykel Healthcare. Taken from [19].

2.2.2 Endotracheal tube

Proper positioning of newborns is essential for successful intubation. To improve lung mechanics and gas exchange in preterm babies, a stepwise *PEEP* strategy after birth was found to be effective without increasing lung injury. Studies also recommend the use of sustained inflation manoeuvres before intubation to clear fluid-filled lungs and achieve early FRC. This involves applying an inflation pressure for a significantly longer period than the normal inspiratory time [21].

Ventilation can then be delivered through the ETT using a bag-valve-mask device or a mechanical ventilator. Invasive PPV through an ETT may be necessary in certain clinical scenarios, such as in extremely premature infants with respiratory distress syndrome or in infants with airway obstruction. Intubation is achieved using a laryngoscope, which can be used in size 0 for preterm and size 1 for infants [21]. Figure 2.4 shows an example of proper intubation in infants.

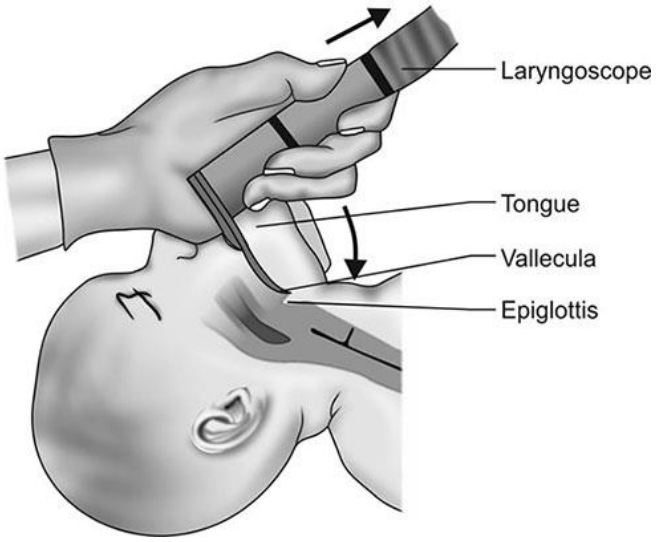


Figure 2.4: Example of proper intubation of the infant. Taken from [22].

The length and radius of the tube have a direct effect on the airway resistance created between the moving gas molecules and the walls of the respiratory system. The airway resistance of novices is relatively large due to the small diameter of the airway, but the magnitude of the total resistance during ventilation also depends largely on the type of gas flow. The Reynolds number R_e [-] determines whether the flow is laminar or turbulent [12, 23]:

$$R_e = \frac{2 \cdot r \cdot v \cdot d}{n}, \tag{2.1}$$

where r [m] is the radius of the tube, v [m/s] is the flow velocity, d [kg/m^3] represents the flow density, and n [kg/m·s] is the viscosity of the tube. In the case of turbulent flow, which is inappropriate in neonatal ventilation, the Reynolds number is greater than 2000 [12, 23].

For the reasons mentioned above, the diameter and depth of tube insertion are selected according to the patient's weight and the gestational week at birth in neonatal pulmonary ventilation. Tables 2.1 and Table 2.2 show the parameters in relation to the characteristics mentioned of a newborn.

Table 2.1: Relationship between endotracheal tube diameter and newborn characteristics [22].

Endotracheal tube diameter (mm)	**Newborn weight (kg)**	**Week of gestational age at birth**
2,5	Less than 1	Less than 28
3	1 – 2	28 – 34
3,5	More than 2	More than 34

Table 2.2: Relationship between tube insertion depth and newborn weight [22].

Tube insertion depth (cm)	Newborn weight (kg)
5,5 – 6,5	Less than 1
7	1
8	2
9	3

2.3 Resuscitation bag

The neonatal resuscitation bag is the fundamental component of the delivery room. It is also known by short BVM meaning big valve mask and self-inflating bag. It is a hand-held device that helps weak infants breathe. Babies who do not respond to drying or additional stimulation are given positive pressure ventilation using a self-inflating bag and mask. The device is commonly referred to by the proprietary name "Ambu bag". The resuscitation bag has undergone various advances, from its discovery to its modern use [3, 10].

2.3.1 Design

Holger Hesse, a German doctor, and his Danish partner, anaesthetist Henning Ruben, created the first bag-valve-mask concept in the middle of the twentieth century [3]. They would later name their device AMBU (Air Mask Bag Unit).

Figure 2.5 represents the first appearance of the self-inflating bag. The main idea was that the bag would automatically re-inflate, refiling itself with new air, while the inflating valve serves to prevent the patient from inhaling exhaled CO_2 [24].

Figure 2.5: First appearance of the self-inflating bag. Taken from [24].

The modern Ambu bag design has undergone improvements that have kept its basic structure while incorporating small additions to each component of the device. These improvements have been made to improve device performance, durability, and usability. The design of the modern self-inflating bag is shown in Figure 2.6.

Figure 2.6: Modern neonatal self-inflating bag (Halo Medical, United Kindgdom). Taken from [25].

2.3.2 Structure

The self-inflating bag typically consists of three components: a bag, a facemask, and a valve regulatory pressure relief system. Furthermore, for a patient using a self-inflating bag, there is a patient connector that involves a unidirectional valve, an exhalation port, and a patient connection port. The patient connection port is connected to an interface, such as a mask, and when the rescuer squeezes the bag, an air volume is administered to the patient [26]. Figure 2.7 shows the basic scheme of the described device.

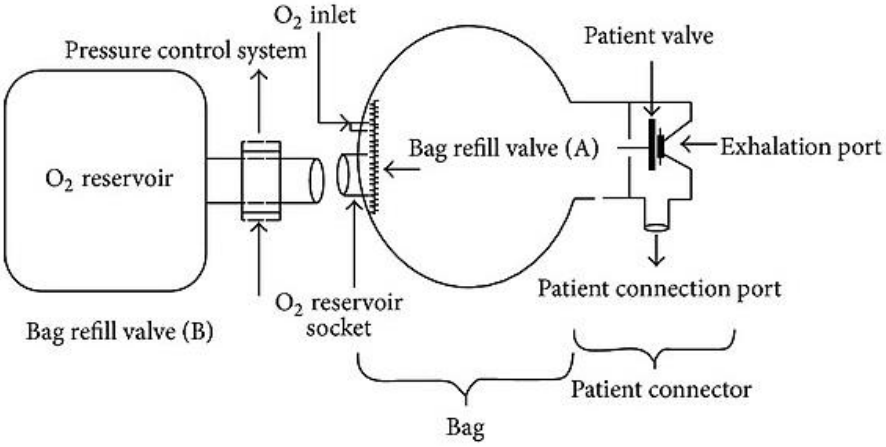


Figure 2.7: Basic components of the big valve mask system. Taken from [27].

Mask

The face mask has been described in the 2.3.1 section of this thesis.

When using a bag-mask device, the mask should be placed over the infant's nose and mouth, forming a seal that allows positive pressure to be delivered effectively. The bag should be squeezed at a rate of $RR = 40–60$ bpm to deliver a tidal volume of approximately $V_t = 5–7$ ml/kg. By observing chest rise and fall, as well as monitoring heart rate *HR* and oxygen saturation SpO_2, adequate ventilation can be confirmed [26].

Bag

The bag represents a flexible air chamber that is attached to a face mask through a shutter valve. When the bag is squeezed, it forces air into the patient's lungs, and when the pressure is released, the bag self-inflates from its other end, drawing in ambient air or low-pressure oxygen flow supplied by a regulated cylinder. It is important to note that when using a self-inflating bag without supplemental oxygen, it delivers an oxygen concentration of 21%, which is generally not sufficient for most sick or injured patients [28].

Valve

Ambu valves are known as single-shutter valves. The valves are constructed from two undirectional flaps made of silicone rubber that resembles mushrooms. One flap facilitates inhalation, while the other facilitates exhalation. This valve is the oldest of its kind used for ventilation and has low resistance flow and a small dead space [26]. The clear presentation of the valve function is shown in Figure 2.8.

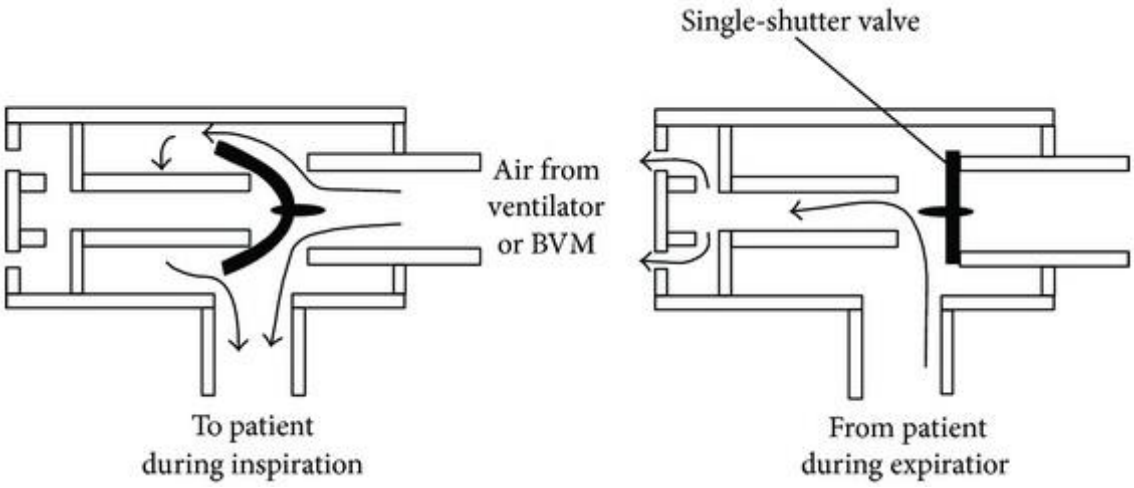


Figure 2.8: Function of the self-inflating single-shutter valve type bag. Taken from [29].

2.4 T-piece resuscitators

T-piece resuscitation is a technique that delivers consistent and controlled positive inspiratory pressure (*PIP*) and positive end expiratory pressure (*PEEP*), which is beneficial for protecting the lungs from injury and establishing functional residual capacity (FRC) [30]. The use of heated and humidified T-piece resuscitation during infant resuscitation has been shown to be more effective in maintaining normal body temperature compared to the use of cold and dry gas [31].

This type of resuscitators gained their name by implementing a T-piece with a ventilation circuit. The importance of a T-piece lies in the fact that it provides an outlet for exhaling gas to be kept out of the mix with the inhaling gas. It can also contain a valve to control *PEEP* or be adjusted for the type of resuscitation system [32].

An example of the incorporation of the T-piece into ventilation processes is presented in Figure 2.9.

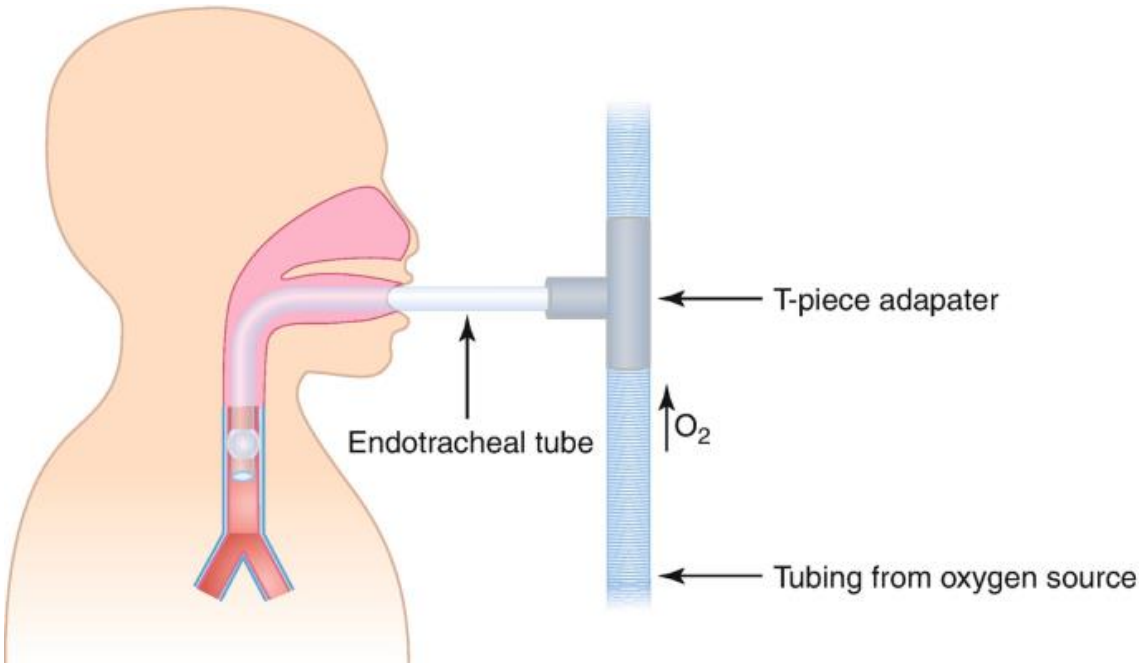


Figure 2.9: Implementation of a T-piece to a ventilation circuit of a resuscitation system. Taken from [33].

The development of a T-piece resuscitator (TPR) represents a great breakthrough in neonatal care because it allows the delivery of humidified and heated gas to an infant patient. This part of the thesis will cover two devices: a conventional Neopuff infant resuscitator and a modern rPAP resuscitator. These devices differ by their control of the *PEEP* and the design of the ventilation circuit and the T-piece.

2.4.1 NEOPUFF

The Neopuff T-piece Resuscitator (TPR) was founded by the New Zealand company Fisher & Paykel Healthcare in 2010. This device is a conventional TPR and is commonly used today in neonatal intensive care units and delivery rooms. Since its founding, Neopuff has been continuously updated with derivatives of this device. Figure 2.10 shows the most modern Neopuff design, series 900. Figure 2.11 shows one of the most widely used Neopuff derivate, named NEO-I.

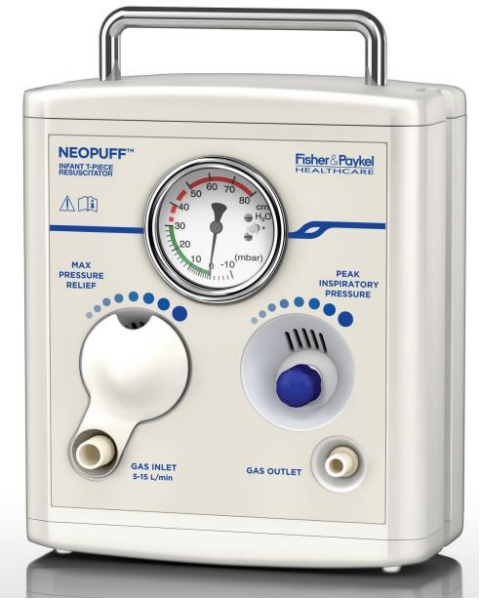


Figure 2.10: Neopuff resuscitator design, series 900 (F&P Healthcare). Taken from [34]

Figure 2.11: Neopuff derivate NEO-I. Photograph: author.

The basic components of Neopuff are represented in Figure 2.12. The manometer is placed in the middle of the front of the device and serves to control the pressure value. On the sides there are an inlet and an outlet port. The main parts are the valve for maximum inspiratory pressure control on the right side and the maximum pressure relief on the left side [34].

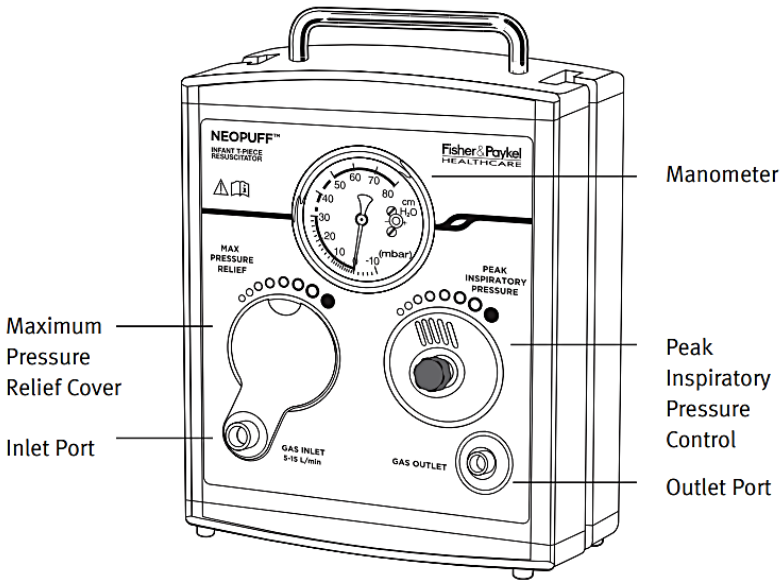


Figure 2.12: Main components of the NEOPUFF device. Taken from [34].

The functional schematic of the main components of the Neopuff device is shown in Figure 2.13. The input port serves to connect to a gas supply, usually a blender. The *PIP* can be controlled directly on the device, while the *PEEP* value is set on the valve of the T-piece part of the ventilation circuit. The outlet port leads the gas to the ventilation circuit, which transports it through a humidifier to the patient [34].

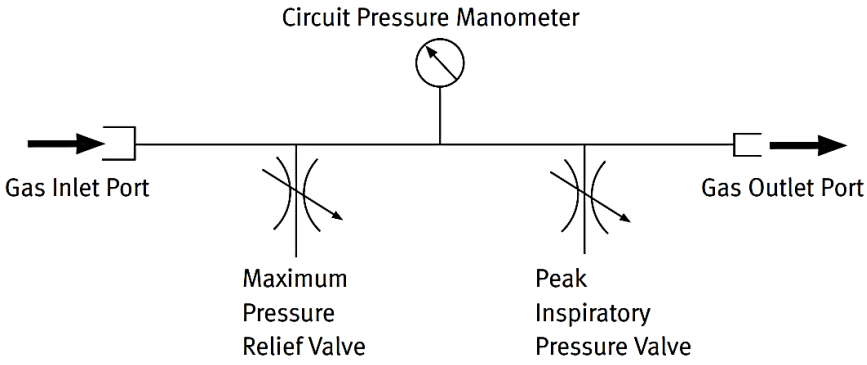


Figure 2.13: Functional schematic diagram of the main components of the Neopuff resuscitator. Taken from [34].

Neopuff equipment consists of a blender connected to a gas supply, a flowmeter, a ventilation circuit containing a T-piece with an adjustable *PEEP* cap, and an interface for direct connection to an infant, usually being a facemask. Figure 2.14 shows the diagram of the NEOPUFF device in a clinical setting.

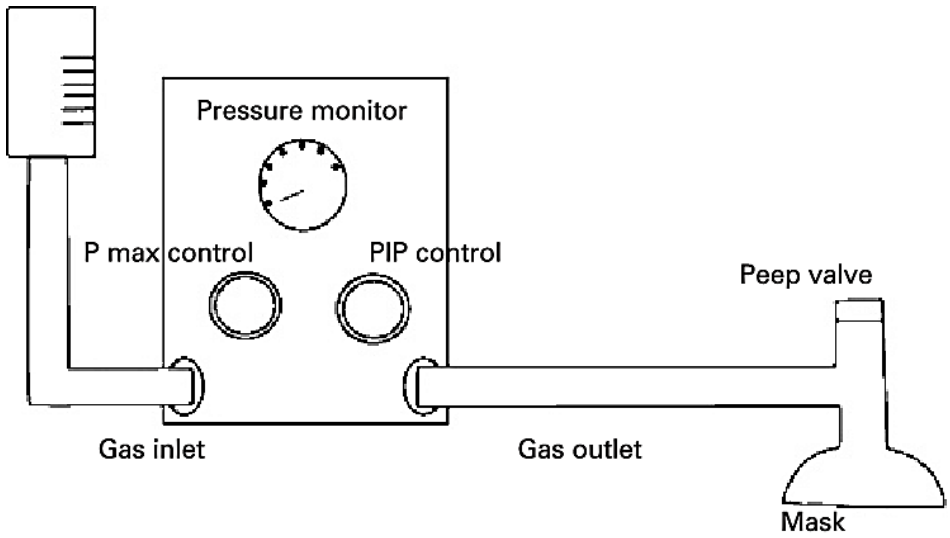


Figure 2.14: Neopuff in connection with its equipment in the clinical setting. Taken from [35].

The main advantage of this device compared to that of Ambubag is that it delivers controlled and consistent pressures *PIP* and *PEEP*. It can deliver oxygen levels of 21 % to 100 %. The device specifications suggest an input gas flow range of 5 to 15 l/min, with a recommended operating gas flow rate of 8 l/min. Depending on the gas flow, *PIP* can be ranging from 2–75 cmH_2O, while *PEEP* from 1–17 cmH_2O. Another major advantage is the possibility of delivering heated and humidified gas to a patient. This spectrum of different values can be achieved by connecting the device to other equipment that helps manipulate the characteristics of the gas being delivered to a patient [34].

2.4.2 rPAP

rPAP is another commonly used TPR device for initial infant stabilisation and resuscitation. It was developed in 2016 by the United Kingdom company Inspiration Healthcare [36]. As it is still a relatively new technology, it is not yet widely accepted in all healthcare facilities. Figure 2.15 shows the design of the rPAP device.

The device consists of a manometer for pressure measuring and *PIP* and *CPAP* valves. *CPAP* is continuous positive airway pressure, representing the same as *PEEP*. Both *PIP* and *PEEP* are directly manipulated by valves placed on the front side of the device [37]. In this case, the inlet port is set at the bottom of the device, while the outlet port is placed on the front right part as in the NEOPUFF device.

Figure 2.15: Design of the rPAP device (Inspiration Healthcare). Taken from [36].

rPAP stands for 'recirculating bubble continuous positive pressure' and its function comes from its name. rPAP works by delivering a constant flow of air or gas through a fluid chamber, resulting in a stream of bubbles. This bubbling stream generates pressure, which aids in maintaining open airways and improves oxygenation by increasing functional residual capacity (FRC). The recirculating feature of rPAP provides a continuous supply of heated and humidified air, preventing the airways of the baby from drying out and becoming damaged [37].

The main advantage of this device compared to traditional infant T-piece resuscitators is low iWOB. Inspire rPAP is designed to work in tandem with infant's own respiratory efforts, preventing fatigue and preserving energy. When it comes to WOB, the founders have provided a graphical comparison with other TPR, presented in Figure 2.16.

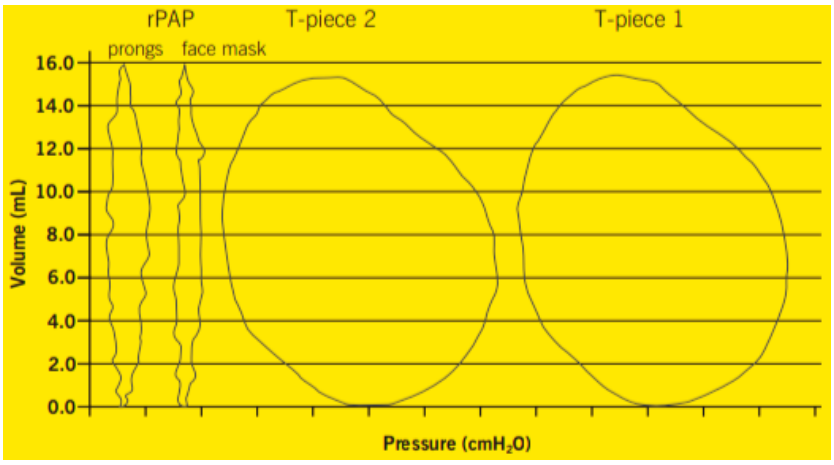


Figure 2.16: WOB comparison of rPAP to other T-piece resuscitators. Taken from [37].

The low iWOB is based on the way rPAP delivers gas to a patient, which is given by the structure of a T-piece used with this device. Inflating breath can be given to infants by blocking the gas outlet, causing all gas from the *PIP* and *CPAP* limbs to be directed toward the infant's lungs until the required *PIP* is achieved . Figure 2.17 shows the inspiratory gas flow during resuscitation [37].

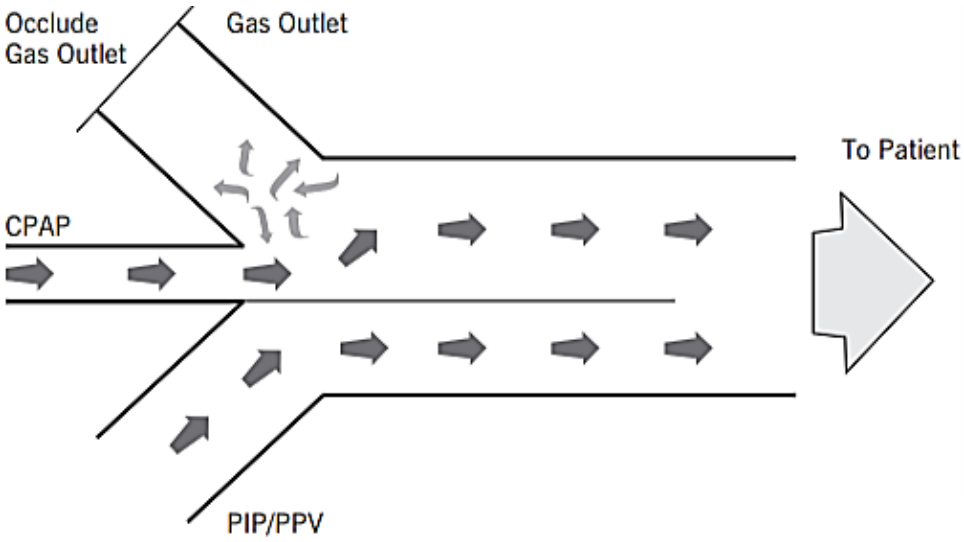


Figure 2.17: Inspiratory gas flow of rPAP during resuscitation. Taken from [37].

The flow direction is reversed when the gas outlet is opened, causing the expired gas to entrain through the gas outlet. As a result, during exhalation, the infant expends significantly less energy. Figure 2.18 shows the expiratory gas flow during resuscitation.

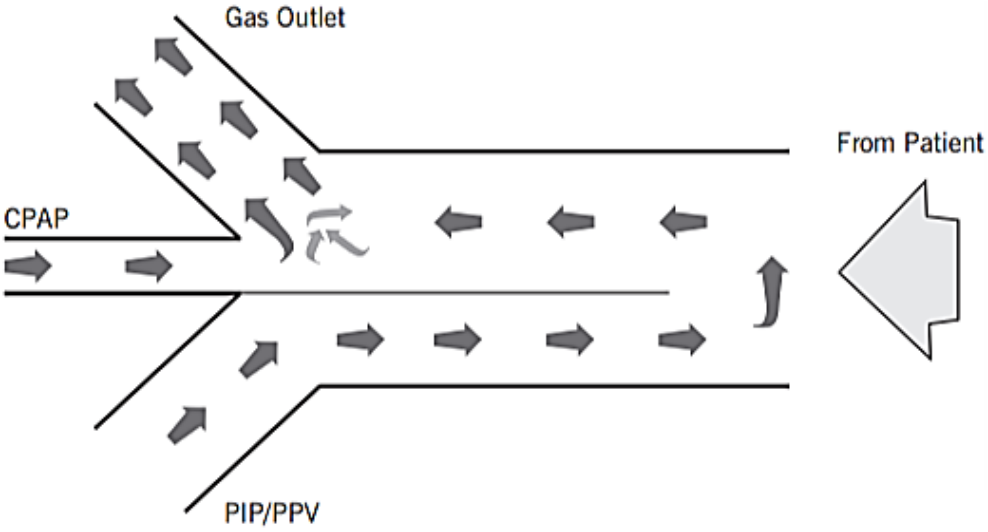


Figure 2.18: Expiratory gas flow of rPAP during resuscitation. Taken from [37].

2.4.3 Recent studies

Not many studies have been conducted to compare the performance of rPAP and NEOPUFF resuscitators, as they still represent relatively new technologies. However, studies have shown some distinction in terms of their ability to provide effective ventilation to newborns. On the basis of this, further research must be done to get a clear picture of their dissimilarity. This part of the thesis will constitute the motivation for its writing.

While providing PPV to a testing compliance model with a few different brands of TPR devices, including rPAP and Neopuff, a study has found that only rPAP remained at the set value of *PEEP* during the increase in *c* from 0.5–5 ml/cmH_2O. Resusctitators that have a range of *PEEP* values could be clinically harmful for preterm newborns with larger compliance during resuscitation [34].

Similar study has been testing inadvertent PEEP while using TPR. They have found that the expiratory time constant increases with increasing value of compliance. The TC value has also increased with higher resistance, lower gas flow, and higher *PEEP* levels [32].

Another study has also found differences in the performance of the Neopuff resuscitator based on its design. While measuring several respiratory parameters, the authors have found that the new Neopuff design delivers a significantly higher tidal volume than the original design. Furthermore, they have found that the new design resulted in a lower *PIP* [38].

Recent studies have found the distinction in regard to delivering pressure, but also when applying heated humidified gas compared to cold dry gas. Cold dry gas has traditionally been used for resuscitation, but with the beginning of the twentieth century, heating and humidifying of gases have become available. The use of heated and humidified T-piece resuscitation during infant resuscitation has been proven to be more effective in maintaining normal body temperature compared to the use of cold and dry gas [31].

While studying the heating of gases during resuscitation, one study has found that there was not a significant difference between flow rates. In this study, and confirmed by other researches, the target temperature and humidity are not always possible to reach. It is necessary for adequate time to pass for a humidifier to reach the required parameter values [39].

Many other studies have been conducted to improve neonatal resuscitation conditions, but a comparison of Neopuff and rPAP T-piece resuscitators in terms of pressure phenomena and a comparison of the delivery of heated humidified gas is lacking. This research will aim to fulfill the lack of information in this area.

3 Aims

The main aim of this project is to research the current possibilities of resuscitation systems designed for babies and compare them by analysing differences in their capabilities, as well as considering what can be improved in their clinical use. Motivated by studies that have identified distinctions in the performance of rPAP and NEOPUFF resuscitators when it comes to delivering pressure, this research will focus on comparing pressure phenomena and resuscitation from the point of heated humidified gas. To achieve the aim, the research will be divided into the following parts:

- The initial step involves determining whether the resuscitation devices exhibit differences in the progression of pressure increase, resulting in varying the time constant and the inspiratory rise time.
- If the first step confirms the existence of differences, the next step will aim to identify the underlying causes of these variations and examine the potential implications associated with the progression of the pressure increase.
- The final step will involve analysing the performance of the resuscitation devices in terms of the application of a heated humidified gas.

The NEOPUFF and rPAP data collected in the laboratory experiment will be processed using Matlab, a language for technical computing, to automatically obtain the results. Additionally, Microsoft Excel will be used for mathematical operations and statistical analysis.

4 Methods

This chapter provides a thorough explanation of the procedures used to perform a practical experiment and the instruments used for its execution. After the experiment, Matlab software was used to analyse the data that had been collected.

4.1 Practical experiment

A practical experiment for this Bachelor thesis was carried out at the Faculty of Biomedical Engineering in Kladno 2023, laboratory A-013.

At the beginning of this study, a schematic concept was developed to later execute the required assignment. The main idea is to compare NEOPUFF and rPAP resuscitators using an improvised scenario that represents a typical clinical situation. They serve their purpose when used in conjunction with other medical tools that regulate the quality and quantity of gas delivered to the patient. The GINA neonatal simulator played a crucial role in simulating the lungs of the infant.

Due to the physical differences between the two systems, separate schematic concepts have been developed for each. First, an experiment was conducted to compare the pressure characteristics of these devices. Subsequently, a comparison while delivering heated and humidified gas was performed.

Comparison of pressure was conducted by simulating about 10 breaths for each different setup of parameter values. The simulation of inhalation was achieved manually by obstructing the T-piece outlet. Outputs of these measurements will be displayed via time parameters: rise time and time constant.

A comparison based on gas characteristics was conducted using a humidifier for heating and humidifying gas. Temperature T and humidity H were measured directly with the TESTO device, which is specialized in measuring the above-mentioned parameters. The results of these measurements should provide insight into the way the target temperature and humidity value are reached.

4.1.1 Comparison of pressures

The first step in this study is to determine whether there exists any distinction in the pressure applied during gas delivery to the patient. To accomplish this, two schemes were constructed: Figure 4.1 represents the concept of the NEOPUFF resuscitation system, while Figure 4.2 represents the realisation of rPAP.

In both cases, resuscitation devices were used in conjunction with a mixer, flowmeter, and GINA simulator. The purpose of these devices in this laboratory

experiment is explained in the Used instruments section. The main difference between these two concepts is the ventilation circuit.

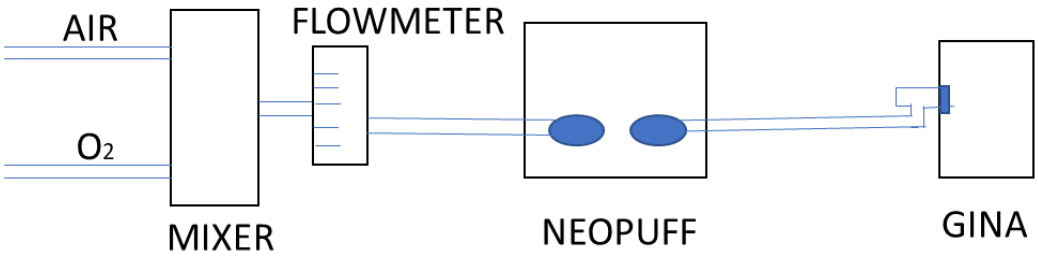


Figure 4.1: Schematic concept of the NEPUFF device for comparison of pressure

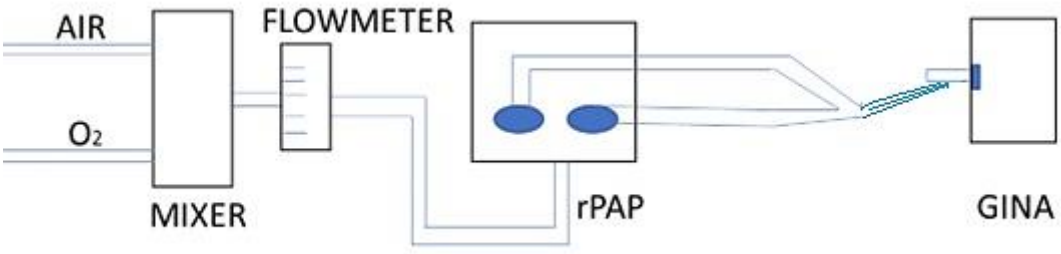


Figure 4.2: Schematic concept of the rPAP device for comparison of pressure

4.1.2 Gas characteristics comparison

Following the comparison of pressure, an experiment was executed for comparison based on the gas characteristics. As in the previous part, two schematic concepts were constructed separately for each system. Figure 4.3 represents the concept of the NEOPUFF resuscitation system, while Figure 4.4 represents the realisation of rPAP. The ventilation circuit once again serves as the primary distinction between these two ideas.

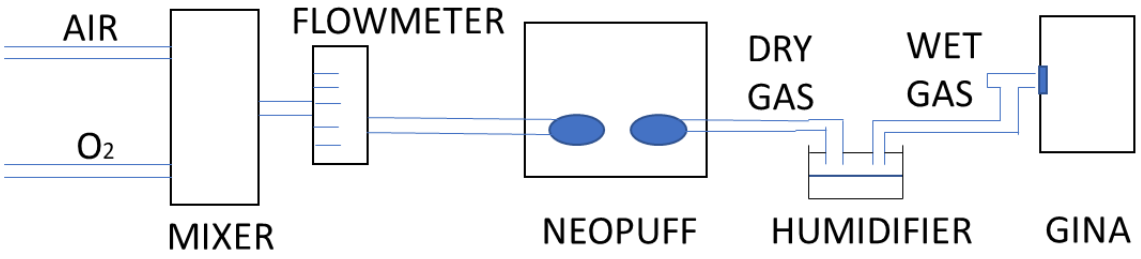


Figure 4.3: Schematic concept of NEOPUFF device for gas characteristics comparison

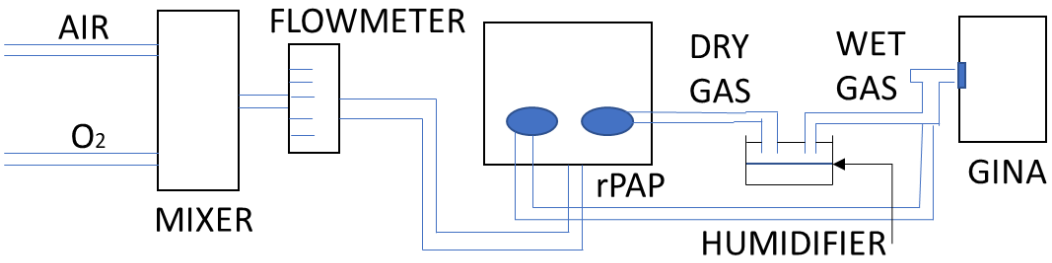


Figure 4.4: Schematic concept of the rPAP device for comparison based on gas characteristics

In this part of the experiment, a humidifier was added to the plan in addition to a mixer, flowmeter, and GINA simulator. This comparison is based on the use of heated and humidified gas to study the behaviour of resuscitation systems.

4.1.3 Parameter settings

Using parameters that simulate patient ventilation for an infant, the experimental procedure was performed under carefully monitored conditions for each device. A blender was used in both comparison settings to keep the oxygen content of the gas provided constant at FiO_2 = 21% during the experiment.

The stable parameters for the primary resuscitation devices during the pressure comparison were *PEEP* = 5 cmH_2O and *PIP* = 25 cmH_2O. Using Neopuff, *PEEP* was controlled by a *PEEP* valve incorporated into a T-piece, while rPAP enabled direct control of both *PIP* and *PEEP*. A flowmeter was used to control the gas flow, which changed for each measurement between 5 and 15 l/min. With settings of 0,3 ml/cmH_2O and 1 ml/cmH_2O, the GINA simulator was used to simulate the compliance of the infant's lung.

During the comparison of gas characteristics, the gas temperature and humidification were managed by a humidifier that was adjusted to T = 37 °C and H = 100 %. This measurement was carried out with the flow set to q = 8 l/min.

4.2 Used instruments

The two main devices used in this Bachelor's thesis are the rPAP and Neopuff resuscitation systems, described previously in Section 2.4 of this Bachelor's thesis. For the execution of the practical experiment, the original rPAP device was used, while Neopuff derivate NEO-I was chosen. The rest of the equipment was selected according to the needs of the experiment. The use of instruments will be explained according to the path that the gas takes to achieve the lung simulator.

4.2.1 Blender and flowmeter

The oxygen and air supply enter directly into the mixer, helping to adjust the correct amount of oxygen according to the ventilation needs. After the correct ratio of oxygen is set, the gas continues its flow through the flowmeter, which is used to adjust the flow value to the resuscitator. The blender and flowmeter were directly connected during the experiment.

The Sechrist 3500 Low Flow Air / Oxygen Mixer was used for the purposes of this study. This device has been specially designed to precisely blend medical grade air and medical grade oxygen. It is meant for fine regulation of pressure and proportioning. With an accuracy level of 3%, it can supply a variety of FiO_2 values to various types of respiratory care equipment, ranging from 21 % to 100 % [40]. During the experiment, FiO_2 was set to a steady value of 21%.

The Oxygen Chrome Flowmeter from Precision Medical was directly connected to the blender. It was used to set the gas flow between 5 l/min and 15 l/min. The value was controlled by turning the flow control knob on the front of the flowmeter.

Both the mixer and the flowmeter used in this experiment are shown in Figure 4.5.

Figure 4.5: Mixer Sechrist 3500 and flowmeter Oxygen Chrome used in the practical experiment. Photograph: author.

4.2.2 Simulator GINA

The Gina simulator is designed exclusively to generate neonatal lung behaviour and can be connected to any ventilating device through a ventilation circuit. The model

includes an electromagnetic lung model integrated with software that is installed on the computer. It is mostly used for training medical personnel and research on clinical artificial ventilation [41]. The neonatology simulator is shown in Figure 4.6.

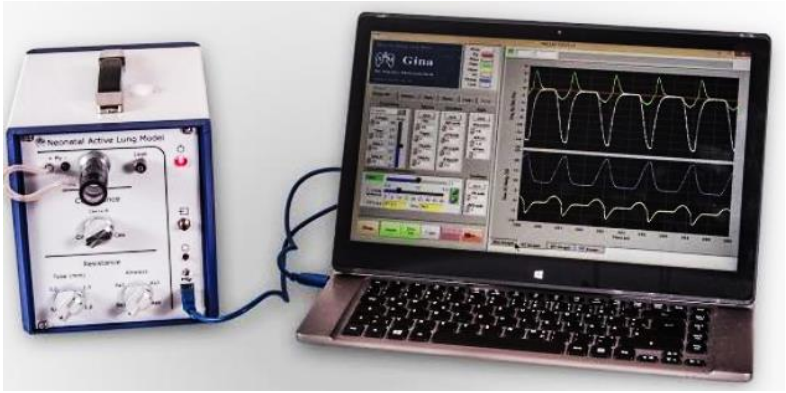


Figure 4.6: Neonatal simulator GINA in combination with computer interface. Taken from [41].

The simulator distinguishes between the airway resistance R_a and the endotracheal tube resistance R_t according to its diameter in millimetres. The compliance can be set as variable internal, denoted C_{int}, or fixed external, denoted C_{ex}. The difference between these is that C_{int} is based on the movement of the piston in the cylinder, whereas C_{ex} contains a defined volume [41]. The aforementioned parameters are controlled using the switches shown in Figure 4.7.

Figure 4.7: Physical model of simulator GINA including the parameter switches. Taken from [41].

The physical lung model contains all the necessary parts for a reliable simulation of the neonatal lung. Along with the fundamental mechanical, pneumatic, and electrical

components that implement the simulation of compliance and resistance, the model is also equipped with sensors that measure volume flow, intrapulmonary and extrapulmonary pressure, and piston position in the cylinder. The manual parameter settings from external sources are transferred via USB to the user interface on the PC, where all further calculations are performed. The progress of the parameters monitored by the simulator can be displayed numerically or graphically [41].

Other important parameters that underlie the GINA simulator principle are shown schematically in Figure 4.8. The value of the resistance *Rt* is determined through switch S1 by controlling the airflow from the input connector through the flow sensor to the switchable tube. The S2 switch sets the magnitude of the breathing resistance R_a. The last switch S3 has a function of air release to variable internal C_{int} or fixed external compliance C_{ex}. In Figure 2.10, P_y represents the Y(T) clamp pressure, P_{etr} endotracheal pressure at the end of the tube, P_{alv} alveolar pressure, and *Flow* volume flow rate and V_{lung} the volume of the cylinder [42].

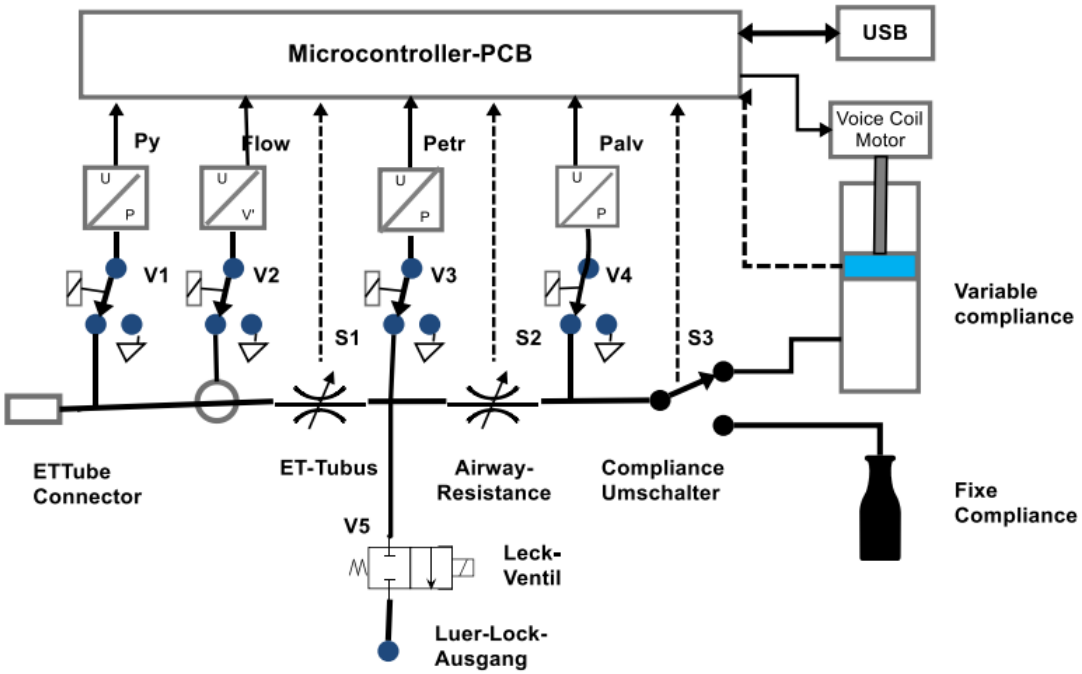


Figure 4.8: Schematic representation of lung model. Taken from [41].

The GINA simulation software has a crucial role in this experiment, as it is used to simulate the infant's respiratory system. Comparison of pressure was conducted by choosing the compliance of C_{int} = 0,3 ml/cmH_2O and C_{int} = 1 ml/cmH_2O. Compliance was being controlled by PC software. The software also provides a graphical representation of the alveolar pressure P_{alv} and the pressure built in the T-piece segment at the gas entrance to the *Py* simulator. During the experiment, software automatically measured time and pressure values, which were saved and later used for analysis.

Figure 4.9 shows the photograph of PC software, which was taken during pressure measurements. The left side enabled setting compliance and saving the measured numerical data, while the right part shows the progression of pressure rise during the inhalation and expiration processes. In the upper right window, the red colour represents the alveolar pressure, while the green line represents the pressure of the T-piece.

Figure 4.9: GINA simulator interface shows the chosen compliance value with a clear graphical representation of the applied pressures (green line in the upper window - *Py;* red line in the upper window - P_{alv}). Photograph: author.

Simulation of inhalation

A crucial aspect of this experiment involved manually simulating the inhalation phase for both resuscitation systems, as illustrated in Figure for rPAP and Figure 4.10 for NEOPUFF.

The primary objective was to prevent gas diffusion and ensure complete insertion of the gas into the simulator. Inhalation simulation was achieved by obstructing the outflow of a T-piece segment of the ventilation circuit, whereas exhalation was simulated by not obstructing the outflow.

Neopuff systems have a gas outlet connected to the *PEEP* valve of a T-piece, while rPAP systems use a T-piece containing an outlet for gas excretion only. Obstruction of gas outflow is shown in Figure 4.10 for Neopuff (left) and rPAP (right).

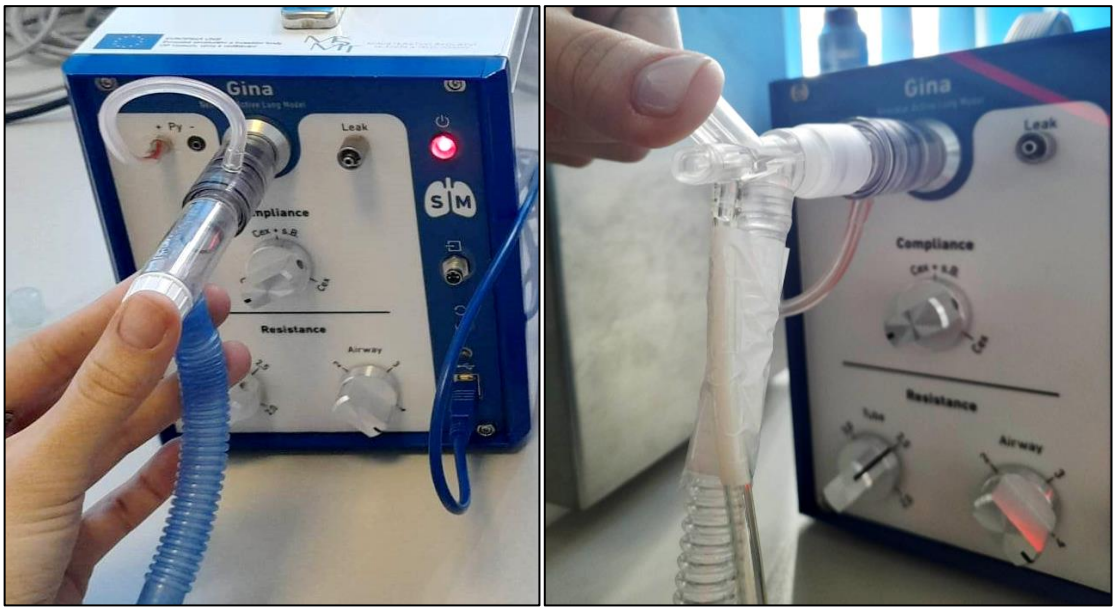


Figure 4.10: Simulation of inhalation for NEOPUFF system (left) and rPAP system (right). Photograph: author.

4.2.3 Humidifier

The MR850 heated humidifier (Fisher&Paykel Healthcare) was used in this practical experiment to achieve a comparison of the gas characteristics. The device was set to target normal body temperature T = 37 °C and *H* = 100%. Figure 4.11 shows the design of the device used.

Figure 4.11: Respiratory humidifier MR850 (Fisher&Paykel Healthcare). Photograph: author.

4.2.4 Hygrometer and termometer

In addition to the humidifier, to compare the performance of the resuscitators in the delivery of heated and humidified gas, a TESTO 635 hygrometer and thermometer was employed. The hygrometer and thermometer automatically measured the relevant parameters by placing its sensor at the entrance of the GINA simulator.

Figure 4.12 shows the design of the TESTO 635 device. Figures 4.13 show the insertion of the TESTO sensor in the T-piece part of the ventilation circuit for rPAP and Figure 4.14 for Neopuff.

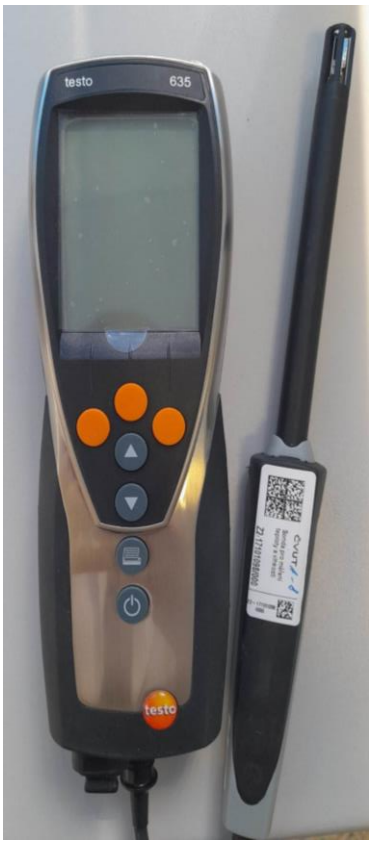


Figure 4.12: TESTO 635 - hygrometer and thermometer. Photograph: author.

Figure 4.13: Insertion of TESTO 635 into rPAP T-piece. Photograph: author.

Figure 4.14: Insertion of TESTO 635 into Neopuff T-piece. Photograph: author.

4.3 Data processing

The data obtained from each pressure measurement were subsequently analysed using the programming platform Matlab. The emphasis was put on two important time parameters: time constant and rise time. Microsoft Excel was used for developing a graphical presentation of the data collected during temperature and humidity measurements on the device TESTO as well as for statistical analysis. Block diagram of data processing is shown in Figure 4.20.

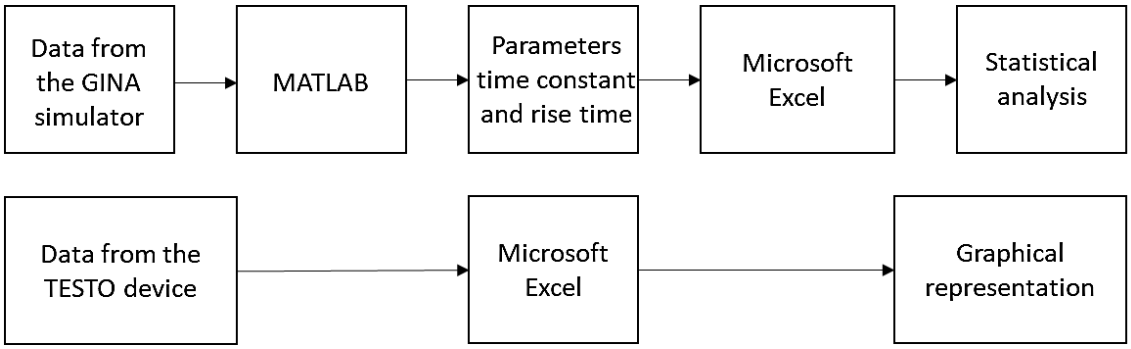
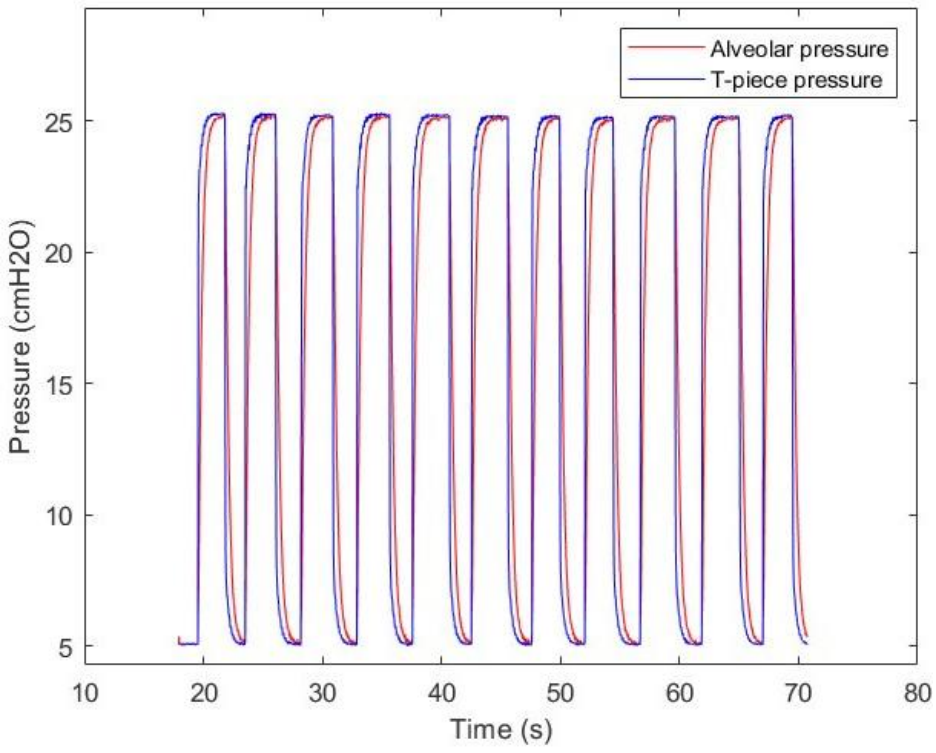


Figure 4.19: Block diagram of data processing.

Figure 4.15 shows the graphical presentation of data imported to Matlab, taken during Neopuff pressure measuring, while q = 15 l/min and c = 1 ml/cmH_2O.



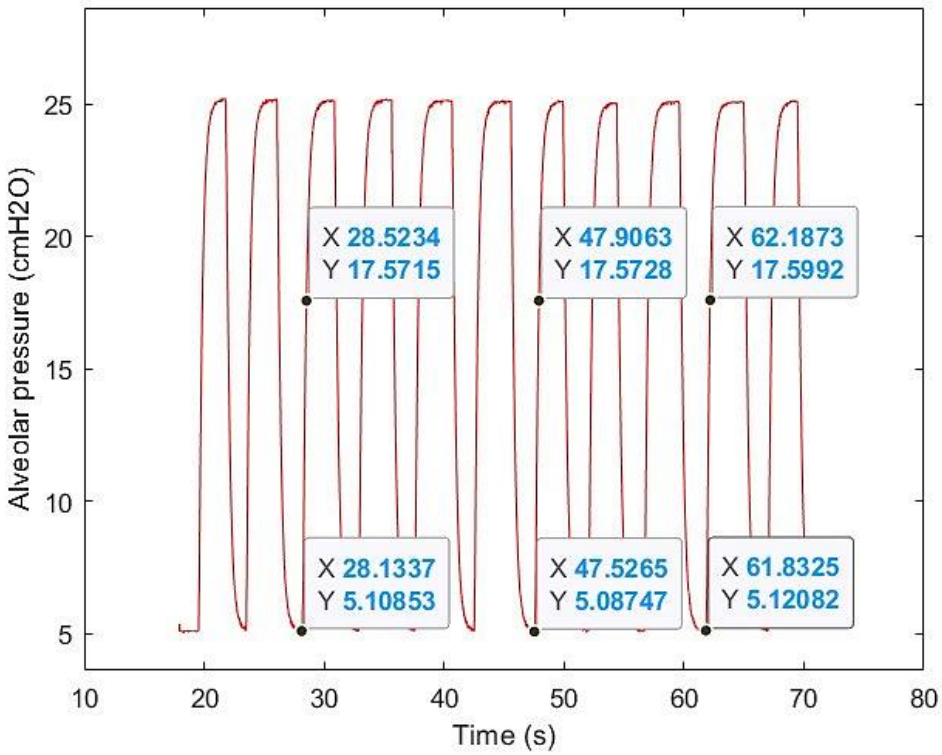
Graph 1: Pressure progression of Neopuff, q = 15 l/min and c = 1 ml/cmH2O.

4.3.1 Time constant

The time constant (*TC*) represents a parameter used in a spectrum of cases. In our case, the time constant of a pressure rise will be calculated. It can be determined as both inspiratory and expiratory *TC*. Inspiratory *TC* is the time duration needed for the pressure to reach 63 % of the final pressure value, which in this experiment is set to *PIP* = 25 cmH_2O. Optimal value is 0,1–0,2 s [42].

The importance of the time constant in this Bachelor thesis lays in the fact that it can be used as a gradient value to determine whether there is a difference in pressure rise progression between an independent set of parameters and resuscitation devices.

The time constant for each measurement was determined manually by Matlab. The graph shows a graphical presentation of the calculating process. Since the highest pressure value is 25 cmH2O, the 63 % value was determined at the 17,6 cmH_2O value of Y on the graph considering that the baseline is set at 5 cmH_2O.



Graph 4.2: Example of TC determination in Matlab.

The final TC value was determined as the mean value of each pressure rise progress during one set of measurements using the following equation [43]:

$$\bar{X} = \frac{\sum X}{N} \tag{4.1}$$

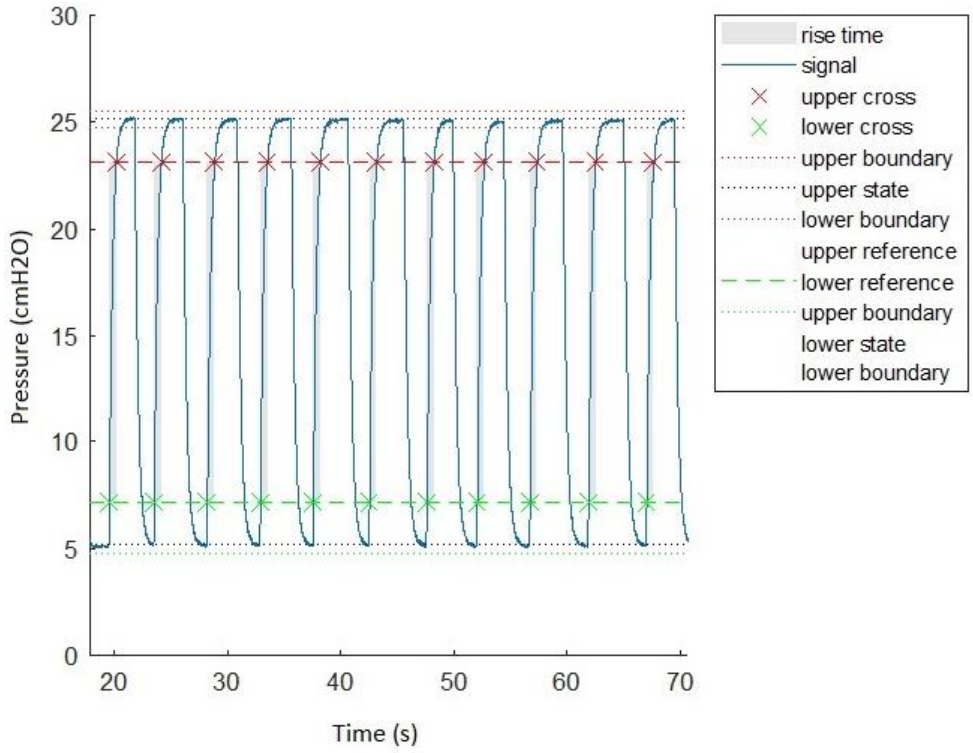
where X is the value of *TC* for one pressure rise, N is the number of rises.

4.3.2 Rise time

Rise time (*RT*) in general stands for the time it takes the signal to achieve its targeted maximum value. When it comes to the respiratory system, the inspiratory and expiratory rise time can be considered. Inspiratory rise time represents a time value that is needed for the pressure to reach its peak value, which in this experiment is set to *PIP* = 25 cmH_2O. The importance of this parameter lies in the fact that it influences the work of breathing, flow, and breathing rate. [44].

It can be calculated in various ways, but the most common one is calculating the time required for a signal to move from 10 % to 90 % of its final value [45].

The inspiratory rise time for each pressure measurement was calculated automatically in Matlab using the *risetime* function. The graphical representation of this function is shown in Graph 4.3.



Graph 4.3: Inspiratory rise time calculation in Matlab.

4.3.3 Statistical analysis

A nonparametric test was used for the statistical analysis of the recorded data due to the lack of information about the distribution of data. The two-tailed sign test was performed to compare resuscitation devices. The test was used to compare the time parameters for the pressure comparison and to compare the temperature and humidity data for the gas characteristics comparison with a confidence value $\alpha = 0{,}05$.

5 Results

In this thesis section, the results gathered from measurements during the practical experiment will be presented. Results are displayed separately for comparison of pressure and comparison based on gas characteristics via tables and graphs. Statistical analyses were also performed after obtaining results.

5.1 Pressure comparison

To compare the pressure phenomena in resuscitation devices, the time constant and the rise time of a pressure rise progress were determined. Parameters were determined for both alveolar pressure P_{alv} and pressure building at the entrance T-piece to the simulator P_t. Tables 5.1 and 5.2 contain the numerical data of the mentioned parameters, while a graphical presentation is shown in Graphs 5.1 and 5.2.

5.1.1 Numerical data

Time constant (τ) is a first determined parameter describing pressure in this thesis, followed by the determination of the rise time. The values for each set of flow values (q) and compliance values (c) for both resuscitation devices are presented in Table 5.1 for the time constant and Table 5.2 for the rise time.

Table 5.1: Time constant of pressure rise progress in resuscitation devices.

Resuscitation device	**Neopuff**				**rPAP**			
***c* (ml/cmH_2O)**	**1**		**0,3**		**1**		**0,3**	
***q* (l/min)**	τ_{alv}	τ_t	τ_{alv}	τ_t	τ_{alv}	τ_t	τ_{alv}	τ_t
5	-	-	-	-	0,43	0,16	0,25	0,18
8	0,43	0,16	0,23	0,12	0,33	0,06	0,29	0,18
10	0,36	0,10	0,22	0,12	0,33	0,05	0,18	0,06
15	0,34	0,09	0,15	0,07	0,33	0,05	0,14	0,05

(τ_{alv}-alveolar pressure time constant, τ_t-T-piece pressure time constant)

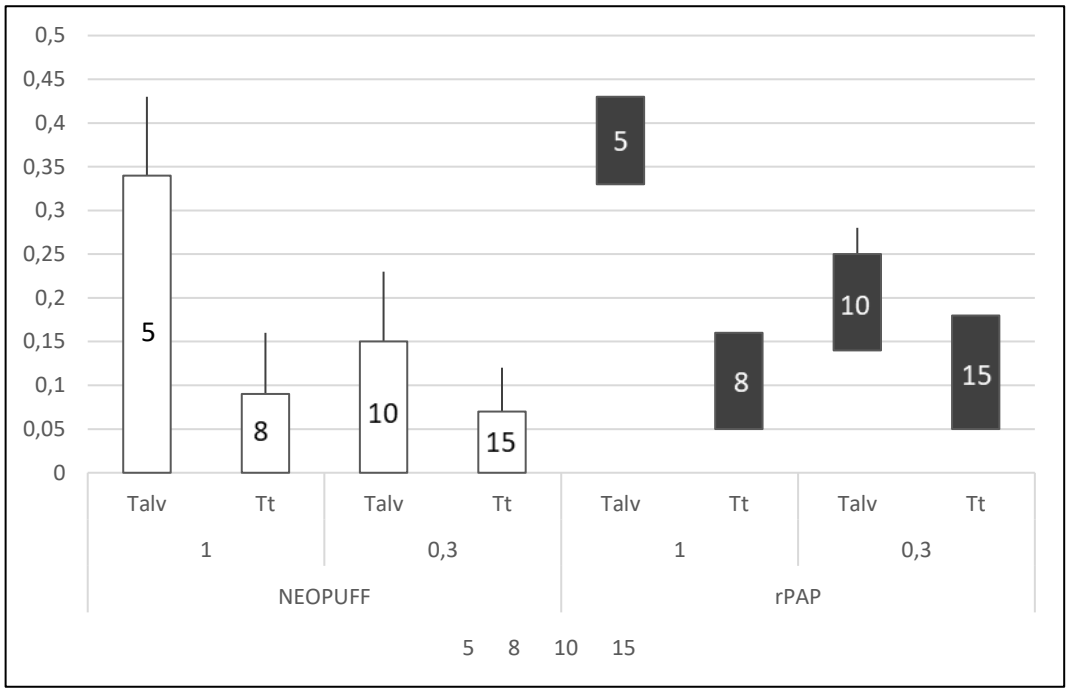
Table 5.2: Rise time of pressure rise progress in resuscitation devices.

Resuscitation device	**Neopuff**				**rPAP**			
***c* (ml/cmH_2O)**	**1**		**0,3**		**1**		**0,3**	
***q* (l/min)**	R_{alv}	R_t	R_{alv}	R_t	R_{alv}	R_t	R_{alv}	R_t
5	-	-	-	-	0,69	0,24	0,32	0,24
8	0,67	0,36	0,29	0,22	0,62	0,15	0,30	0,18
10	0,63	0,17	0,25	0,13	0,62	0,17	0,25	0,10
15	0,63	0,16	0,23	0,09	0,63	0,15	0,23	0,06

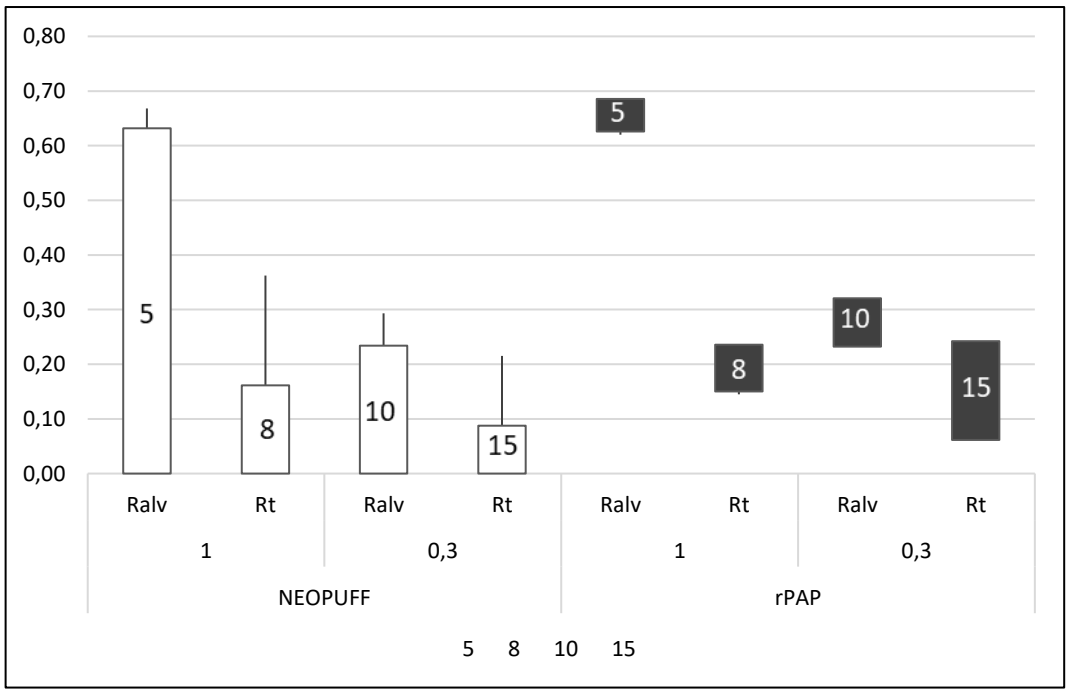
(R_{alv}-alveolar pressure rise time, R_t-T-piece pressure rise time)

5.1.2 Graphical comparison

The graphical comparison of the resuscitation devices is shown in Graph 5.1 for the time constant and Graph 5.2 for the rise time values.



Graph 5.1: Time constant comparison of resuscitation systems (T_{alv}-alveolar pressure time constant, T_t-T-piece pressure time constant; numbers on boxes represent flow values).



Graph 5.2: Rise time comparison of resuscitation systems (R_{alv}-alveolar pressure rise time, R_t-T-piece pressure rise time; numbers on boxes represent flow values)..

5.2 Gas characteristics comparison

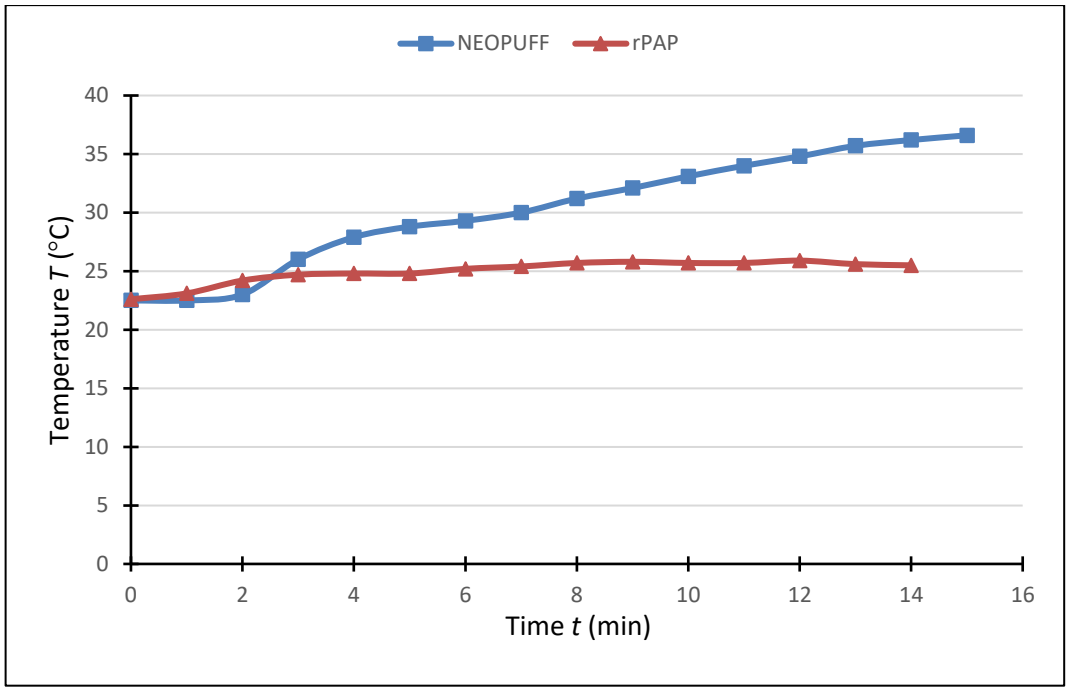
Comparison based on gas characteristics was conducted measuring temperature and humidity values over a required time duration. Data gathered are presented in Table 5.4, while the graphical comparison is presented in Graphs 5.3 and 5.4. Statistical analysis later conducted is presented in Table 5.5

5.2.1 Temperature and humidity

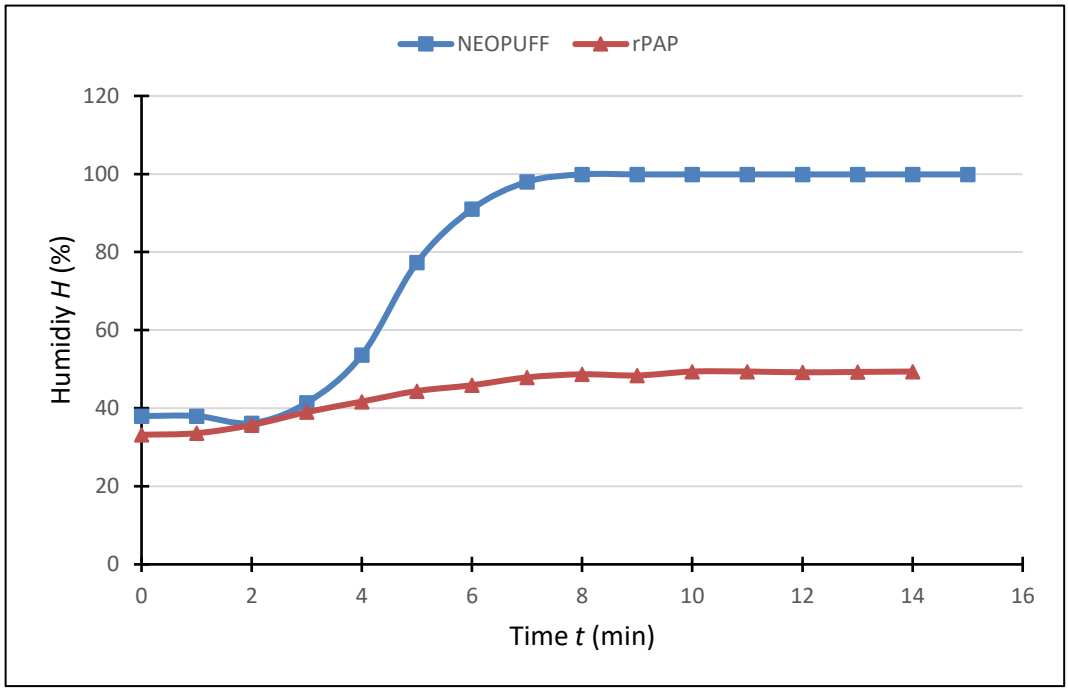
The temperature and humidity values conducted over time are presented in Table 5.4 for both resuscitation systems. Graphical comparison of temperature rise in time is presented on Graph 5.3, while the humidity rise in time is presented on Graph 5.4.

Table 5.4: Temperature and humidity data of resuscitation systems.

	Neopuff		**rPAP**	
Time *t* (min)	**Temperature *T* (°C)**	**Humidity *H* (%)**	**Temperature *T* (°C)**	**Humidity *H* (%)**
0	22,5	38	22,6	33,2
1	22,5	38	23,1	33,6
2	23	36,2	24,2	35,7
3	26	41,4	24,7	39
4	27,9	53,6	24,8	41,7
5	28,8	77,3	24,8	44,4
6	29,3	91	25,2	45,9
7	30	98	25,4	47,9
8	31,2	99,9	25,7	48,7
9	32,1	99,9	25,8	48,4
10	33,1	99,9	25,7	49,4
11	34	99,9	25,7	49,4
12	34,8	99,9	25,9	49,2
13	35,7	99,9	25,6	49,3
14	36,2	99,9	25,5	49,4
15	36,6	99,9	-	-



Graph 5.4: Temperature comparison of resuscitation systems.



Graph 5.5: Comparison of humidity of resuscitation systems.

5.3 Statistical analysis

The time parameters of each resuscitation system as well as temperature and humidity data were compared using a nonparametric two-tailed sign test. The results for time, temperature, and humidity data are presented in Table 5.3. While processing time data, measurements for q = 5 l/min were not considered, since Neopuff failed to produce ventilation.

Table 1: Statistical analysis of time, temperature, and humidity data while alpha value $\alpha = 0{,}05$.

Compared data	Number of differences	Critical value	Statistically important difference
Time data	19	4	Yes
Temperature data	16	3	Yes
Humidity data	16	0	Yes

6 Discussion

The main finding of this work is that there is a difference in the progress of pressure rise between Neopuff T piece resuscitators and rPAP, as well as the difference in the reach of the target temperature and humidity values during heated humidified resuscitation.

The used resuscitator NEO-I has not produced gas flow at the flow value set at q = 5 l/min. The rPAP resuscitator has managed to achieve better results in achieving maximum pressure values, both alveolar and T-piece pressure, according to the rise time and time constant values in Table 5.1 and Table 5.2.

The device rPAP has failed to achieve targeted values of both temperature and humidity during the delivery of heated humidified gas. Neopuff needs an adequate time duration to reach the target values.

6.1 Pressure phenomena

In order to compare the Neopuff and rPAP resuscitation systems, the inspiratory time constant (τ) and rise time (R, RT) were calculated using the Matlab programming language after conducting a practical experiment. The parameters were determined for each set of resuscitation parameters, flow ranging from 5–15 l/min and compliance set to 0,3 ml/cmH_2O or 1 ml/cmH_2O. The oxygen fraction was kept at a constant value of 21 %, while $PEEP$ = 5 cmH_2O and PIP = 25 cmH_2O. The alveolar pressure P_{alv} and the pressure in the T-piece at the entrance of the simulated airway P_t were taken into consideration.

Table 5.1 provides an overview of time constant values and based on these pressure gradient values. It can be concluded that the two resuscitation systems have different rise progress. The device rPAP showed a faster progression of pressure increase in both P_{alv} and P_t, except for the values during q = 8 l/min, c = 0,3 ml/cmH_2O. This abbreviation is not significant when comparing the overall performance of the rPAP device and has been ranked as a mistake of manual determination of time constant. Time constant values deviate from its optimal value during alveolar pressure measuring when compliance is set to 1 ml/cmH_2O. Lower compliance has proved to produce lower values of the time constant parameter for both types of pressures. Both Neopuff and rPAP devices show decreasing values with increasing gas flow. The best results were achieved during q = 15 l/min. The device Neopuff failed to produce gas flow at q = 5 l/min, which is why this flow value was not considered when performing the statistical analysis.

Inspiratory rise time values are presented in Table 5.2. It can once again be said that with increasing value of gas flow, rise time has a decreasing value. The longest time it takes for a device to achieve maximum pressure is for rPAP to achieve PIP for P_{alv} at

q = 5 l/min and c = 1 ml/cmH_2O, while the lowest was also for rPAP to achieve *PIP* for P_t at q = 15 l/min and c = 0,3 ml/cmH_2O.

The graphic presentation of the mentioned time parameters is shown in Graphs 5.2 and 5.3. Resuscitator rPAP shows more precise time parameters, especially in Graph 5.3, where rise time values are presented. The Neopuff shows a larger range of values as it has not been able to produce gas flow at the flow set at q = 5 l/min. This gas flow value was not considered while performing the statistical analysis.

Statistical analysis using the two-tailed nonparametric sign test has shown that there is a difference in the performance of the rPAP and Neopuff resuscitation systems on confidence level of 5 %. With the results described above, we can say that rPAP showed better results when it comes to pressure rise progress. It can produce gas flow at any flow value compared to that of Neopuff. It has also shown faster *PIP* achievement for both alveolar and T-piece pressure and a more precise range of values for a unique set of parameters.

6.2 Heated humidified gas

A similar practical experiment was conducted to compare resuscitation systems from the point of delivery of the heated humidified gas. A humidifier was added to the schematic concept to change the characteristics of the gas from cold and dry to heated and humidified gas. The temperature target was set to normal body temperature T = 37 °C, while humidity was set to a target H = 100 %.

Table 5.4 serves as a presentation of the temperature and humidity data recorded over time. Neopuff has managed to achieve the closest temperature value at T = 36,6 °C and humidity H = 99,9 %. rPAP has not achieved any of the mentioned targeted values, stoping heating at T = 25,5 °C and humidifying at H = 49,4 %.

Graph 5.3 presents a graphical comparison of temperature levels, where it is clear that rPAP never achieves the target value, while Neopuff takes a specific amount of time. The Neopuff has achieved the closest value to the target temperature in a time duration of t = 15 min. Graph 5.4 presents a graphical comparison of the measured humidity levels, where it is clear that Neopuff shows much better performance reaching closest to the target value in the time duration of t = 8 min, while rPAP was able to reach only 50 % of the value Neopuff has reached.

When statistical analysis for gas parameters was performed, it was confirmed that there is a difference in both heating and humidification of gas in resuscitation devices Neopuff and rPAP on the confidence level of 5 %.

6.3 Final assessment

During neonatal resuscitation, every set parameter can have a significant influence on saving the lives of infants. It is important to access this part of neonatal care with great care. Pressure values are important in infant resuscitation, where the *PEEP* and *PIP* values play a major role. The pressure phenomena evaluated in this bachelor thesis focused on the progress of the inspiratory rise time of a pressure and its time constant. Caring for the neonatal lung means using heated humidified gas during resuscitation, so this part of neonatal resuscitation was also assessed between two resuscitation systems: Neopuff and rPAP.

Both alveolar and T-piece pressures were taken into account. Neopuff has failed to produce gas flow at $q = 5$ l/min, while rPAP overall showed greater consistency in achieving the maximum set pressure. The flow rate influences the progress of the pressure rise in such a way that the rise time decreases with increasing flow value. The influence of compliance depends on its value, where lower values require less time to achieve *PIP*.

However, rPAP has failed to achieve the target values needed for optimal heated and humidified resuscitation. Neopuff was able to reach both the target temperature and the humidity in an adequate time period.

In the clinical setting, rPAP would be a better option while considering the impact of pressure characteristics on infants' lungs and the impact resuscitation could have on infant life. On the other hand, Neopuff has produced heated humidified resuscitation and has not shown great deviations during pressure comparison, except in one described case. According to the overall performance of the two resuscitation systems, the traditional T-piece resuscitator Neopuff could achieve better results in neonatal resuscitation compared to the modern TPR rPAP by delivering heated humidified gas with a gas flow set to a higher value than 5 l/min, ideal $q = 15$ l/min.

7 Conclusion

In the framework of this bachelor thesis, a practical experiment was designed in order to compare resuscitation systems from the point of pressure phenomena and the heated humidified gas. Data collected during the experiment were processed in Matlab and MS Excel.

The performance of a traditional T-piece resuscitator Neopuff and a modern T-piece resuscitator rPAP , both used in clinical practice, was compared. Lower values of pressure time parameters were displayed with the increasing gas flow rate and compliance value. rPAP has shown overall better performance resulting in lower values of the time constant and the inspiratory rise time. However, modern TPR has failed to produce heated humidified resuscitation compared to Neopuff which reaches target values in an adequate time duration. Further research of pressure phenomena can be done to more precisely determine the optimal use of these resuscitation systems in clinical practice.

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Attachment D: Content of the enclosed ZIP

1. Key words
2. Abstract
3. Bachelor’s thesis assignment
4. Bachelor thesis
5. Methods
    - Experimental data
    - Codes