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ΣΧΟΛΗ ΜΗΧΑΝΙΚΩΝ

ΤΜΗΜΑ ΜΗΧΑΝΙΚΩΝ ΒΙΟΪΑΤΡΙΚΗΣ

Study of rainout effect on the heating of water-based humidifiers and related alarms

ΣΚΟΥΡΗ ΜΑΡΙΑ

Αριθμός Μητρώου: 15097

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Η υπογράφουσα Σκουρή Μαρία του Βασιλείου, με αριθμό μητρώου 15097 φοιτήτρια του Τμήματος Μηχανικών Βιοϊατρικής της Σχολής Μηχανικών του Πανεπιστημίου Δυτικής Αττικής, δηλώνω υπεύθυνα ότι:

«Είμαι συγγραφέας αυτής της διπλωματικής εργασίας και κάθε βοήθεια την οποία είχα για την προετοιμασία της είναι πλήρως αναγνωρισμένη και αναφέρεται στην εργασία. Επίσης, οι όποιες πηγές από τις οποίες έκανα χρήση δεδομένων, ιδεών ή λέξεων, είτε ακριβώς είτε παραφρασμένες, αναφέρονται στο σύνολό τους, με πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Επίσης, βεβαιώνω ότι αυτή η εργασία έχει συγγραφεί από μένα αποκλειστικά και αποτελεί προϊόν πνευματικής ιδιοκτησίας τόσο δικής μου, όσο και του Ιδρύματος.

Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του διπλώματός μου».

Ημερομηνία

31/3/2023

Ο/Η Δηλών/ούσα

Abstract

The purpose of this thesis project is to establish the consequences of the rainout effect on the performance of a MR850 humidifier using a mesh nebulizer and during non-invasive mechanical ventilation. A basic breathing circuit used for ICU patients consists of a ventilator, a heated humidifier and a nebulizer. While heated humidifiers (HH) used with nebulizers are important to prevent problems in mechanical ventilators, they can result in the ventilator circuit condensing as well, resulting in occlusion alarms.

Temperature, pressure, and related alarms were studied with a non-invasive positive pressure ventilator the NIPPV 3+ at different pressure rates. The humidification system was a basic model of heated humidifier the MR850 (Fisher & Paykel, Auckland, NZ), which has a single heated circuit. The nebulization system was a piezoelectric nebulizer, the Aeroneb Pro (Aerogen, IE) which was tested in 3 nebulizer circuit positions. The circuit was completed with a standard test lung 6006832, Adult 190 (1 Liter) (Maquet, DE). The nebulizer was tested at three positions including at the dry side of the humidifiers, between the Y- piece and the circuit and finally the ventilator outlet. In general, the pressure rate did not dramatically affect the number of alarms during trials. Depending on the placement of the nebulizer device, the respective temperature is affected and therefore the alarms. Placing the nebulizer far from the temperature probe of the humidifier developed significantly fewer alarms than placing it near them. Our results showed that the best position for the placement of the nebulizer is at the ventilator's outlet although the manufacturers do not recommend it. It should be noted, however, that these experiments were conducted in the laboratory and not in a clinical environment, where our findings remain to be confirmed.

Keywords

Active humidification, non-invasive ventilation, humidifier, nebulizer, water condensation, alarm fatigue, ICU

Περίληψη

Ο σκοπός της εργασίας ήταν να καθορίσει την επιπτώσεις που έχει το φαινόμενο ‘rain out’ στη χρήση ενός υγραντήρα σε συνδυασμό με έναν νεφελοποιητή κατά τη διάρκεια μη επεμβατικής αναπνευστικής υποστήριξης. ενός μη επεμβατικού αναπνευστήρα. Ένα βασικό κύκλωμα για την στήριξη του αναπνευστικού συστήματος, το οποίο χρησιμοποιείται σε ασθενείς στην μονάδα εντατικής θεραπείας απαρτίζεται από έναν αναπνευστήρα, έναν υγραντήρα και έναν νεφελοποιητή. Κατά τη χρήση των υγραντήρων και των νεφελοποιητών παρατηρείται αύξηση στην συγκέντρωση υδρατμών στο σύστημα το οποίο οδηγεί σε μείωση της θερμοκρασίας του κυκλώματος και εν τέλει στην ενεργοποίηση συγκεκριμένων συναγερμών. Οι συναγερμοί που ενεργοποιούνται στην συγκεκριμένη ιατρική συσκευή του υγραντήρα έχουν ως σκοπό να ελέγξουν την μείωση της θερμοκρασίας του κυκλώματος. Για τις μετρήσεις χρησιμοποιήθηκε ένας μη επεμβατικός αναπνευστήρας, συγκεκριμένα η συσκευή NIPPY 3+ η οποία δοκιμάστηκε σε διαφορετικές πιέσεις. Για την διαδικασία της ύγρανσης χρησιμοποιήθηκε ένας υγραντήρας MR850 του κατασκευαστή Fisher & Paykel ο οποίος μέσω κατάλληλου κυκλώματος μονής θέρμανσης ήταν συνδεδεμένος με έναν νεφελοποιητή της εταιρίας Aerogen ο οποίος δοκιμάστηκε σε τρείς διαφορετικές θέσεις μέσα στο κύκλωμα. Τέλος το κύκλωμα κατέληγε σε ένα δοκιμαστικό πνεύμονα 6006832 Maquet. Ο υγραντήρας τοποθετήθηκε σε 3 διαφορετικές θέσεις μέσα στο κύκλωμα οι οποίες ήταν στην είσοδο του υγραντήρα, στην είσοδο της αναπνευστικής οδού του ασθενή, και τέλος στην είσοδο του αναπνευστήρα. Οι μετρήσεις της θερμοκρασίας σαν συνάρτηση της πίεσης για διαφορετικές θέσεις του νεφελοποιητή έδειξαν πως ανάλογα με την θέση αλλάζει και η αντίστοιχη θερμοκρασία και κατά συνέπεια οι συναγερμοί. Η θέση με τους λιγότερους συναγερμούς ήταν η εκείνη που ο νεφελοποιητής βρισκόταν σε απόσταση από τους ανιχνευτές θερμοκρασίας, η οποία στην συγκεκριμένη περίπτωση ήταν η έξοδος του αναπνευστήρα.

Λέξεις Κλειδιά

Αναπνευστήρας, νεφελοποιητής, υγραντήρας, συναγερμοί, υδρατμοί, μονάδα εντατικής θεραπείας

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1.0 Introduction

Hospital patient safety is commonly understood to be compromised by alarm fatigue. Alarms are one of the most significant technology concerns that have for years posed a threat to patient safety. Data from research conducted nationally by the American Healthcare Technology Foundation in 2006, 2011, and 2016 with significant participation revealed that the issue worsens gradually over time. The frequency of harmful incidents related to patient safety associated with clinical alarms was 18 % in 2011 and 30 % in 2016, and it was discovered that a significant proportion of healthcare workers were unaware of this.

Invasive care units and operating rooms are specialist wards providing intensive care, treatment and monitoring, for people who are in a critically ill or unstable condition. Patients are connected to and surrounded by several medical devices. These devices emit various alerts depending on the condition of the patient, the equipment, or both. Alarms signals are triggered by both clinical and non-clinical factors. The frequency of false alarms produced by medical equipment is an important factor in the rising noise levels in these settings. Many studies indicate that the increasing number of medical device alarms has created an unsafe, noisy, and annoying environment.

False alarms may be categorized into three different groups: clinical, technological, and intervention related. When a physiological signal surpasses a specific threshold but is not clinically important, it is referred to as a clinical false alarm. This means that the change in condition of a patient may not be accurately reflected by the physiologic monitor's default alert setting. Determining the causes of false alarms and systematically addressing these causes can have a positive effect on patient safety. For the past 6 years, clinical alarms have been included on the ECRI Institute list of the top 10 health technology hazards. ECRI (originally founded as Emergency Care Research Institute) is a global, independent authority on healthcare technology and safety. For 2020, the ECRI Institute listed an alarm-related hazard among their Top 10 Health Technology Hazards.

For patients who experience severe respiratory failure, mechanical ventilation is one of the most effective treatment options. During mechanical ventilation, the anatomy that provides natural conditioning is bypassed by using dry, piped gas instead of ambient

air to ventilate the lungs and the vital function of natural humidification can be compromised. Dry gas has a negative impact on the respiratory tract in intubated patients, destroying the epithelium and making secretions more viscous, making the germs stay in our lungs which can lead to lung infections. Active humidification systems including heated humidifiers are essential to the normal defense mechanisms of the airway. By the time inspired gas reaches the alveolar surface, it must be at body temperature to allow gas exchange and protect lung tissue. Most specifically a maximum delivered gas temperature between 37°C and 41°C at the circuit Y-piece is recommended. It is important that the temperature is not above 41 because it could lead to thermal injury. Heated humidifiers are prone to “rainout” effect, namely the a formation of water in the tubing of the breathing circuits' lowest points. This effect can also occur while using a nebulizer. Nebulizers create a cool mist that is supplied sporadically, as opposed to humidification, which continuously delivers warm water vapor to prevent harm to the tracheobronchial tree's airway lining. The rainout effect causes alarms during the use of a humidifier and a nebulizer.

This study evaluated temperature alarms under different pressure rates and in 3 different nebulizer circuit positions. Chapter 2 gives a brief description of the respiratory system and related biomedical technology. Materials and methods used in this study are described in Chapter 3. Chapter 4 presents the results and Chapter 5 the conclusions.

2.0 Background and Significance

In this chapter, a brief overview of the respiratory system and the aspects of mechanical ventilation will be given.

2.1 The respiratory system

Our body's respiratory system—a group of organs and tissues—allows us to breathe, and it includes the airways, the lungs as well as the blood vessels and muscles attached to them. The respiratory system does two very significant things. First, it brings oxygen into our body and secondly it allows us to exhale carbon dioxide from our body. Additionally, it has the nose and nasal cavity, which serve a variety of purposes, such as warming and hydrating the air we breathe (see Figure 1). The throat, also known as the pharynx, is a tube that carries air from the nasal cavity via the larynx and down the trachea. (Tu, Inthavong & Ahmadi, 2013)

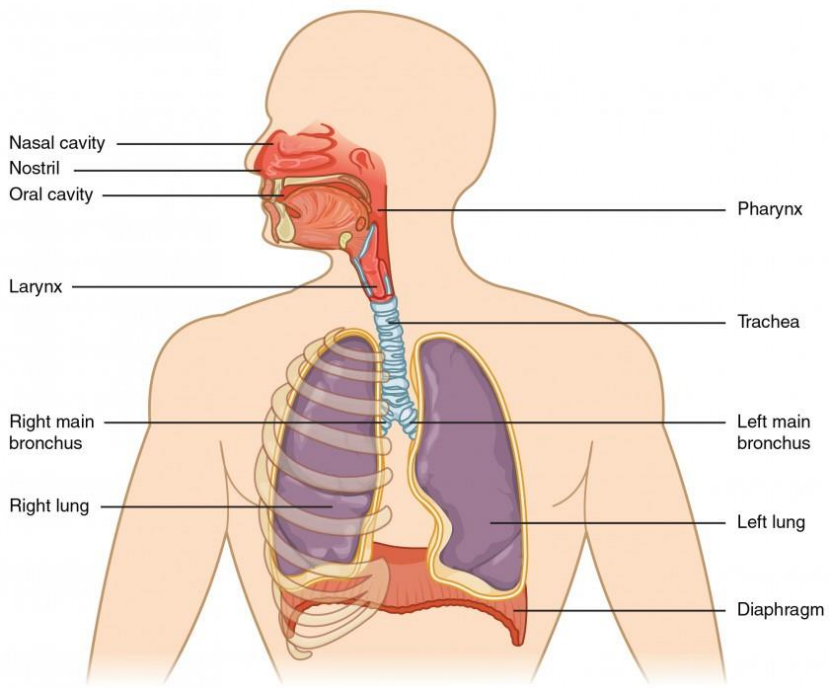

Figure 1. The major respiratory structures span the nasal cavity to the diaphragm.

2.1.1 How breathing works

The lungs' anatomy makes them ideally suited to the effective transfer of gases from the atmosphere into the blood and vice versa. Air from outside the body enters the bronchial tree and alveolar gaps during breathing, also known as ventilation, and subsequently exits the body in the opposite direction. The motions that cause this movement of air are known as inspiration or inhalation and expiration or exhalation. When a person inhales, the air travels down to the end of the breathing tubes, where enters the tiny air sacs. This process is called inhalation.

2.1.2 Mucus transport system

Humidity is critical to human respiratory health and wellbeing. To function correctly and maintain good health, our lungs require warm, humid air. Naturally, when it travels through our mouth and nose, some of this warmth and moisture is added. Our airways spontaneously adjust inhaled air to a level of humidity and temperature that supports physiological equilibrium. When this natural balance is disrupted the the lungs' ability to function properly is inhibited. Maintaining this physiological harmony is vital to a patient’s outcome. The human lung's conducting airways are mostly coated by a thin liquid layer of mucus. This thin liquid is a viscoelastic secretion that protects the underlying mucosa from drying and at the same time it retains cellular debris and xenobiotic material that comes into touch with it. Our respiratory defense system includes the mucociliary clearing process. Foreign objects and germs are removed from the airways by the mucus transport system. Even in the most pristine environment the air that we breath in is not clean and pure. We inhale everyday thousands of parts of dust, smoke, and virus particles. The mucus that lines the airways is sticky and traps foreign particles. then carries the trap material into the larynx in a process known as mucociliary clearance and it fails when the mucus dries out. During mechanical ventilation, the anatomy that provides this natural conditioning is bypassed by using dry, piped gas instead of ambient air to ventilate the lungs and the vital function of natural humidification can be compromised. (Michael Foster, 2002)

Compilations of dry air

- Failure to humidify inspired gas

- Drying and cracking of epithelium
- Failure of mucociliary transport system
- Inspissation of secretions
- Respiratory infection
- Obstruction and cracking of the tube

2.2 Mechanical ventilation

Ventilation is used to offer breathing assistance to individuals whose lungs have been considerably impaired owing to infection (pneumonia), or other factors that have resulted in severe respiratory issues. Patients with acute respiratory distress syndrome (ARDS), including those with COVID-19, must almost always be placed on mechanical ventilators. They are typically used in emergency rooms, critical care units, home care, and as a part of general anesthesia equipment. Essentially, the ventilator assists in the mechanical pumping of oxygen into your body. Oxygen treatment combined with mechanical breathing is intended to help patients maintain an appropriate oxygen saturation (>88%) in their arterial blood. The ventilator employs positive pressure to deliver oxygen into the lungs via the inner channels and totally manage the patients' breathing process. Medical ventilation is basically of two types: a) invasive mechanical ventilation and b) non-invasive ventilation. (Lei, 2017)

Emergency tracheal intubation, which involves inserting an endotracheal tube (ETT) or a tracheostomy tube into the trachea, is necessary in cases of respiratory failure. Since the development of the first positive pressure ventilators in the 1940s and the usage of iron lung negative pressure ventilators during the polio outbreak, invasive ventilation has undergone a major evolution. While reducing breathing effort, invasive ventilation helps transport gases into and out of the patient's lungs. The first noninvasive ventilation methods first began to be used in the late 1980s, in patients with acute respiratory failure as a possible substitute to endotracheal intubation. Non-invasive mechanical breathing is being used more frequently to avoid or support intubation. and this technique is mostly used to treat chronic obstructive pulmonary disease (COPD) exacerbations and cardiogenic pulmonary oedema. In certain patients with acute respiratory failure, it raises survival rates and lowers morbidity and it delivers the same physiological

benefits of reduced effort of breathing and enhanced gas exchange, when compared to invasive mechanical ventilation. (Nava & Hill, 2009)

Non-invasive positive pressure ventilation (NIPPV) is a breathing treatment. It uses a portable positive pressure ventilator linked by tubing to an interface that provides airflow into the nose and/or mouth. The NIPPV system provides intermittent positive airway pressure, which actively aids ventilation. The big advantage of the non-invasive ventilation will be to avoid the procedure of intubation. In that case the patient does not need to be sedated, so the patient can be awake, can eat, drink and most importantly communicate.

2.3 Humidification

During mechanical ventilation, the anatomy that provides natural conditioning is bypassed by using dry, piped gas instead of ambient air to ventilate the lungs and the vital function of natural humidification can be compromised. Dry gas has a negative impact on the respiratory tract in intubated patients, destroying the epithelium and making secretions more viscous, making the germs stay in our lungs which can lead to lung infections. Mixing additional oxygen into the air can cool and dry the breathed air even more. Humidification of inspired air is essential to the normal defense mechanisms of the airway. For therapeutic application, a variety of humidifier types have been developed to reduce these challenges. A humidifier adds the missing warmth and moisture to the air and oxygen for people on respiratory support. The upper airway is responsible for 75% of the heat and moisture delivered to the alveoli thus the humidifier needs to supply this missing heat and moisture. It also assists the movement of mucus to clear the airways of contaminants. (Anon, 2016)

Warming and humidifying gasses provided to mechanically ventilated patients are currently accessible through two methods. Two different humidification methods are the active humidification and the passive humidification. In this study we focused on the use of active humidification which includes an inserted device that produces humidity by exposing the inspiration gas to a reservoir of sterile water. These devices are called heated humidifiers and they are based on the method of “flow by”. By the “flow by” method it means that the airflow passes over a bath of heated sterile water, picking up moisture and warmth as it goes of a thin permeable absorbent material

(wick), which increases the efficiency of the humidifier. Heated humidifiers work actively to raise the temperature and water vapor concentration of the inspired gas. (Restrepo & Walsh, 2012). When providing active humidification to patients who are invasively ventilated, it is suggested that the device provide a gas temperature between 34°C and 41°C with a RH of 100% to keep secretions in the artificial airway from drying out. Utilizing a humidifier and nebulizer simultaneously will result in condensation and the creation of droplets, during low temperature. This is what describes best the "rainout" effect.

2.3.1 Humidification alarms

Most humidifiers have various alarms that indicate malfunction or erroneous performance of the system. The MR850 humidifier used in this study includes alarms for malfunction of connectors, airflow issues, and other as shown in Figure 2. To have continuous temperature monitoring, the humidifier has a temperature indicator that can monitor the temperature at the chamber and at the airway temperature.

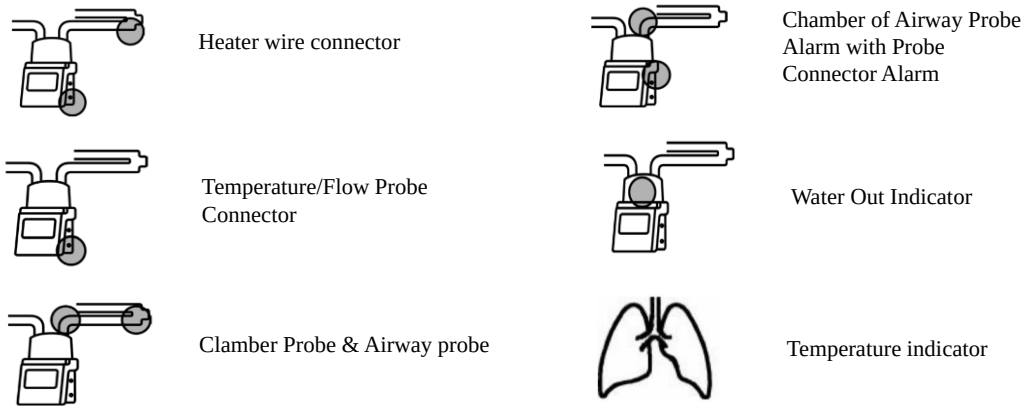

Figure 2. List of alarms of a MR850 humidifier

In this study we focused on the temperature indicator, which warns if the gas temperature exceeds or drops below a predetermined performance threshold. In situations where the temperature variation from the desired temperature is significant, for example during "rainout" effect, it warns us by triggering an alarm (diagram shown in Figure 3). In this study we are going to focus on the low temperature warning. The low temperature warning (visual only) and alarm (visual and audible) are both disabled during warm-up conditions. The temperature monitor shows the patient's saturated gas

temperature, which is the lower of the patient's airway or chamber outlet in °C. This display will normally show the Chamber Outlet temperature. The Chamber Outlet temperature and subsequently the airway temperature are shown by pressing and holding the Mute Button for 1 second. The display will then revert to normal operation. The alarm notifies the user that a low temperature air is being delivered to the patient. It indicates that the temperature on display remains below a certain performance threshold for a set period. The temperature indicator will turn on if the reading remains below 35.5 °C for 25 seconds. If the temperature remains below this level for too long, then the temperature alarm is activated. The time taken for the humidifier to alarm is based on temperature deviation under 35.5 °C, the greater the deviation the sooner the alarm.

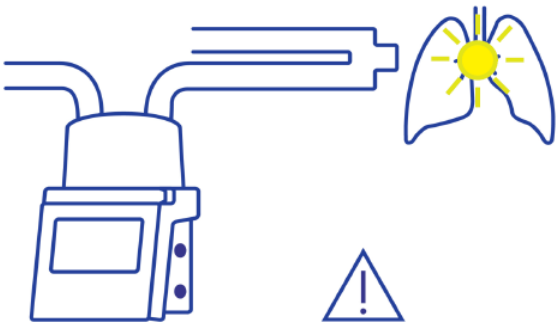

Figure 3. Indicator of temperature alarm as it is defined by the manufacturer.

2.4 Nebulization

Patients on mechanical ventilation who are intubated get several drugs via nebulizers in the form of aerosols. A nebulizer is a device that converts liquid drugs into mist as microscopic droplets that can be breathed into the lower respiratory tracts of ventilator-dependent patients, to treat pulmonary and systemic disorders. The inspiratory gas carries medicine particles to the patient's respiratory system and lungs during inspiration. The most widely used medical equipment is the mesh nebulizer. Mesh nebulizers have been the primary choice for developing novel nebulized medicinal drugs.

The active vibrating mesh technology, which is shown in Figure 4, where energy applied to the vibrational element (PZT actuator), causes vibration of each of the 1000 funnel shaped apertures within the mesh. The central plate is just 5mm in diameter. The mesh functions as a micropump pushing liquid through the pores, producing that way droplets 1-5microns in diameter, and generating a low velocity aerosol optimized for targeted medicine administration to the lungs. Rayleigh theory predicts that the droplet will be about twice as big as the mesh hole. The vibrating mesh nebulizers are assembled with the metallic holder and piezoelectric (PZT) ring actuator. The holes in the mesh are conical in form, with the largest cross-section of the cone coming into contact with the liquid medicine. When the mesh is in use, the liquid comes into touch with its upper surface, which is driven into vibration by the laterally vibrating PZT actuator. Piezo element causes the mesh to vibrate, which pushes liquid drug through the mesh. The liquid then exits the mesh as droplets, creating the aerosol, with a theoretically 100% respirable aerosol content. (Olszewski et al., 2016)

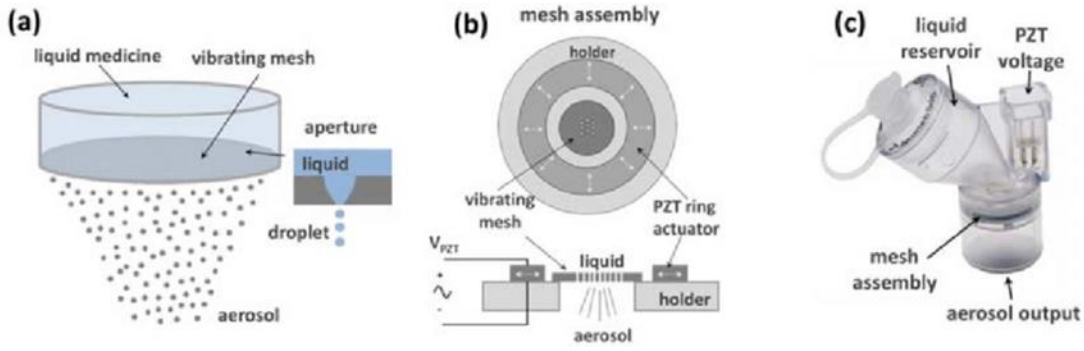

Figure 4. (a) Technology used in vibrating mesh nebulizers, (b) Mesh assembly diagram, showing mesh, holder, and PZT actuator and (c) currently accessible vibrating mesh nebulizer from Aerogen Ltd.

For patients who experience severe respiratory failure, mechanical ventilation is one of the most effective treatment options. Most devices operate by forcing ambient dry air into the lungs until a predetermined airway pressure is achieved. Dry gas has a negative impact on the respiratory tract in intubated patients, destroying the epithelium and making secretions more viscous. Humidification of inspired air is essential to the

normal defense mechanisms of the airway. During mechanical ventilation many medications are administered as aerosols via nebulizers. In contrast to humidification, which continuously delivers warm water vapor to protect the tracheobronchial tree's airway lining, nebulization only creates cold mist that is delivered on demand. (Aung et al., 2019)

3.0 Materials and Methods

This study was conducted at the Mater Misericordiae University Hospital which is based in Dublin's north inner city. The Mater Hospital is a level 4 teaching hospital that offers a variety of primary and specialized services on a local, state, and federal level. The hospital was founded by the Sisters of Mercy in 1852 and it opened in 1861. The hospital offers:

- 719 beds - 150 of these are inpatient beds are single ensuite rooms
- 206-day beds
- 16 Operating Theatres (12 Main & 2 Minor Theatres & 2 Theatres Awaiting Funding) and is the national center for:
- Heart surgery
- Heart and lung transplants
- Extra corporeal life support (ECLS) - a procedure that uses a machine to take over the work of the lungs and sometimes the heart
- Spinal injuries
- Pulmonary hypertension - a rare lung disorder
- Bone anchored hearing aid
- National isolation unit

Mater hospital also has a clinical engineering department that consists of the chief of the department, three senior members and two junior members. This study was conducted during an internship period that was extremely educational and productive. The topic of the study was proposed by the chief of the department as it was an issue that was of interest to the engineers and the clinical staff. The experiment was carried out in its entirety in the clinical engineering section of the hospital, which was equipped with all the tools necessary for the measurements and tests on the ventilator.

The study was performed with a NIPPV3+. NIPPV 3+ is a pressure controlled positive pressure ventilator. It is manufactured by Breas Medical, and is supplied and supported

in Ireland and Northern Ireland by RespiCare. This device operates by forcing air into the lungs until a predetermined airway pressure is achieved. It takes ambient air through a filter at the rear of the device and then that air is delivered through the outlet at the front where the breathing tube is attached. The NIPPV 3+ is intended for use by individuals who require respiratory support via a mask or other interface. Respiratory parameters were as follows: and IPAP (Inspiratory Positive Airway Pressure) rises per 5 cm H2O.

The inspired gas was warmed and humidified utilizing a standard heated humidifier model (MR850 Fisher & Paykel, Auckland, New Zealand). For the purpose of nebulization we used a model of piezoelectric nebulizer (Aeroneb Pro,Aerogen). The Aeroneb Pro nebulizer, In 2015, Aerogen Ltd. reintroduced and began selling the 2002-introduced Aeroneb Pro nebulizer as the Aeroneb Solo nebulizer type. The Aerogen Pro and Aerogen Solo mesh nebulizers have emerged as the preferred delivery methods for use with both invasive and noninvasive ventilators. The main medical devices that we used during the trials are shown in Figure 5-7. For the tests, the circuit's inspiratory limb was connected to the HH output and the patient end was connected to the test lung for the testing. Mono-heated wire circuit was attached to the mechanical ventilator and humidifier circuit in which only the inspiratory limb is heated by a wire. Each circuit was evaluated at 8 IPAP (Inspiratory Positive Airway Pressure) different pressures (5, 10, 15, 20, 25, 30, 35 and 38 cmH2O). For all tests, Expiratory Positive Airway Pressure stable at 5cm H2O and fraction of inspired oxygen (FiO2) to 40%. The ventilators were used in volume targeted assist control mod.

Figure 5. A NiPPV ventilator from RespiCare

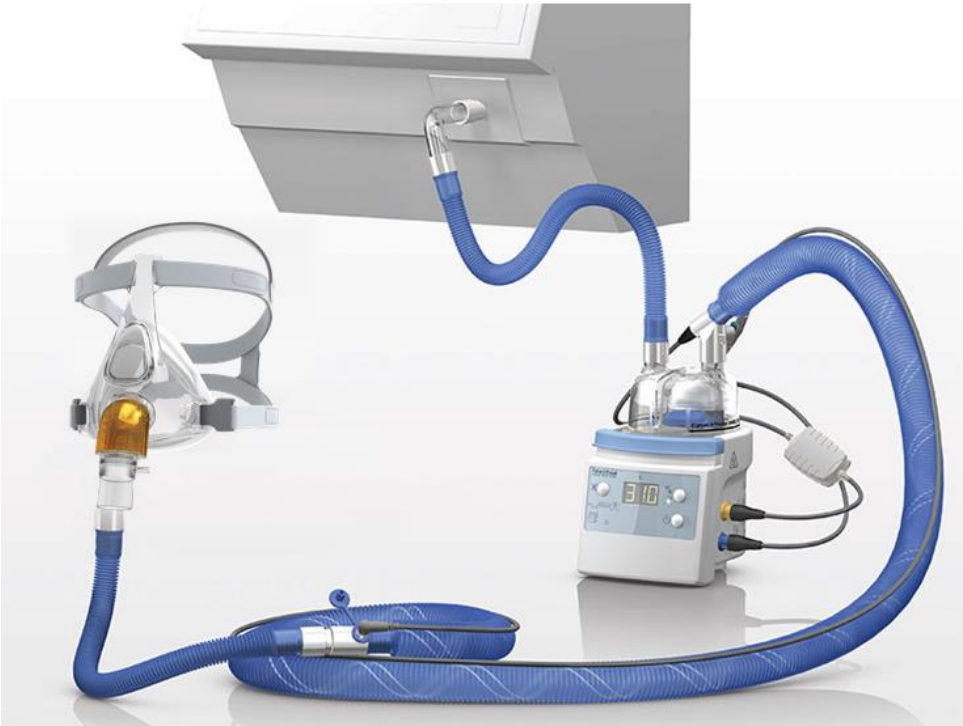

Figure 6. MR850 humidifier by Fisher & Paykel

Figure 7. Mesh nebulizer from Aerogen Ltd.

As per the guidelines provided by the manufacturer, the inspiratory limb of the ventilator circuit should be lined up with the Aerogen Solo, before the patient Y-piece. The nebulizer may also be installed at the dry port (inlet) of the humidifier as presented in Figure 8.

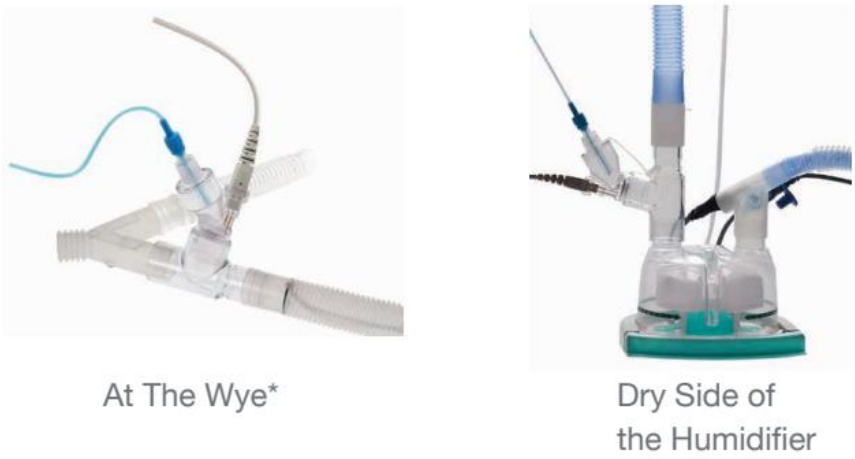

Figure 8. Position of Aerogen Solo as they recommended from the manufacturer.

In this project the vibrating-mesh nebulizer was tested in 3 ventilator circuit positions, that are shown in Figure 9:

Position A: At the dry side of the humidifier as suggested by the manufacturer.
Position B: Between the Y- piece and the circuit.
Position C: At the ventilator outlet.

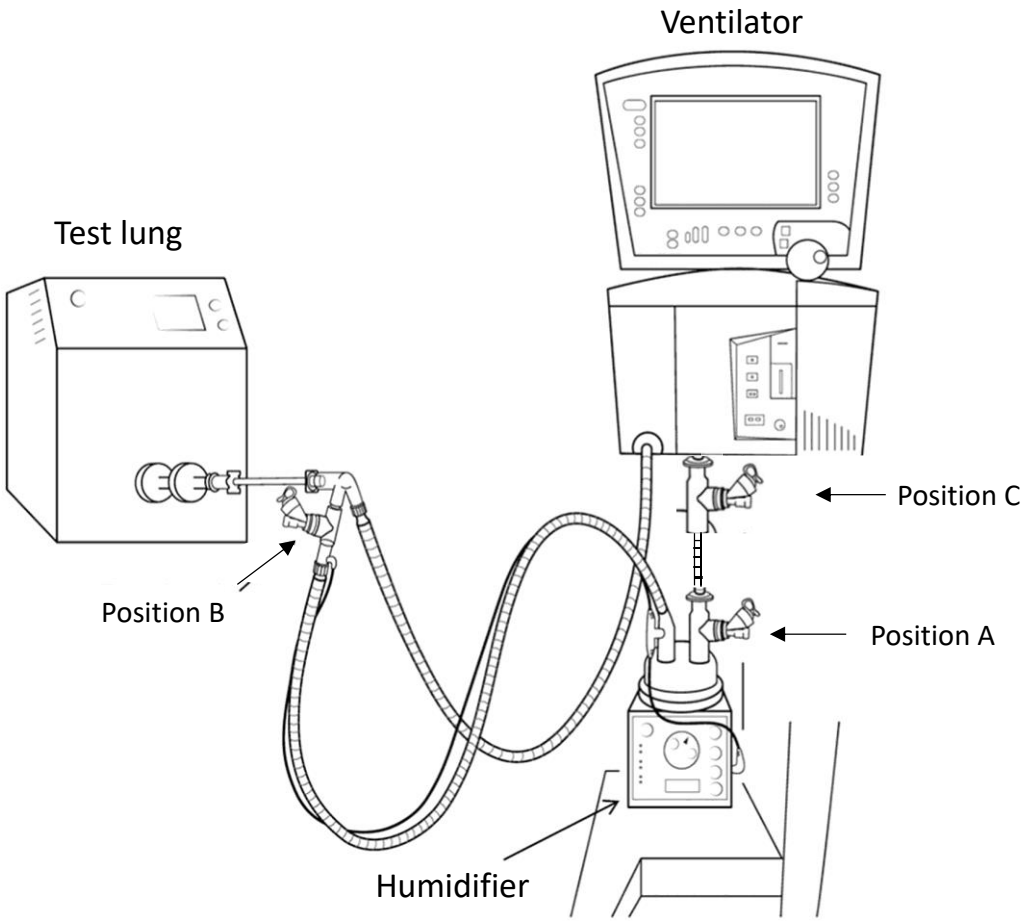

Figure 9. Schematic diagram of the breathing circuit

Temperature was measured in 2 set ups:

1. With the nebulizer on but inactivated, termed as nebulizer off.
2. With the nebulizer activated

A steady room temperature was used for the measurements at 21°C, during a period of 36 days. Data were collected manually and recorded in an EXCEL spreadsheet. Breathing systems were maintained horizontal always to prevent limb leakage into the test lung during expiration. The endotracheal tube's natural curvature was preserved to retain a clinical viewpoint. The nebulizer was run continuously until it no longer produced aerosol.

4.0 Results

An analysis of the temperatures of each nebulizer position as a function of pressure is presented in Figures 10-15 for the various combinations of positions and setups. Placing the nebulizer at position C triggered significantly fewer alarms compared to position A and position B. Of the total alarms triggered during the study, some were unrelated to the heating units. Mainly, 3 alarms were seen at position A, 4 alarms at position B and finally 3 at position C. At position A and C alarms occurred at 35-31 °C and at position B occurred at 37-35 °C.

Alarms by nebulizer's mode

During the trials no alarms occurred when the nebulizer was at the OFF position. Hence, it was concluded that the nebulizer's activation causes the rainout phenomenon. As presented in Figures 10, 12, and 14, while the pressure was rising, the airway and chamber temperatures at every set up were slowly decreasing without exceeding the predetermined threshold. Figure 10 depicts a strange decrease in airway temperature at a pressure of 16 cm H_2O. This may be due to a small cooling effect inside the heated tube. Usually, fluctuations typically result from system adjustments, or the presence of a water drop close to the temperature probe, which cause the temperature to decrease for a few seconds.

Effect of Position

Position A: Placing the nebulizer at the dry side of the humidifier caused the activation of alarms because of the low chamber temperature. As presented in Figure 11 for position A, but also in Figures 13 and 15 for positions B and C respectively, alarms occurred for a pressure greater that 25 cmH_2O and continued to occur until the end of trials. It is important to mention that IPAP should not exceed 20 cmH_2O. The system had difficulties to adjust the temperature in pressures higher than 20 cmH_2O because it is not made for those levels of pressure. This level of support should be considered when intubation is required.

Position B: Placing the nebulizer near the patient's airway caused the activation of alarms because of the low airway temperature. Figure 13 confirms that there were no significant variations in the chamber temperature. We can also detect a slight rise in temperature within the chamber, indicating that the humidifier's heated plate has sufficient time to heat up and maintain the desired temperature. The temperature dropped higher when the nebulizer was close to the airway temperature probe, to 35,5 °C, making it more challenging for the humidifiers to reach the normal temperature.

Position C: The placement of the mesh nebulizer proximal to the ventilator (position C) requires the aerosol to pass down the 2-m inspiratory-limb tubing, achieved the greatest efficiency. Compared to positions A and B, we experienced the same number of alerts, but the system was more effective at heating up and bringing the temperatures back to normal.

Figures 10-15 present the variations of temperature as a function of IPAP. Figures also include inserts, which show the magnitude of temperature drop at the points where alarms were initiated, and the lowest temperature observed at each pressure. In Figure 13, we notice that the temperatures at pressure 35 and 38 cmH_2O did not deviate significantly from the threshold. For this reason, the drop in temperature is not discernible.

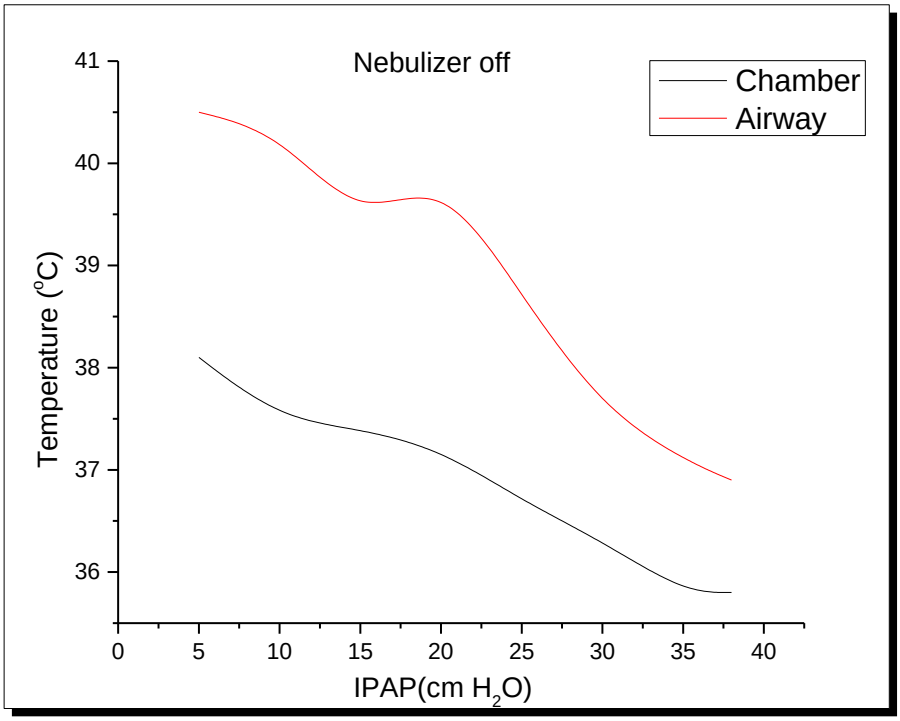

Figure 10. Temperature as a function of IPAP at the chamber (black line) and the airway (red line) when the nebulizer is off at position A.

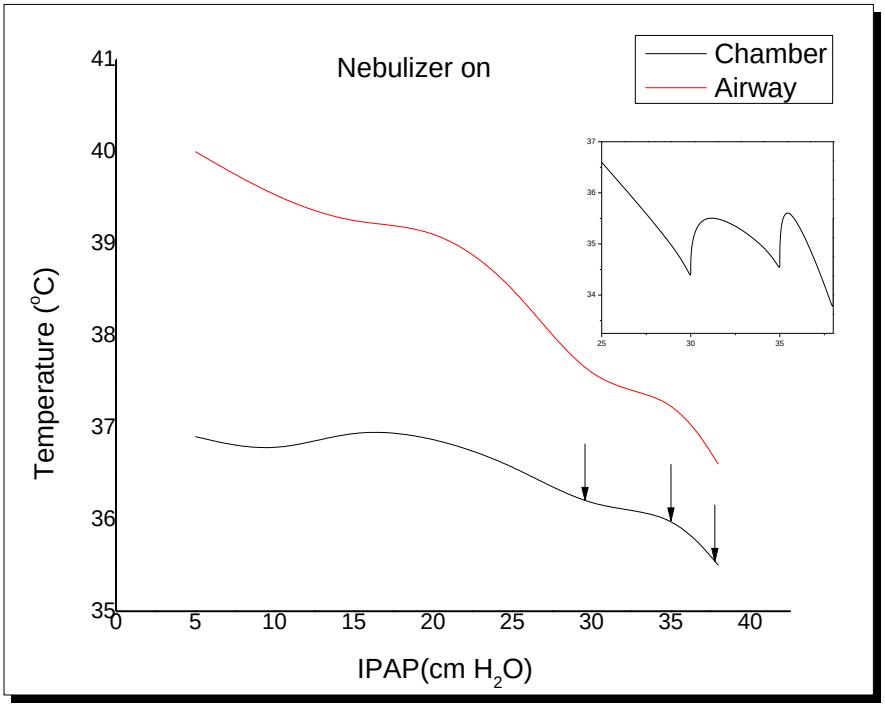

Figure 11. Temperature as a function of IPAP at the chamber (black line) and the airway (red line) when the nebulizer is on at position A. The arrows indicate four pressure points where alarms were observed due to temperature change. The insert shows the magnitude of temperature drop at the corresponding points that caused the alarms.

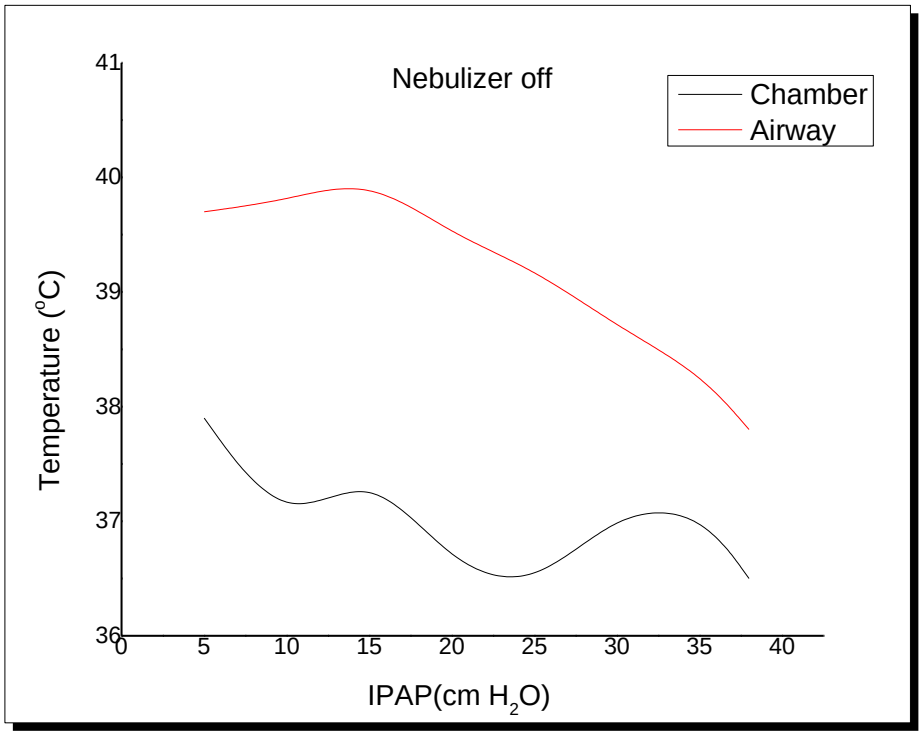

Figure 12. Temperature as a function of IPAP at the chamber (black line) and the airway (red line) when the nebulizer is off at position B.

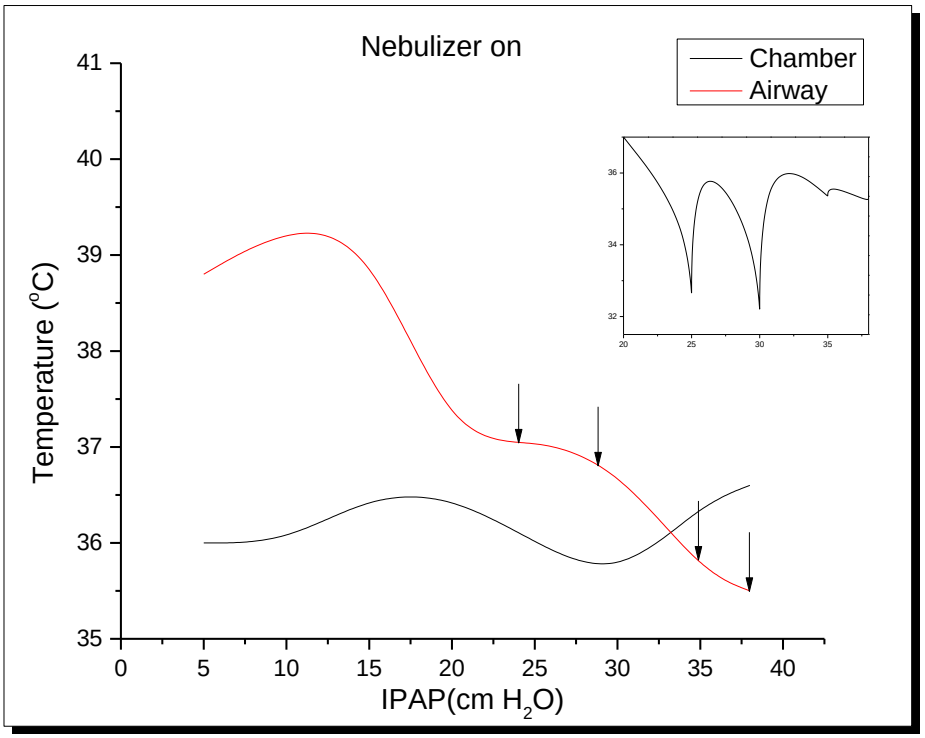

Figure 13. Temperature as a function of IPAP at the chamber (black line) and the airway (red line) when the nebulizer is on at position B. The arrows indicate four pressure points where

alarms were observed due to temperature change. The insert shows the magnitude of temperature drop at the corresponding points that caused the alarms.

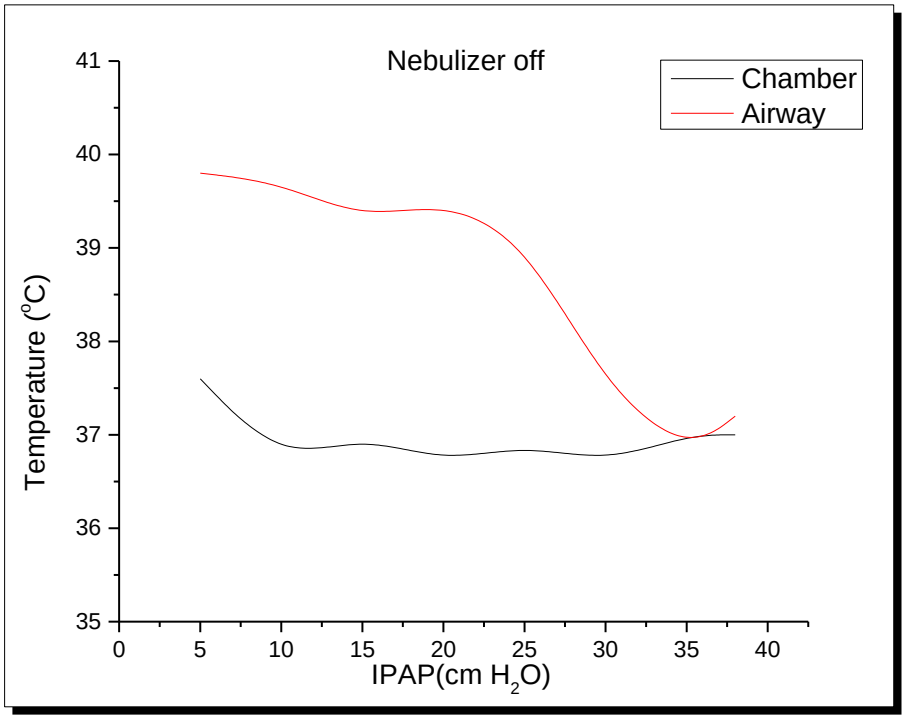

Figure 14. Temperature as a function of IPAP at the chamber (black line) and the airway (red line) when the nebulizer is off at position C.

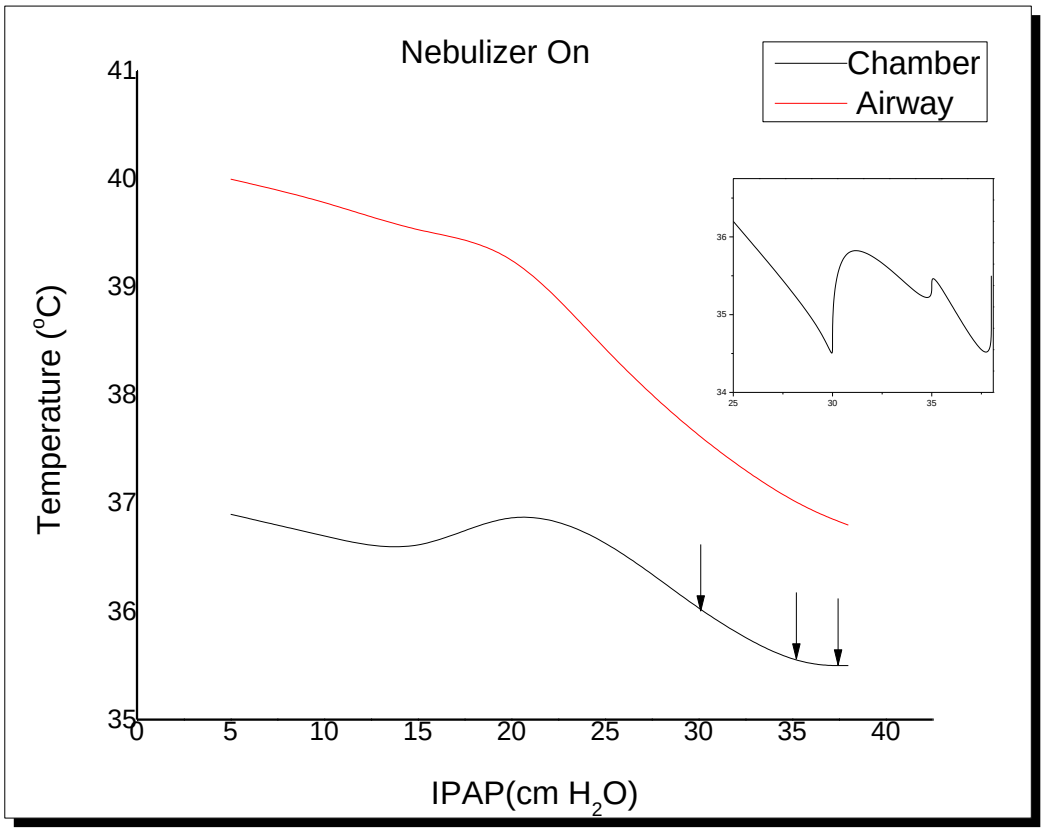

Figure 15. Temperature as a function of IPAP at the chamber (black line) and the airway (red line) when the nebulizer is on at position C. The arrows indicate four pressure points where alarms were observed due to temperature change. The insert shows the magnitude of temperature drop at the corresponding points that caused the alarms.

As presented by the previous graphs, temperature depends on the placement of the nebulizer device. According to the final measurement output, although position A did influence the chamber's temperature, it was not able to influence the airway temperature and, therefore, the patient would have received the appropriate temperature that is required without being in danger. When the nebulizer is placed near the Y piece (position B) the exact opposite occurs, and the airway temperature drops by a larger extent than in any other test. The most important finding is that at position B the alarm lasts for the same amount of time as the nebulization. This is caused mainly because the placement of the nebulizer is near the Y-piece and so the air does not have the time to heat up as it travels inside the tube, meaning that during the nebulization the temperature remains low. When a mesh nebulizer is placed at the humidifier output, cold gas is introduced, lowering the temperature at the thermistor and potentially setting

off alarms. The probability of alarms is decreased by placing the nebulizer at the humidifier's input, which permits gas and aerosol to be warmed before leaving the humidifier.

5.0 Conclusions

To the best of our knowledge, this is the first study that addresses the issue of rainout effect and related alarms during the use of nebulizers in the ventilators. It is important to define techniques that minimize the appearance of the alarms in mechanically ventilated patients and, hence, determine optimum application of the ventilator and its components.

Our results showed that the placement of the mesh nebulizer proximal to the ventilator (position 3) achieved the greatest efficiency, but this is not in agreement with the manufacturer's recommendation. Placement of the nebulizer at the humidifier's input enables gas and aerosol to be warmed before exiting the humidifier, which reduces the possibility of alarms. A different number of alarms was recorded at the three different positions. This may be due to the distance of the nebulizer from the temperature probes. This also explains the fact that the number of alarms were lower in position C than the other two positions. As we mentioned above the humidifier has a temperature indicator that can monitor the temperature at the chamber and at the airway temperature which relates to two temperature probes. When the placement of the nebulizer is near the probes, the cold air from the nebulizer does not seem to have the time to heat up and the humidifier is unable to stabilize the temperature.

As mentioned earlier, our results differ from the manufacturer's recommendation. This may be explained by the fact that the tested humidifier was in the clinical engineering workshop and not in a clinical setting. The humidifier was also an older model with unknown number of hours of usage and a new model may yield different results. Further study in a clinical setting with continuous monitoring during active ventilation could provide a better understanding of our result and clarify the discrepancy. It should also be noted that during normal clinical use, pressures higher than 20 cmH_2O should be considered when intubation is required. In our testing, pressure was raised every time the temperature was at a stable level, and this does not reflect the real use of the breathing circuit. In addition, there was just one set of settings used to run the ventilator, without any changes commonly used in ventilators. Other limitations include the removal of the nebulizer every time a set of measurements was completed while the

humidifier was running. Because this study was primarily designed to measure alarms, we did not interrupt testing to drain off condensation or to correct pressure errors.

Placement of the nebulizer in the ventilator circuit affects aerosol drug delivery during mechanical ventilation. Many factors influence the efficiency of aerosol delivery to the lower respiratory tract in mechanically ventilated patients, including the presence of humidity and the position of the nebulizer. Hence, it is of paramount importance to clarify this issue with further research that will also determine the setup for optimum performance of a nebulizer.

References

Anon (2016) *Humidification of inspired gases during mechanical ventilation*. https://www.researchgate.net/publication/221770662.

Anon (n.d.) *System Instruction Manual Aerogen ® Solo System Instruction Manual*. www.aerogen.comwww.aerogen.com.

Aung, H.H., Sivakumar, A., Gholami, S.K., Venkateswaran, S.P., Gorain, B. & Shadab (2019) An Overview of the Anatomy and Physiology of the Lung. In: *Nanotechnology-Based Targeted Drug Delivery Systems for Lung Cancer*. Elsevier. pp. 1–20. doi:10.1016/b978-0-12-815720-6.00001-0.

Lei, Y. (2017) *Medical Ventilator System Basics: A clinical guide*. Oxford University Press. doi:10.1093/med/9780198784975.001.0001.

Michael Foster, W. (2002) Mucociliary transport and cough in humans. In: *Pulmonary Pharmacology and Therapeutics*. 2002 Academic Press. pp. 277–282. doi:10.1006/pupt.2002.0351.

Nava, S. & Hill, N. (2009) Non-invasive ventilation in acute respiratory failure. *The Lancet*.374 (9685) pp.250–259. doi:10.1016/S0140-6736(09)60496-7.

Olszewski, O.Z., Macloughlin, R., Blake, A., O'Neill, M., Mathewson, A. & Jackson, N. (2016) A Silicon-based MEMS Vibrating Mesh Nebulizer for Inhaled Drug Delivery. In: *Procedia Engineering*. 2016 Elsevier Ltd. pp. 1521–1524. doi:10.1016/j.proeng.2016.11.451.

Restrepo, R.D. & Walsh, B.K. (2012) Humidification during invasive and noninvasive mechanical ventilation: 2012. *Respiratory Care*. 57 (5), 782–788. doi:10.4187/respcare.01766.

Tu, J., Inthavong, K. & Ahmadi, G. (2013) *The Human Respiratory System*. In: pp. 19–44. doi:10.1007/978-94-007-4488-2_2.