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Does Increasing Flow to a High Flow Nasal Cannula Affect Mean Airway Pressure in an In Vitro Model?

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DOES INCREASING FLOW TO A HIGH FLOW NASAL CANNULA AFFECT

MEAN AIRWAY PRESSURE IN AN IN VITRO ADULT MODEL?

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Abstract

DOES INCREASING FLOW TO A HIGH FLOW NASAL CANNULA AFFECT MEAN AIRWAY PRESSURE IN AN IN VITRO MODEL?

Introduction: High-flow nasal cannulas (HFNC) have become popular with many institutions for administration of oxygen (O_2). HFNCs are also being used in pediatric and neonatal populations for administration of continuous positive airway pressure (CPAP) as a treatment for respiratory distress. Adult patients are being treated with HFNCs in a effort to provide a high percentage of O_2 and correct hypoxemia and other related conditions. The purpose of this study was to examine the effect of increasing flow via a HFNC to an in vitro model to examine the effect of flow on mean airway pressure (M_{PAW}).

Method: An in vitro model to simulate non-labored and labored spontaneous breathing was developed using a Michigan Instrument Laboratory Test and Training Lung (MIL TTL) driven by a Hamilton Galileo ventilator to produce a negatively based, inspired tidal volume. Flow was introduced to the MIL TTL via a 41 French double lumen endotracheal tube. Airway pressure measurements were observed via a pressure monitoring port placed between the MIL TTL and the endotracheal tube and connected to the auxiliary pressure monitoring port located on the front of the Galileo ventilator. A Vapotherm 2000i with adult transfer chamber and adult cannula, a Fisher Paykel Optiflow, and a generic HFNC consisting of a concha column and a Salter labs high-flow cannula were tested at 20, 30, and 40LPM flowrates. Data was recorded using two respiratory rates (12 and 24) and two peak flowrates (35 and 65LPM) to simulate non-labored and labored breathing. All other parameters were unchanged and the I:E ratio was consistent.

Data Analysis: SPSS 16.0 for Windows was used to analyze all data for this study. Descriptive statistics, one-way analysis of variance (ANOVA), and post hoc Bonferroni was used for this study. A p value less than 0.05 were considered significant.

Results: Average M_{PAW} for all devices were increased at all three flowrates. M_{PAW} was highest at 40LPM flow producing 3.1cmH_2O averaged for all HFNCs and both respiratory patterns. The difference in M_{PAW} produced by the three HFNCs were also significant with at p=0.000 at all flow rates. Post hoc Bonferroni adjusted probabilities further showed all device comparisons significant except for Vapotherm-Vapotherm Labored at 30 and 40 LPM flow rates and Vapotherm-Generic Labored at 20 LPM at p<0.05. These three comparisons were at p>0.05 and were statistically equal. The generic HFNC produced the highest M_{PAW} (3.5cmH_2O).

Conclusion: Increased flow via a HFNC does increase M_{PAW}. The Vapotherm, Optiflow, and generic HFNC did not produce the same level of M_{PAW} in this study.

DOES INCREASING FLOW TO A HIGH FLOW NASAL CANNULA AFFECT MEAN AIRWAY PRESSURE IN AN IN VITRO ADULT MODEL?

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Abbreviations

ACPE	Acute CardioPulmonary Edema
ARDS	Adult Respiratory Distress Syndrome
BiPAP	Bi-level Positive Airway Pressure
CHF	Congestive Heart Failure
COPD	Chronic Obstructive Pulmonary Disease
FiO_2	Fraction of Inspired Oxygen
HAI	Hospital Acquired Infection
HFNC	High Flow Nasal Cannula
HFT	High Flow Therapy
LFT	Low Flow Therapy
LOS	Length of Stay
LPM	Liters Per Minute
mgH_2O/L	Milligrams of Water per Liter
MI	Myocardial Infarction
MIL	Michigan Instrument Labs
M_{PAW}	Mean Airway Pressure
NiPPV	Noninvasive Positive Pressure Ventilation
NIV	Noninvasive Ventilation
O_2	Oxygen
PACU	Post Anesthesia Care Unit
PaO_2	Partial Pressure of Arterial Oxygen
PEEP	Positive End Expiratory Pressure
PIP	Peak Inspiratory Pressure
P_{MIN}	Minimum Pressure
PPV	Positive Pressure Ventilation
RTs	Respiratory Therapists

T_E	Expiratory time
T_I	Inspiratory Time
TTL	Training and Test Lung
T_{tot}	Total Cycle Time

Chapter I

Introduction

Oxygen (O_2) therapy is a simple task taught in the first days of respiratory therapy education. The importance of O_2 therapy is often overlooked by respiratory therapists (RTs) who focus on other technical procedures. The indications for use are dictated by signs and symptoms directly observed by caregivers. Oxygen is considered a drug thus requiring a physician's order to prescribe it and a licensed practitioner to administer it. However, the reality of O_2 therapy is that it is often neglected until a patient's condition worsens to a point that requires very high amounts or alternative methods of delivering it. New methods of delivering oxygen via nasal cannula style devices have been gaining popularity (Waugh & Granger, 2004). Devices range from simple and affordable to specialized with high humidity. Humidification systems have become more efficient allowing higher flows to be administered. Patient comfort and tolerability has been improved for patients not able to cope with oxygen masks. As new technology leads to the development of new oxygen delivery tools, RTs must alter their focus on an overlooked therapy and learn to adapt high flows and high humidity to treat respiratory disease processes. RTs must learn when to correctly use these new methods of high-flow delivery to better serve the patients and the health care centers.

There are many reasons to examine high flow oxygen therapy. Health care centers across the country are focused on shorter stays and infection prevention. Fiscal

shortfalls have forced many hospitals and clinics to look for alternative therapies for treatment. Hospital acquired infection (HAI) has become a major motivator for change in practices. With the proper use of high-flow therapy in patients with adult respiratory distress syndrome (ARDS), acute cardiogenic pulmonary edema (ACPE), or chronic obstructive pulmonary disease (COPD), patients may have the opportunity to reduce the need for more invasive procedures such as mechanical ventilation or bi-level positive airway pressure (BiPAP). The net result of this is less opportunities for patients to develop HAI which can increase the length of stay (LOS).

Mortality rates vary among different disease states. ACPE has a mortality rate of 21% (Fiutowski, Waszyrowski, Krzeminska-Pakula, & Kasprzak, 2008). When ACPE requires mechanical intervention and is complicated with myocardial infarction (MI), the mortality rate increases to 67% (Fiutowski et al., 2008). ARDS also has an exceptionally high mortality rate; however, studies have shown some variance. When averaged, the pooled mortality rate for ARDS is 43% (Zambon & Vincent, 2008). Attributed to this high mortality rate is difficulty in treating ARDS and the complications that occur with positive pressure ventilation (PPV). COPD is a costly pathology both fiscally and in the number of lives lost. COPD is currently the fifth leading cause of death in the United States and is expected to rise to the third leading cause of death by 2020 (Ai-Ping, Lee, & Lim, 2005). COPD exacerbations are a leading cause of hospitalizations in the United

States. The average cost per COPD patient per year who suffers an exacerbation and becomes hospitalized is $6000 (Ai-Ping et al., 2005).

The primary administration route with high flow oxygen is with a nasal cannula. This method is minimally obstructive and best tolerated by all patient populations. The nasal cannula has required some modification for high flow application. Larger bores, light weight materials, and adaptability to different flow generators are some of the modifications that have occurred.

High flow nasal cannulas (HFNC) mode of operation has been questioned in the literature. Is it the oxygen that elicits the positive effects of high flow therapy or is it the pressure generated by the high flow (Finer, 2005)? Either factor has led to HFNCs becoming very popular among neonatal and pediatric populations. High flow therapy has demonstrated a clear therapeutic advantage in these populations reducing the need for invasive respiratory machinery. But, is it possible to achieve a reduction of invasive respiratory procedures in the adult population with the use of HFNCs? If possible this would provide a cost efficient tool to treat respiratory distress.

Research is needed to determine the effect high flow has on adult patients. There is a need to determine flow-rates so that flow from these devices may be used appropriately and quickly. Pressure generated from high flow devices must be determined so patient selection can occur. The education for respiratory staff must also

be adequate as high flows alter breathing mechanics. The view of O_2 therapy must change from a supportive modality to an interventional therapy with the use of HFNCs.

Purpose

The purpose of this study was to examine the effect of nasal high flow gas therapy on mean airway pressure (M_{PAW}) in adult patients. The experimental study will be carried out in vitro in lieu of using human subjects. Much can be learned by investigating what happens when gas flow is manipulated to determine the effect of M_{PAW}.

Study Questions

Two questions were addressed by the study. Does increasing flow increase M_{PAW} in an adult breathing model? The devices used in this study were the Vapotherm 2000i, the Optiflow, and a nasal cannula device fabricated from general stock of a respiratory care department. The results obtained from the 3 units were examined to determine if the devices yielded the same results.

Significance

The product of high flow rates in spontaneous breathing persons is unknown. By using an in vitro lung model in this study, it was possible to isolate the effect of high flowrates during negative pressure ventilation. This study compared two commercial products and a fabricated high flow system from standard respiratory stock to determine if all 3 devices produced the same effect. This provided M_{PAW} readings that could be suggestive of actual pressures experienced by patients who utilize this therapy. This

study controlled all variables including respiratory time constants allowing the computation of mean airway pressure.

Chapter II

A Review of Literature

The literature used to perform this literature review covers multiple areas: Low flow therapy, high flow therapy, neonatal and pediatric respiratory care, humidified high flow nasal oxygen, Vapotherm, and Optiflow. Literature was obtained using PubMed, CINAHL, and Web of Science using search terms such as *Vapotherm, high flow nasal cannula, humidified high flow nasal cannula, high flow oxygen, and Optiflow*. Very few studies were found with regards to adult use. Data from neonatal and pediatric studies were used for comparative means. The literature search was limited to the last 15 years; however, literature from other countries will be used due to the lack of research in this area on adult subjects.

Low Flow Therapy

Low flow oxygen therapy (LFT) is practiced in every hospital in the United States. Administration of low flow therapy (LFT) includes devices such as nasal cannulas, simple masks, and partial and non rebreather masks. Low flow oxygen devices provide fixed flows that can result in a fraction of inspired oxygen (FiO_2) that is "neither precise or predictable" (Branson, Hess, & Chatburn, 1995, p. 56). People who are oxygen sensitive can be affected by the non-precise FiO_2 concentration especially in the COPD population. It is known that if hypoxic drive is eliminated the result is death. Branson et al. (1995) state the accepted FiO_2 for a 6 liter per minute (LPM) nasal cannula is 44%. However, current studies focusing on oxygen (O_2) concentrations suggest

otherwise. According to one report, a 6LPM nasal cannula produces a FiO_2 between 36-66% with a mean of 47.9% (Wettstein, Shelledy, & Peters, 2005). This was performed with a closed mouth breathing technique. Individuals within the study achieved a higher FiO_2 while breathing with their mouth open compared to those who breathed with their mouths closed. The results from open mouth breathing at a liter flow of 6LPM were 40-86% with a mean of 59.6% (Wettstein, et al., 2005). Previous studies have not agreed on the effect of open mouth/closed mouth on FiO_2. Wettstein's et al. (2005) methodology attempted to correct criticism of previous studies. Contrary to name, a high flow nasal cannula system (6-15LPM) does not use a blender for gas mixing and falls into the low flow category. The reason is due to a variable FiO_2 dependent upon patient breathing style. The same principle discussed above applies to cannula systems that use flows higher than 6LPM. Wettstein's et al. (2005) results found means of 69.8% and 80.6% on a Salter Labs high flow nasal cannula with closed mouth and open mouth techniques respectively. Because the Salter Labs high flow nasal cannula is limited to 15LPM flow and by definition is a low flow device, it will not be used in this study. A closer examination of high flow therapy will occur in the following section.

High Flow Therapy

High flow therapy (HFT) is a smaller part of O_2 therapy. High flow devices provide a fixed FiO_2 independent of the flow which provides a known FiO_2 at all times (Branson, Hess, & Chatburn, 1995). High flow cannula systems such as the Vapotherm and the Optiflow use a source gas from a blender to feed the system providing a precise

FiO_2 regardless of the patients breathing style or pattern. Traditional HFT devices such as the air entrainment mask or venti-mask use a manufactured air entrainment port to mix oxygen with entrained room air to provide a calculated and predictable FiO_2. HFT has been the standard for hypoxic drive patients. Due to controlled FiO_2, predictable oxygen delivery to the patient can be monitored; therefore, the partial pressure of oxygen in arterial blood (PaO_2) threshold remains intact. The high flow nebulizer (HFN) device is if often used with face tents or aerosol face masks and has been used in the post anesthesia care units (PACU) for years. The advantage is that it provides humidity and precise oxygen control. High flow systems as Vapotherm 2000i have been proven to provide a very reliable FiO2 in patients who have high respiratory rates and increased work of breathing (Wagstaff & Soni, 2007).

Vapotherm 2000i

Figure 1. Vapotherm 2000i

An oxygen delivery device produced by Vapotherm (Vapotherm, Annapolis, Maryland) has been able to cross the threshold of delivering oxygen at a higher liter flow than any other device. Vapotherm 2000i (Figure 1) is an oxygen delivery device that can deliver a gas flow of up to 40LPM while providing 100% relative humidity. The device is indicated for patients who are able to maintain a normal

carbon dioxide level but are suffering from poor oxygenation (Price, Plowright, Makowski, & Misztal, 2008). This could also aid in better ventilation perfusion matching. The device consists of a temperature control unit, a vapor transfer cartridge, a heated delivery tube, and a patient interface (Vapotherm 2000i, n.d.). Other items needed are a medical gas blender and sterile water. The device functions by heating the sterile water to a temperature of 33-43°C. Once at temperature, the gas water vapor enters the disposable vapor transfer cartridge which is filled by hollow tubes. The mixed medical gas travels through the tubes within the vapor transfer cartridge and is humidified with the gas water vapor. It is then transported to the patient via a water jacketed circuit which is also heated in order to prevent the loss of humidity of the inspired gas. In a study performed by Waugh and Granger (2004), the Vapotherm produced 43.3 mgH_2O/L for all measured flowrates. The patient interface is separate and interchangeable of the delivery tube. The patient interface is a nasal cannula with large nasal openings that is worn in the same manner as a low-flow nasal cannula. The device can be used with neonates, pediatric, and adult patients. Due to the high level of humidity, most patients are able to tolerate the increased flows provided by the Vapotherm. It has been shown to reduce respiratory rates, reduce the use of NiPPV, and the need for positive pressure ventilation (PPV) (Calvano, Sill, Kemp, & Chung, 2008). Also, Turnbull (2008) demonstrated through a collection of case studies how high flow nasal therapy can stop the progression of respiratory decline and artificial ventilation.

Optiflow

Another device currently available is the Optiflow gas system (Fisher and Paykel, Auckland, New Zealand). The Optiflow (Figure 2) can deliver up to 50LPM when connected to a high flow source (Fisher and Paykel Healthcare: Patient Interfaces, n.d.). Optiflow is adaptable to different flow generators. Optiflow may be driven via a high-flow flowmeter or a blender just as other high flow devices. However, Optiflow can also be used in conjunction with continuous positive airway pressure (CPAP) generators. This allows the Optiflow system to be used in many different areas including the home. A heater must also be used in conjunction with this device. Used with a Fisher and Paykel heater set at 37 degrees Celsius and a heated inspiratory limb, 44mgH_2O/L of water content can be delivered (Parke, McGuiness, & Eccleston, 2009). The Optiflow is a traditional heated bath system incorporating no new design; however, it does allow increased flow over traditional nasal cannula systems. The scope of this device is for adult patients and no neonatal information existed in the literature. Clinically, these devices can be utilized to treat many different pathologies.

Figure 2. Optiflow HFNC

(Fisher & Paykel Healthcare, 2009)

Clinical Uses

High-flow nasal oxygen is capable of treating numerous ailments. For the most part, high-flow oxygen was viewed as a modality to provide supplemental oxygen to hypoxic patients. Since the introduction of the Vapotherm 2000i, high-flow heated oxygen has become a therapy within itself. Vapotherm has had a significant role in treating chronic obstructive pulmonary disease (COPD) and asthma (Price, Plowright, Makowski, & Misztal, 2008). The high flow may generate positive pressure that can help alleviate collapsed or narrowed bronchioles allowing trapped gas to escape. Other published uses of Vapotherm include ventilatory failure, congestive heart failure (CHF), trauma, myocardial infarction (MI), and hypothermia (Turnbull, 2008). The suspected reasoning why Vapotherm therapy helps treat the pathologies is due to the humidified gas. Without the 100% humidity supplied to the gas by the Vapotherm unit, it is doubtful that patients would be able to tolerate such high gas flows.

Vapotherm has gained popularity for treatment of hypothermia victims (Turnbull, 2008). Patients who suffer from low core body temperatures can inhale warm humidified air into the thoracic cavity to help re-warm the body. Vapotherm allows the gas to be heated from 33 to 43°C facilitating a controlled warm-up. Vapotherm can also be utilized to enhance the transition from mechanical ventilation to spontaneous breathing without artificial airway (Turnbull, 2008; Woodhead, Lambert, Clark, & Christensen, 2006). This has been reported for neonatal, pediatric, and adult patients. As reported by Woodhead, Lambert, Clark, and Christensen (2006) no neonates given humidified high-

flow oxygen via Vapotherm required re-intubation. Along with the humidity provided by Vapotherm, it is also believed that the generation of a higher than normal mean airway pressure is a byproduct of the high liter flow which plays an active role in Vapotherm therapy. Studies have shown an increase in mean airway pressure in patients who are on Vapotherm therapy (Groves & Tobin, 2007). This phenomenon helps explain the success in obstructive pathologies and CHF patients. COPD and asthma patients benefit from the humidified gas but may benefit greater from the continuous positive airway pressure (CPAP) generated by the high flows of Vapotherm (Ai-Ping, Lee, & Lim, 2005). By increasing airway pressure, the bronchioles are stabilized thus allowing trapped air to escape and reverse the condition of air trapping. Another health issue that Vapotherm has been helpful in treating is the need for high FiO_2 by patients suffering from mental pathologies such as claustrophobia and dementia. Patients suffering from claustrophobia generally may not tolerate oxygen by mask or noninvasive positive pressure ventilation (NiPPV) due to the feeling of smothering caused by the mask touching the face. Vapotherm provides the higher FiO_2 without the mask as long as the patient does not breathe through their mouth. Patients suffering from impairments such as dementia often instinctively remove oxygen devices from their face. In one such case described by Calvano, Sill, Kemp, and Chung (2008), a patient who did not tolerate oxygen mask therapy to treat hypoxemia was placed on Vapotherm with a significant improvement in the measured PaO_2 and observed respiratory rate.

HFNC may be used to treat many different pathologies. Evidence exists supporting the role of high humidity in this therapy's success. However, if positive pressure is generated by HFNC, then positive pressure must also be considered as an element leading to the success of this therapy.

High Flow Generates Positive Pressure

Current modalities are changing the methods of healthcare delivery. Patients in the past suffering from respiratory failure had only one choice, the ventilator; however, with the development of noninvasive ventilation (NIV), the pathway to recovery for many has changed. NIV requires cooperative patients who will tolerate wearing a tightly fitted mask. If they are unable to tolerate the mask, their only alternative is invasive ventilation. NIV uses high flow rates and a sealed mask to generate pressure to augment ventilation. If positive pressure is generated by high flow nasal oxygen, an alternative delivery method may increase the tolerance of NIV.

The Vapotherm 2000i has not been used in any published studies to determine if positive pressure is generated with adult subjects. However, research does exist detailing that Vapotherm produces positive pressure in neonatal and pediatric subjects. Calvano, Sill, Kemp, and Chung (2008) note in their literature review that high flow nasal oxygen has been proven to be equivalent to noninvasive CPAP therapy in pediatrics. This is also the conclusion arrived in a similar study performed on neonates (Sreenan, Lemke, Hudson-Mason, & Osiovich, 2001). The positive pressure generated by high flow nasal therapy is variable and patient dependent. Many factors weigh on the degree of positive

pressure produced. Open mouth, closed mouth, respiratory rate, volume of breath, and depth of cannula in nares can influence the level of positive pressure.

The Optiflow has been the focus of two published studies. All studies have been performed outside the United States. The Australian study concluded that high flow nasal oxygen produces an increased oropharyngeal pressure when compared to conventional therapies (Groves & Tobin, 2007). A similar study performed by Auckland City Hospital in Auckland, New Zealand concluded the same results (Parke, McGuiness, & Eccleston, 2009). Groves and Tobin (2007) used 5 healthy males and 5 healthy females placed on Optiflow system at flows starting at 0LPM up to 60LPM. Measurements taken via a 10 French nasal catheter were recorded. They concluded that increasing nasal flow also increases oropharyngeal pressure. Their research concluded that breathing with a closed mouth generates 5.5 cmH_2O pressure at 40LPM flow and 7.4 cmH_2O at 60LPM (Groves & Tobin, 2007). Adult male pressures were less than adult female pressures which may be attributed to nasal orifice size.

Parke, McGuiness, and Eccleston (2009) conducted a study using 15 post cardiac operative patients for the study group. This group had a 10 French nasal catheter placed while under anesthesia. Recordings were made the morning following surgery with no set amount of time stated. Their results were presented as group mean only and showed a mean oropharyngeal positive pressure of 2.70 cmH_2O at 35LPM with closed mouths (Parke et al., 2009). The study concluded that high flow nasal therapy produces low level positive airway pressure at 35LPM. Park et al. (2009) also noted that the variability of

airway pressures observed in their study was most likely attributed to varying nasal orifice sizes. However, generation of positive airway pressure resulted in the generation of positive end expiratory pressure (PEEP) and increased M_{PAW}.

Mean Airway Pressure

Mean airway pressure (M_{PAW}) is generally associated with mechanical ventilation. It is a relationship of pressure over time. However, if airway pressure is increased by a noninvasive source, theoretically M_{PAW} is also increased. The difficulty in calculating M_{PAW} in noninvasive ventilatory patients is the unknown time constants associated with spontaneous respiration. M_{PAW} is defined as inspiratory time (T_I) multiplied by peak inspiratory pressure (PIP) plus expiratory time (T_E) multiplied by peak end expiratory pressure (PEEP) divided by total cycle time (T_{tot}). The written formula appears as $M_{PAW=}$ $(T_I \text{ x } PIP)+(T_E \text{ x } PEEP)/T_{tot}$. Without the ability to set or measure the time constants associated with breathing, M_{PAW} calculations are not possible.

Conclusion

HFNC is an accepted treatment for hypoxia. HFNC also has been documented to produce CPAP in pediatric and neonatal applications. A limited body of literature exists supporting its use in the adult population. HFNC has the potential to lower the cost of treatment for some diseases. It reduces cost by preventing the need for invasive procedures such as mechanical ventilation and the associated risk of infections. But many questions remain as to how best use this therapy in the adult environment. Further study of the pressure effect produced by HFNC is needed. Starting points for flow

selection need to be determined so that M_{PAW} can be targeted to treat specific pathologies. There is a need to compare the Vapotherm 2000i and the Optiflow to determine if both devices produce the same outcome. Many questions concerning this emerging therapy remained unanswered.

CHAPTER III

RESEARCH METHODS

The purpose of this study was to measure pressures associated with high flow nasal cannula (HFNC) system during spontaneous breathing. Specifically, the study is designed to address the question does increasing flow to a HFNC increase mean airway pressure. Spontaneous breathing is associated with negative intrathoraic pressure. To produce this type of respirations in vitro, a ventilator was used to ventilate one side of a double lung model. Figure 3 demonstrates the set-up used for this study. Side A of the double lung was positive pressure ventilated which mechanically raised side B of

Figure 3. Testing Model set-up with Optiflow HFNC

artificial lung via a board clamped at the outer edges. Side B of the artificial lung represents a negative pressure model. A double lumen 41 French oral endotracheal tube (Figure 4) trimmed to the upper cuff was used to simulate the nares of the model. The cuff was inflated to seal inside a 6 inch 22mm internal diameter vinyl tubing. A 22mm outside diameter pressure line adaptor was connected to the other end of vinyl tubing which was connected to the test lung tubing. The HFNC was setup to manufacturer specifications minus humidity and powered by a high flow oxygen flow meter designed to deliver flow up to 80 liters per minute (LPM). The nasal cannula was positioned via a clamp so that the cannulas were slightly inserted into the in vitro nose. Flow through the HFNC system was manipulated at 20, 30, and 40 LPM flowrates. Measurements were taken via small bore oxygen tubing by the auxiliary pressure monitor port on the Galileo ventilator.

Figure 4

41 French double lumen endotracheal tube

Lung Model

In this study, an in vitro lung model as seen in Figure 3 was used to simulate adult patient respiration. The Michigan Instruments Labs (MIL) Dual Adult TTL Lung (Michigan Instruments, Inc. Grand Rapids, Michigan) was used in conjunction with an

adult ventilator. The MIL adult lung has 2 independent chambers that can be independently ventilated. Compliance was manipulated independently. Compliance of 0.5L/cmH_2O was used for the study for both the positive pressure and negative pressure chambers. No resistors were used in this study.

Ventilator

A Hamilton Galileo Gold ventilator (Hamilton Medical, Inc. Reno, Nevada) was used with a standard 72 inch adult circuit (Figure 5). The Hamilton Galileo is a microprocessor based ventilator. The Galileo was chosen because of an accessory auxiliary pressure port located on the front of the ventilator. Ventilator settings were chosen to mimic adult ventilation. Two sets of parameters were chosen to simulate non-labored and labored breathing. Non-labored parameters were respiratory rate of 12, 450mL tidal volume, no PEEP, 21% oxygen, and a flowrate of 35LPM which yielded an inspiratory/expiratory (I:E) ratio of 1:3.1. Labored parameters were a respiratory rate of 24, 450ml tidal volume, no PEEP, 21% oxygen, and a flowrate of 65LPM which yielded a I:E ratio of 1:2.8. The Hamilton Galileo was calibrated per manufacturer guidelines before use

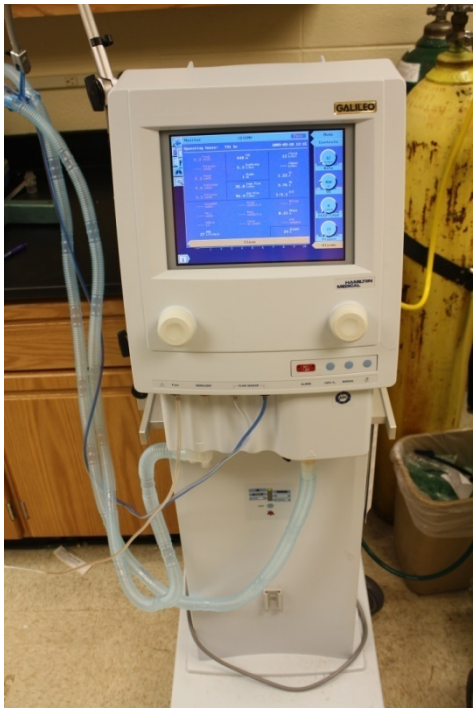

Figure 5

Hamilton Galileo Gold

in this study. The ventilator was connected directly to side A of the MIL lung. Parameters manipulated during this study were respiratory rate and flow. Flow was manipulated to produce inspiration/expiration ratios (I:E Ratio) similar to normal breathing. All other parameters remained constant.

Fabricated High-flow Device

The fabricated high-flow device seen in Figure 6 was constructed of materials found available in a respiratory therapy department. The device consisted of products manufactured by Hudson RCI (Teleflex Medical, Research Triangle Park, NC). The device consisted of Hudson Concha 4 heater column with nipple adaptor. This was connected to a heated wire circuit also manufactured by Hudson RCI. The circuit was connected to a Salter Labs HFNC (Salter Labs, Inc. Arvin, CA) via a second nipple adaptor. The Salter Labs HFNC was chosen because it is designed to deliver flows of 6-15 LPM.

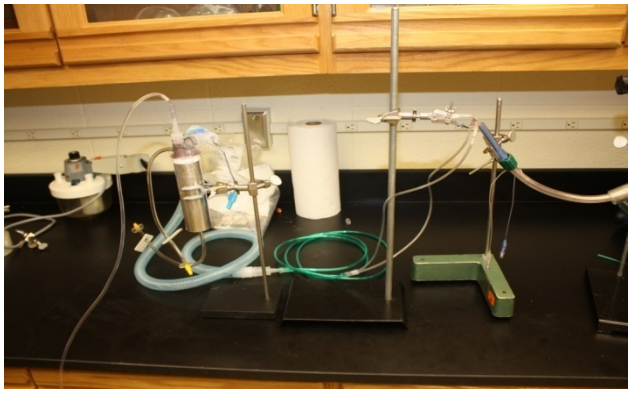

Figure 6

Generic HFNC

Data Collection

Data was collected in accordance to the protocols listed in Appendix A and Appendix B. Data was monitored via the Galileo ventilator. Three pressures were recorded for this study. The minimum pressure (P_{MIN}) represents the lowest pressure

generated during the breath. Positive end-expiratory pressure (PEEP) and positive inspiratory Pressure (PIP) were recorded. After the warm-up periods described by the protocols were completed, recordings from 12 breaths were recorded.

From the data collected, mean airway pressure (M_{PAW}) was able to be calculated. Calculations were possible due to the known time constants of the recorded breaths. Using the formula $M_{PAW=} (T_I \times PIP)+(T_E \times PEEP)/T_{tot}$, M_{PAW} was calculated for all breaths.

Data Analysis

Data was analyzed using SPSS for Windows (version 16.0). The data analysis included a one way ANOVA, a Bonferroni test, and descriptive statistics.

Conclusion

The research methods were directed by two study questions: (1) Does increasing flow through a high flow nasal cannula increase M_{PAW}? and (2) does the devices used in this study yield results that are statistically different? A Hamilton Galileo, with auxiliary port pressure monitoring, was used in this study. The Hamilton Galileo is capable of measuring pressures to the tenth of a centimeter of water pressure. A MIL adult dual test lung was also used in this study. The ventilator was used to ventilate one chamber of the test lung which triggered a spontaneous negative breath in the second chamber via a clamped board. A 41 French double lumen endotracheal tube trimmed to the high cuff was used to simulate the nares. The study focused on the Vapotherm 2000i with adult transfer chamber, Optiflow, and a generic built high flow nasal cannula system.

Chapter IV

Results

The primary focus of this study was the effect of increasing flow to a high flow nasal cannula (HFNC) on mean airway pressure (M_{PAW}). The research was also directed by the research question: Are the outputs of two commercial devices, the Vapotherm 2000i and Optiflow, and a high flow system constructed of available equipment from a respiratory therapy department, statistically different?

Analysis was performed using descriptive statistics and a one way ANOVA. Post hoc analysis utilizing a Bonferroni was also used. Descriptive statistics for non-labored and labored breathing can be seen in Table 1 and 2.

Non-Labored Statistics

	N	Mean	Std. Deviation	Variance
FLOW20LPM	36	.467	.1265	.016
FLOW30LPM	36	1.503	.3282	.108
FLOW40LPM	36	2.981	.4880	.238

Table 1. Descriptive analysis of non-labored breathing by liter flow.

Labored Statistics

	N	Mean	Std. Deviation	Variance
FLOW20LPM	36	.444	.0607	.004
FLOW30LPM	36	1.542	.1156	.013
FLOW40LPM	36	3.144	.1963	.039

Table 2. Descriptive analysis of labored breathing by liter flow.

For this study, 72 M_{PAW} calculations were recorded. As shown in Tables 1 and 2, the statistical mean for all 3 flowrates were positive indicating M_{PAW} was increased when on HFNC. The statistical mean trends upward as flow increases. Figures 7 and 8 provides side by side comparison of the devices depicting M_{PAW} for each device at the three liter flows recorded for non-labored and labored breathing patterns.

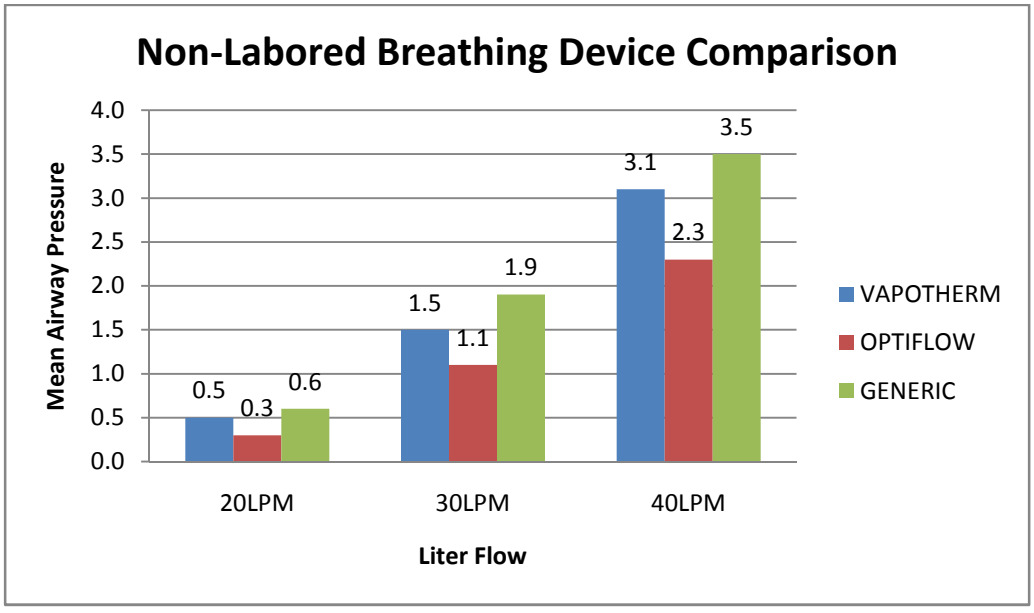

Figure 7. Device Comparison of Mean Airway Pressure for non-labored breathing pattern

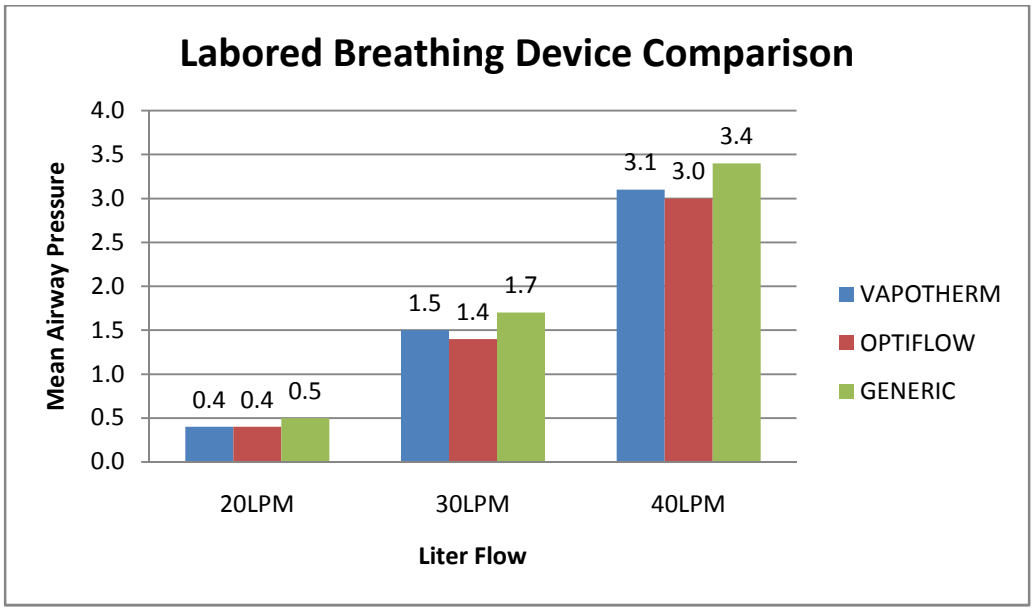

Figure 8. Device Comparison of Mean Airway Pressure for labored breathing pattern

One way ANOVA results can be found in Table 3. The overall effects were significant F (5,66) = 191.481, 1237.704, and 1975.356 respective to liter flow. p = 0.000 for all flowrate comparisons. Further analysis via Bonferroni adjusted probabilities can be found in Tables 4, 5, and 6. The Bonferroni adjusted probabilities determined all comparisons were significant except for Vapotherm-Vapotherm Labored at 30 and 40 LPM flow rates and Vapotherm-Generic Labored at 20 LPM. These three comparisons all were at the $p > 0.05$ level. At this level, the devices produced the same outcome in regards to M_{PAW}. All other comparisons had significant differences at the $p < 0.05$ level.

Table 3. One way ANOVA analysis

		Sum of Squares	df	Mean Square	F	Sig.
FLOW20LPM	Between Groups	.653	5	.131	191.481	.000
	Within Groups	.045	66	.001		
	Total	.698	71			
FLOW30LPM	Between Groups	4.219	5	.844	1237.704	.000
	Within Groups	.045	66	.001		
	Total	4.264	71			
FLOW40LPM	Between Groups	10.101	5	2.020	1975.356	.000
	Within Groups	.068	66	.001		
	Total	10.169	71			

Table 4. Pairwise analysis of 20LPM flowrate data

	VT20	OF20	GEN20	VT20LAB	OF20LAB	GEN20LAB
VT20		.2000*	-.1000*	.1083*	.0667*	-.0083*t*
OF20	-.2000*		-.3000*	-.0917*	-.1333*	-.2083*
GEN20	.1000*	.30008		.2083*	.1667*	.0917*
VT20LAB	-.1083*	.0917*	-.2083*		-.0417*	-.1167*
OF20LAB	-.0667*	.1333*	-.1667*	.0417*		-.0750*
GEN20LAB	.0083*t*	.2083*	-.0917	.1167*	.0750*	

VT20=Vapotherm 20LPM OF20=Optiflow 20LPM GEN20=Generic 20LPM
VT20LAB=Vapotherm 20LPM Labored OF20LAB=Optiflow 20LPM Labored
GEN20LAB=Generic 20LPM labored *p<0.05 *t* = p > 0.05

Table 5. Pairwise analysis of 30LPM flowrate data

	VT30	OF30	GEN30	VT30LAB	OF30LAB	GEN30LAB
VT30		.3917*	-.4000*	.0000*t*	.0667*	-.1917*
OF30	-.3917*		-.7917*	-.3917*	-.3250	-.5883
GEN30	.4000*	.7917*		.4000*	.4667*	.2083
VT30LAB	.0000*t*	.3917*	-.4000*		.0667*	-.1917*
OF30LAB	-.0667*	.3250*	-.4667*	-.0667*		-.2583*
GEN30LAB	.1917*	.5833*	-.2083*	.1917*	.2583*	

VT30=Vapotherm 30LPM OF30=Optiflow 30LPM GEN30=Generic 30LPM
VT30LAB=Vapotherm 30LPM Labored OF30LAB=Optiflow 30LPM Labored
GEN30LAB=Generic 30LPM labored *p<0.05 *t* = p > 0.05

Table 6. Pairwise analysis of 40LPM flowrate data

	VT40	OF40	GEN40	VT40LAB	OF40LAB	GEN40LAB
VT40		.7583*	-.4000*	.0083*t*	.1583*	-.3000*
OF40	-.7583*		-1.1583*	-.7500*	-.6000*	-1.0583*
GEN40	.4000*	1.1583*		.4083*	.5583*	.1000*
VT40LAB	-.0083*t*	.7500*	-.4083*		.1500*	-.3083*
OF40LAB	-.1583*	.6000*	-.5583*	-.1500*		-.4583*
GEN40LAB	.3000*	1.0583*	-.1000*	.3083*	.4583*	

VT40=Vapotherm 40LPM OF40=Optiflow 40LPM GEN40=Generic 40LPM
VT40LAB=Vapotherm 40LPM Labored OF40LAB=Optiflow 40LPM Labored
GEN40LAB=Generic 40LPM labored *p<0.05 *t* = p > 0.05

Conclusion

In conclusion, the results of this study answered the two questions. As seen in Figure 1, HFNC systems produce a positive M_{PAW} at the 20, 30, and 40LPM flowrates. The one way ANOVA analysis indicates that there is a statistical significance in the outcomes of the devices used in this study. The generic HFNC system produced a M_{PAW} consistently higher than the Vapotherm or Optiflow at all liter flows. All values for the generic system were significantly greater when compared to other devices.

Chapter V

Discussion

This study was designed to answer two research questions. The primary question was to evaluate the relationship of flow via a high flow nasal cannula (HFNC) on mean airway pressure (M_{PAW}) in an adult model. The second question was to evaluate the M_{PAW} pressures generated by three HFNC systems. The study compared the Vapotherm 2000i, the Optiflow, and a system constructed of different parts stocked in a hospital respiratory department.

Using the in vitro model, breathing was simulated and recordings were made using three different high flow systems. Average M_{PAW} for all three liter flows were greater than 0 cmH_2O for all systems. M_{PAW} averages for 20LPM, 30LPM, and 40LPM were 0.5cmH_2O, 1.5cmH_2O, and 3.1cmH_2O respectively. These averages are inclusive of both the unlabored and labored groups. It can be concluded that HFNC increases M_{PAW} in the in vitro model. It can also be deducted that HFNC produces PEEP in this model based on the mathematical formula $M_{PAW=}$ $(T_I \times PIP)+(T_E \times PEEP)/T_{tot}$. In this study, the expiratory time (T_E) was 2.8 to 3.1 times greater than the inspiratory time (T_I). Therefore, for M_{PAW} to be positive PEEP must be present.

Side by side comparison of the devices at the different flow rates yielded additional information. The three devices were compared by the M_{PAW} delivered. The two commercially available devices, Vapotherm and Optiflow, were compared and determined that Vapotherm produces a higher M_{PAW} than Optiflow in this study. When

the generic HFNC system was compared to the commercial systems, the generic delivered a higher M_{PAW} than either the Vapotherm or Optiflow. At 40LPM, the highest M_{PAW} was produced and the generic system produced the highest average pressure at 3.65cmH_2O. Vapotherm averaged 3.1cmH_2O and Optiflow produced 2.65cm$H_2$0. One way ANOVA also showed the differences were statistically significant as the liter flow increased. As flow increased, the F ratio also increased. Post hoc Bonferroni adjusted probabilities were compared in pairwise tables. When comparing the three devices, it can be concluded that the generic system was superior in terms of M_{PAW} and the Vapotherm produced a higher M_{PAW} than the Optiflow system in this study.

This study controlled all variables in order to isolate M_{PAW}. Similar studies using HFNC systems used human subjects and were unable to calculate M_{PAW} (Groves & Tobin, 2007). Parke, McGuiness, and Eccleston (2009) performed a study that concluded 35LPM flow via the Optiflow generated 2.70cmH_2O of M_{PAW}; however, stated in the study as a limitation was the uncertainty that the pressure was M_{PAW} even though the researchers named the pressure M_{PAW}. Parke et al. (2009) did refer to the recorded pressure as M_{PAW}. Parke et al. (2009) recordings at 35LPM fall between the two data averages recorded in this study. However, the in vitro model study average M_{PAW} pressures for 30 and 40LPM are 1.5cmH2O and 3.1cm H_2O respectively and the two studies do correlate. Unfortunately, Parke et al. (2009) did not include data to reproduce their findings at the liter flow described. Respiratory rates, tidal volumes, and breathing styles were unknown for the Parke et al. (2009) study.

Groves and Tobin (2007) utilized the Optiflow system at flows of 40 and 60LPM. They used healthy males and females and recorded average expiratory pressures of 5.5cmH_2O and 7.4cmH_2O, respectively. When compared to the in vitro study at 40LPM, a significant difference can be seen. The Optiflow system averaged 2.7cmH_2O at 40LPM using the in vitro lung model. The generic system produced the highest average M_{PAW} at 3.5cmH_2O which is still lower than the study conducted by Groves and Tobin (2007). Groves and Tobin measured oropharyngeal pressure and not M_{PAW}. This could be attributed to differences in pressures recorded. This study isolated variables such as time constants in order to calculate M_{PAW}. Groves and Tobin (2007) used healthy human subjects to collect data. Pressures presented by Groves and Tobin cannot be a calculated M_{PAW} average as spontaneous breathing subjects cannot breathe in a manner to isolate inspiratory and expiratory time constants.

HFNCs do not function as a normal nasal cannula. It is capable of providing a higher FiO2 concentration as well as increased pressures. The increased flow generates resistance to expiratory flow thereby increasing M_{PAW}. Increased M_{PAW} can be utilized to treat patients suffering from ailments such as COPD exacerbations, congestive heart failure (CHF), or hypoxic failure. Correct utilizations of the therapy are also important and an understanding of the physiological effects must be understood by respiratory therapists using this therapy.

Limitations

There are limitations to any study performed. Many limitations have been identified for this study. The following limitations have been taken into account by the researcher for this study.

1. In vitro study findings can be difficult to generalize due to the fact that a bench model is not an actual person. The simulator may not model the actual condition being studied.
2. The artificial nose and airway is not physiologically correct. In an actual human subject, the flow introduced by a HFNC will meet a much higher level of resistance as the flow is introduced to the human nose. This could account for the differences.
3. The design of the artificial nose could also influence flow in a laminar pattern. It is reasonable to consider that flow through a human nose may be more turbulent in nature and thereby increase resistance to expiratory flow.
4. The model is not to scale in terms of length when compared to a physiological model. The model is constructed of noncompliant smooth vinyl with little resistance. The tracheal rings that are present in a human subject could increase resistance or influence turbulent flow.
5. Orifice sizes of the cannulas were not measured for this study. There is a possibility that the nasal cannulas could have different orifice sizes which could influence M_{PAW} levels.

6. No tests included humidity. Vapotherm and Optiflow are both documented to provide 100% relative humidity (Waugh & Granger, 2004; Parke, McGuiness, & Eccleston, 2009). Therefore, the tests were not conducted using humidity. The generic system was not tested for relative humidity produced. It is a possibility that the comparison is unreasonable as this system may fail to deliver 100% relative humidity. Also, the humidified air may have a larger molecular makeup when compared to the dry gas used in this study. The larger molecular makeup of humidified gas could produce a higher M_{PAW}.

Need for further Research

Further research evaluating HFNC systems should be performed to better understand the effect in adult patients. A comparison study needs to be performed using adult subjects to further evaluate the devices used in this study. There is a lack of literature pertaining to adults and HFNC therapy.

Research exists in the neonatal and pediatric populations where HFNC therapy has found a high level of success. Kubicka, Limauro, and Darnall (2008) performed a bench study and human trials with HFNC on neonates. Bench study measurements were conducted with an anesthesia bag with an estimated leak to represent a patient's nose and mouth. They observed HFNC producing 4.5cmH_2O at 8.0LPM flow in vitro (Kubicka et al., 2008). When the study was transitioned to in vivo they discovered that 4.0LPM flow generated 4.3 to 4.8cmH_2O oral cavity pressure with a closed mouth (Kubicka et al.,

2008). Weiner et al. (2008) also reported oral cavity pressures ranging from 2.5 to 3.5cmH_2O at the 5.0LPM flow.

For this study, however, it must be noted that it is difficult to compare adults to neonates due to differences in physiological features. Many nasal cannulas used in high-flow therapy are snug in the nares which may contribute to a higher level to pressure. Also, the nasopharyngeal cavity is much smaller and may provide a lower level of resistance. Adult patient nares have a larger opening and are not likely to be occluded by a nasal cannula. Adults also have a much larger nasopharyngeal cavity to distribute the flow generated by HFNC. Due to these physiological differences, neonatal and pediatric studies do not offer an effective comparison for adult interpretation.

There is also a need for an evaluation of devices constructed to deliver high flow therapy to determine if they are capable of delivering the high levels of humidity that the Vapotherm and Optiflow systems are capable of. This therapy is a combination of two therapies, humidity and high flow. Any system constructed must be capable of providing both.

Conclusion

HFNCs are a new spin on an old device. They provide a level of humidity that was once only delivered with closed systems. HFNCs deliver flows that exceed the scale on most flow meters. They deliver FiO_2 percentages higher than some of the masks that have been used for many years in respiratory care. It cannot be assumed by respiratory therapists that they only deliver oxygen.

As this study has shown, HFNCs have a profound physiological effect. HFNC produce PEEP and increase M_{PAW}. As flow increases, M_{PAW} also increases. This has the potential to be an effective therapy for numerous ailments in the adult population. HFNC profoundly affected care in the pediatric and neonatal populations. HFNC does possess the ability to do the same for adult patients.

Appendix A

Protocol

Non-labored Breathing

1. Power on Galileo Ventilator
2. Run manufacturer flow-sensor calibration
3. Program ventilator with selected parameters
    a. Respiratory rate of 12
    b. Tidal volume 400
    c. Flow of 35LPM
        i. Produces I:E of 1:3.1
    d. Sine Waveform
    e. Oxygen 21%
    f. No PEEP
4. Connect ventilator circuit to positive pressure side of test lung
    a. Lung compliance set at 0.5 L/cmH_2O
5. Activate auxiliary pressure port
    a. Connect auxiliary pressure line to front of ventilator
    b. Connect auxiliary pressure line to adaptor placed in negative airway
6. Start ventilator and allow to cycle for 1 minute
7. Start Measurement of control with no cannula at the orifice of double lumen tube

Vapotherm

1. Recalibrate Galileo flowsensor
2. Allow to cycle for 1 minute
3. Connect Vapotherm unit to H cylinder and turn flow to 20 LPM via high flow flow-meter
4. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
5. After cannula in place cycle ventilator for 1 minute
6. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)

7. Recalibrate Galileo flowsensor
8. Allow to cycle for 1 minute
9. Connect Vapotherm unit to H cylinder and turn flow to 30 LPM via high flow flow-meter
10. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
11. After cannula in place cycle ventilator for 1 minute
12. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
13. Recalibrate Galileo flowsensor
14. Allow to cycle for 1 minute
15. Connect Vapotherm unit to H cylinder and turn flow to 40 LPM via high flow flow-meter
16. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
17. After cannula in place cycle ventilator for 1 minute
18. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)

Optiflow

1. Recalibrate Galileo flowsensor
2. Allow to cycle for 1 minute
3. Connect Optiflow unit to H cylinder and turn flow to 20 LPM via high flow flow-meter
4. Position adult nasal Optiflow cannula with clamp stand so that nasal prongs rest inside double lumen tube
5. After cannula in place cycle ventilator for 1 minute
6. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
7. Recalibrate Galileo flowsensor
8. Allow to cycle for 1 minute
9. Connect Optiflow unit to H cylinder and turn flow to 30 LPM via high flow flow-meter
10. Position adult nasal Optiflow cannula with clamp stand so that nasal prongs rest inside double lumen tube
11. After cannula in place cycle ventilator for 1 minute
12. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)

13. Recalibrate Galileo flowsensor
14. Allow to cycle for 1 minute
15. Connect Optiflow unit to H cylinder and turn flow to 40 LPM via high flow flow-meter
16. Position adult nasal Optiflow cannula with clamp stand so that nasal prongs rest inside double lumen tube
17. After cannula in place cycle ventilator for 1 minute
18. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)

Generic HFNC

1. Recalibrate Galileo flowsensor
2. Allow to cycle for 1 minute
3. Connect Generic unit to H cylinder and turn flow to 20 LPM via high flow flow-meter
4. Position adult nasal Generic cannula with clamp stand so that nasal prongs rest inside double lumen tube
5. After cannula in place cycle ventilator for 1 minute
6. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
7. Recalibrate Galileo flowsensor
8. Allow to cycle for 1 minute
9. Connect Generic unit to H cylinder and turn flow to 30 LPM via high flow flow-meter
10. Position adult nasal Generic cannula with clamp stand so that nasal prongs rest inside double lumen tube
11. After cannula in place cycle ventilator for 1 minute
12. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
13. Recalibrate Galileo flowsensor
14. Allow to cycle for 1 minute
15. Connect Generic unit to H cylinder and turn flow to 40 LPM via high flow flow-meter
16. Position adult nasal Generic cannula with clamp stand so that nasal prongs rest inside double lumen tube
17. After cannula in place cycle ventilator for 1 minute
18. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)

Appendix B

Protocol

Labored Breathing

1. Power on Galileo Ventilator
2. Run manufacturer flow-sensor calibration
3. Program ventilator with selected parameters
    a. Respiratory rate of 24
    b. Tidal volume 400
    c. Flow of 65LPM
        i. Produces I:E of 1:2.8
    d. Sine Waveform
    e. Oxygen 21%
    f. No PEEP
4. Connect ventilator circuit to positive pressure side of test lung
    a. Lung compliance set at 0.5 L/cmH_2O
5. Activate auxiliary pressure port
    a. Connect auxiliary pressure line to front of ventilator
    b. Connect auxiliary pressure line to adaptor placed in negative airway
6. Start ventilator and allow to cycle for 1 minute
7. Start Measurement of control with no cannula at the orifice of double lumen tube

Vapotherm

1. Recalibrate Galileo flowsensor
2. Allow to cycle for 1 minute
3. Connect Vapotherm unit to H cylinder and turn flow to 20 LPM via high flow flow-meter
4. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
5. After cannula in place cycle ventilator for 1 minute
6. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)

7. Recalibrate Galileo flowsensor
8. Allow to cycle for 1 minute
9. Connect Vapotherm unit to H cylinder and turn flow to 30 LPM via high flow flow-meter
10. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
11. After cannula in place cycle ventilator for 1 minute
12. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)
13. Recalibrate Galileo flowsensor
14. Allow to cycle for 1 minute
15. Connect Vapotherm unit to H cylinder and turn flow to 40 LPM via high flow flow-meter
16. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
17. After cannula in place cycle ventilator for 1 minute
18. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)

Optiflow

1. Recalibrate Galileo flowsensor
2. Allow to cycle for 1 minute
3. Connect Optiflow unit to H cylinder and turn flow to 20 LPM via high flow flow-meter
4. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
5. After cannula in place cycle ventilator for 1 minute
6. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
7. Recalibrate Galileo flowsensor
8. Allow to cycle for 1 minute
9. Connect Optiflow unit to H cylinder and turn flow to 30 LPM via high flow flow-meter

10. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
11. After cannula in place cycle ventilator for 1 minute
12. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)
13. Recalibrate Galileo flowsensor
14. Allow to cycle for 1 minute
15. Connect Optiflow unit to H cylinder and turn flow to 40 LPM via high flow flow-meter
16. Position adult nasal Vapotherm cannula with clamp stand so that nasal prongs rest inside double lumen tube
17. After cannula in place cycle ventilator for 1 minute
18. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)

Generic HFNC

1. Recalibrate Galileo flowsensor
2. Allow to cycle for 1 minute
3. Connect Generic unit to H cylinder and turn flow to 20 LPM via high flow flow-meter
4. Position adult nasal Generic cannula with clamp stand so that nasal prongs rest inside double lumen tube
5. After cannula in place cycle ventilator for 1 minute
6. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)
7. Recalibrate Galileo flowsensor
8. Allow to cycle for 1 minute
9. Connect Generic unit to H cylinder and turn flow to 30 LPM via high flow flow-meter
10. Position adult nasal Generic cannula with clamp stand so that nasal prongs rest inside double lumen tube

11. After cannula in place cycle ventilator for 1 minute
12. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)
13. Recalibrate Galileo flowsensor
14. Allow to cycle for 1 minute
15. Connect Generic unit to H cylinder and turn flow to 40 LPM via high flow flow-meter
16. Position adult nasal Generic cannula with clamp stand so that nasal prongs rest inside double lumen tube
17. After cannula in place cycle ventilator for 1 minute
18. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)
19. After 1 minute record P_{MIN}, PIP, and PEEP for 12 breaths (1 minute)
    a. Start recording on breath number 2
    b. Record even number breaths for total of 12 recordings (n=12)

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