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Measured continuous positive airway pressure in a non-invasive pediatric airway and lung model

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Abstract

Background: Bronchiolitis is the most common cause of admission in children under 2 years of age in the United States. The standard of care involves supportive measures, including non-invasive interventions such as CPAP. CPAP is traditionally delivered through a full facemask; however, pediatric intensive care units have been exploring the use of the RAM cannula by Neotech as a mode of CPAP delivery, but the level of CPAP delivered is uncertain. We, therefore, completed an in vitro study to determine the level of CPAP delivered via the RAM cannula utilizing a pediatric lung model.

Methods: 3D-printed models of seven sizes of pediatric upper airways were connected to an ASL 5000 Breathing Simulator. We applied each size of RAM cannula to weight-appropriate airway and lung compliance parameters, delivering pressures of 5, 7 and 10 cmH_2O using a ventilator in the CPAP mode. Leaks of 0%, 20%, 40% and 60% were generated to emulate a complete seal or poor fit and/or open-mouth breathing. The outcome measure was the difference in CPAP, referred to as '%leak effect', measured by the lung simulator relative to the CPAP set on the ventilator.

Results: We found that set CPAP of 5 through 10 cmH_2O generated measured CPAP ranging from 2.6 to 9.7 cmH_2O. For set CPAP of 5, 7 and 10 cmH_2O the mean '%leak effect' of measured CPAP from the set CPAP was: -25%, -26% and -25.7%, respectively. For each specific cannula-airway combination, increasing the set pressure and decreasing the air leak resulted in higher levels of CPAP delivered.

Conclusion: RAM cannula delivers varying amounts of CPAP, with a percent loss of approximately -25% depending on the level of leak in the system. With minimal leak, it is conceivable that the RAM cannula can be used to deliver clinically meaningful CPAP.

Key Words: non-invasive ventilation, CPAP, PEEP, child, pediatric intensive care units, RAM cannula

QUICK LOOK

Current knowledge

The RAM cannula has become a viable option for delivering CPAP in pediatrics, but the delivered level of CPAP is uncertain. To our knowledge, no publication describes the CPAP delivered by the full array of RAM cannula, and therefore the literatures excludes several key pediatric ages/sizes.

What this paper contributes to our knowledge

RAM cannula delivers varying amounts of CPAP, with a '%leak effect' of approximately -25%, depending on the level of leak in the system. Increasing set CPAP and decreasing leaks resulted in greater levels of measured CPAP. With minimal leak, it is conceivable that the RAM cannula can be used to deliver clinically meaningful CPAP.

Introduction

Bronchiolitis is the inflammation of the small airways of the lungs and it is predominantly caused by a viral illness, usually affecting infants and children aged up to two years. It is a frequent cause of emergency department visits and hospitalization among infants[1-3]. Within the first year of life, 10% of children are diagnosed with bronchiolitis[4]. This illness is usually a mild, self-limiting disease, but 2–5% of children require hospitalization[5-10] and 1–2.7% of them require critical care support[11, 12]. The standard management of bronchiolitis involves supportive care such as ensuring adequate fluid intake, antipyretics, and humidified oxygen supplementation if hypoxia is present[13]. However, due to dynamic narrowing of the peripheral airways on expiration exacerbated by inflammation, a recent Cochrane review suggested that continuous positive airway pressure (CPAP) may help keep inflamed airways open, thereby increasing the functional residual capacity throughout the respiratory cycle[14-16].

CPAP may be given non-invasively to infants using nasal prongs, nasopharyngeal tube, an infant nasal mask, and facemask. CPAP is administered using a commercially available circuit in conjunction with a continuous flow source, or a ventilator. A next-generation nasal cannula (RAM cannula, Neotech, Valencia, California) is currently being used as an interface to provide noninvasive ventilatory support, such as nasal intermittent positive-pressure ventilation, continuous positive airway pressure and noninvasive neurally adjusted ventilatory assist[17]. However, there is currently a dearth of information in the pediatric population on the amount of CPAP delivered through the RAM cannula. We believe that it is of paramount importance for providers and clinicians to know the relationship between set and delivered pressures in order to better serve our patients. To help bridge this knowledge gap, we designed this study to quantify the effect of the RAM cannula system on airway pressures in various simulated spontaneously breathing pediatric lung models with different leak conditions at a range of pressures typically used for the pediatric population. We hypothesized that the measured CPAP level would increase with increasing set CPAP and decrease as the system leak increased.

Methods

Experimental Setup and Apparatus

A Servo-i ventilator (Maquet, Wayne, New Jersey) was used in conjunction with the ASL 5000 Breathing Simulator (version 3.5, IngMar Medical, Pittsburgh, Pennsylvania) to evaluate the delivery of CPAP across seven RAM cannula sizes N4900-N4906. The ventilator was connected to the lung model using age and size-appropriate standard corrugated tubing (Neonatal and Pediatric Breathing Circuit, Hudson RCI-Teleflex, Morrisville, North Carolina) (Table 1, Figure 1 and 2).

Lung Model settings

The ASL 5000 was programmed to simulate seven patient models with different lung mechanics based on weights of 0.5kg, 1kg, 2kg, 4kg, 8kg, 15kg, and 20kg to correlate with the RAM cannula sizes tested. The lung models were based on normally compliant lungs to simulate a healthy individual. Previous bench studies, clinical studies, and preset lung models from the ASL 5000 lung simulator were used to determine the various respiratory settings for each model[18-27] . Table 2 summarizes each model setting.

RAM cannula Specifications and Upper Airway Model

Seven sizes of Neotech RAM cannulas were evaluated: N4900, N4901, N4902, N4903, N4904, N4905, and N4906. The upper airway model was developed based on the work of Sivieri et al[26]. The amount of turbulence generated by the turbinates and bends in the airway will differ between every single patient due to varied anatomy, therefore these variables were circumvented using this predicate model[26, 28, 29]. The external diameter of each RAM cannula prong at its base attachment to the delivery tubing was measured with a Mitutoyo digital caliper (Mitutoyo, Aurora, Illinois) with 0.1mm resolution. Measurements were made with air flow going through the cannulas to ensure accurate estimation of the cannulas' diameter during use. This measurement was made with the manufacturers recommended flow moving through the cannulas. The manufacturer recommended flow per RAM cannula size are as follows: 2.5 LPM for sizes N4900-N4903 and 15 LPM for sizes N4904-N4906.

A simulated upper airway was developed from corrugated tubing and a simulated nasal passageway was created with a 3-dimensional printer (Figure 1). The size of the nasal passageway was approximately 1 mm in diameter wider than the size of the RAM cannula prongs at their base attachment to the delivery tubing, resulting in a perfect, occlusive fit in each cannula-model pair. The nasal passageway was 5.0 cm in length and was connected to a simulated trachea which was then connected to the port of an endotracheal tube of various sizes depending on the lung model (Figure1 and Table 1). A T-shaped connector and valve were inserted between the endotracheal tube fitting and the trachea, which were used to create leak percentages of 0%, 20%, 40%, and 60%. The leak percentages were utilized to simulate CPAP delivery via RAM cannula, wherein there is no leak (closed mouth and tight-fitting nasal prongs: 0% leak), as well as a child with an open mouth (and/or leak around the prongs) of increasing leak contributions (20%, 40%, and 60%). Leak flow and percentage of total system flow were determined by a PTS 2000 ventilator tester (Puritan-Bennett Mallinckrodt, Carlsbad, California). To set the leak percentages, the Servo-i was set to the desired CPAP level and 100% of the flow from the ventilator ran through the PTS 2000. The 0%, 20%, 40% and 60% leaks were mathematically calculated from the liters of flow per minute that were registered at 100% leak at the specific CPAP level. The endotracheal tube was then attached to the ASL 5000.

CPAP Delivery System and Ventilator Settings

The Servo-i ventilator was connected to a Siemens air compressor (Siemens, Lancaster, Pennsylvania) for both air and oxygen. The Servo-i ventilator was used in NIV mode for all sizes of the RAM cannula. For sizes N4900-N4904 the ventilator was on infant, nasal CPAP mode. The neonatal breathing circuit was used for these cannula sizes. The customizable settings for infant, nasal CPAP mode were as follows: Oxygen concentration: 21% and PEEP: 5 cmH_2O, 7 cmH_2O, or 10 cmH_2O depending on the trial. For sizes N4905 and N4906 the ventilator was on adult, Pressure Control mode and used the pediatric breathing circuit. The customizable settings for adult, Pressure Control mode were as follows: Oxygen concentration: 21%, PC above PEEP: 0, PEEP: 5 cmH_2O, 7 cmH_2O, or 10 cmH_2O depending on the trial, respiratory rate:15, inspiratory time: 0.9 seconds, and T inspiratory rise: 0.2 seconds. Apnea backup ventilation for this mode was activated and set at 40 seconds.

Protocol

The specific pressures measured within the CPAP delivery system during each trial were: alveolar pressure (peak inspiratory, peak expiratory and end expiratory pressure). Each cannula and lung model pairing were evaluated with different leak and CPAP settings. Each configuration was tested once. After establishment of the specific CPAP and leak in each model, pressures were recorded for three minutes. Pressure data was collected at 200 Hz, recorded on computers, and saved for analysis. Data from the acquisition module and the ventilator tester were time synchronized with the ASL 5000. Measurement of peak, minimum and mean pressures were determined from 10 breaths after three minutes of running the simulator during each recording period.

Statistical Analysis

Alveolar pressure data were collected using the IngMar Medical ASL 5000 software (IngMar Medical, Pittsburgh, Pennsylvania). Results are expressed as mean values ± standard deviation unless otherwise stated. A Pearson's correlation and multiple linear regression model were run to assess the relationship between set CPAP, leak, cannula size and measured CPAP. Measured CPAP was determined with a 99.9% confidence interval and statistical significance was set at $p<.001$. We also measured an outcome variable, referred to as '%leak effect' which reflects the difference in set CPAP from the measured CPAP based on the amount of leak in the system. This difference was calculated as a '%leak effect'= [(measured CPAP – set CPAP)/set CPAP] *100%. Thus, negative values indicate that the measured CPAP was less than the set CPAP. Statistical analysis was conducted using SPSS 24.0 (SPSS, Illinois, Chicago).

Results

There was an overall increase in the measured CPAP as the set CPAP increased and as the leak decreased. The mean measured CPAP across various leaks and cannula sizes (n=84) are depicted in table 3. We noted the highest measured CPAP in the larger RAM cannulas (mint/teal[N4905] and purple [N4906]) and the lowest measured CPAP in the smaller RAM cannula (blue [N4902] and white [N4900]). Figure 3 demonstrates the mean measured CPAP when keeping the cannula size and set CPAP constant, while varying the leak. Figure 4 demonstrates the mean measured CPAP when keeping the leak and set CPAP constant, while varying the cannula size.

A Pearson's correlation was run to assess the relationship between set CPAP, leak, RAM cannula and measured CPAP. There was a statistically significant, strong positive correlation between set CPAP and measured CPAP $r(80) = .641$, p<0.0005; moderate positive correlation between cannula size and measured CPAP $r(80) = .41$, $p < .0005$ and moderate negative correlation between leak and measured CPAP $r(80)=-.5$, p<.0005.

A multiple linear regression model was calculated to understand the effect of set CPAP and leak on measured CPAP. A significant regression equation was found, $F(2,81) = 76.969$, $p < .0005$) with an R^2 of .647. The predicted 'measured' CPAP is equal to 1.615+ [(0.737) * Set CPAP]+ [(-0.052) * Leak], where CPAP is measured in cmH_2O and leak is denoted in %'s. Both set CPAP and leak were significant predictors of measured CPAP.

Lastly, we averaged all the measured CPAP and RAM cannula sizes and calculated the '% leak effect' for set CPAP 5, 7 and 10 cmH_2O as -25%, -26% and -25.7% respectively.

Discussion

In this simulation-based experiment, we evaluated the use of the Neotech RAM cannula to deliver CPAP. To our knowledge, this is the first in vitro study of the RAM cannula attached to a ventilator with the intention of supplying CPAP across varying leak percentages, in varying sizes of pediatric lung models, utilizing the full spectrum of RAM cannula sizes. Most importantly, our in vitro study showed that the pressure delivered is regulated and prevented from exceeding the set level by more than 1 or 2 cmH_2O. There were 3 primary findings in our study: 1. Increasing leak resulted in decreased measured CPAP; 2. Increased set CPAP resulted in increased measured CPAP; 3. Larger cannula sizes resulted in increased measured CPAP per a set CPAP. Our results show that transmission of pressure across the nasal interface is dependent on the amount of leak, across the interface and/or open mouth, with good pressure transmission when the nasal cannula is properly sized using a template as recommended by the manufacturer.

Iyer and Chatburn conducted a neonatal lung based model study using the RAM cannula and showed a loss of 25-37% from the set pressure[30]. Their model was based on nasal cannula and nostril size. However, the study did not state the amount of leak that was present in the circuit, which our study aimed to overcome. Another in vitro study using RAM cannula, showed a loss of 60% of the pressure from the set CPAP[31]. This study tested a wide variety of settings in addition to different nare sizes and open mouth models used in the neonatal population. Another in vivo study investigating delivered pressures using the RAM cannula in preterm infants and showed a loss of 40-50% of the set CPAP[32]. Our study differs from the previous two studies in a couple of ways. We studied the full array of RAM cannula sizes and commensurate pressures commonly used across the pediatric population. We also aimed to overcome deficits in the prior studies by using a wide range of leaks to simulate a patient with an open mouth and/or crying versus closed mouth. The intent was to try to simulate real-world situations so that these data could be more fully translated to the bedside. We found that when the CPAP were averaged over the entire array of cannula sizes, the loss of CPAP with a 0% leak was 6-7% and for those pressures delivered with 20% leak approximates 14-17%. In other words, with a leak of 0%, simulating a closed mouth complete seal scenario, we measured CPAP of ~93-94%, and for leaks of 20%, simulating an 80% occlusion best fit scenario, we delivered 83-86% of set CPAP. Armed with these data points, a care provider may feel more secure in the level of CPAP being delivered to the alveoli using the RAM cannula and may confidently adjust the ventilator settings to accommodate the level of leak determined at the bedside.

As mentioned earlier, we did note an increasing trend in the measured CPAP as the cannula size increased. We hypothesize that as the larger cannula requires greater flow and, in our experience, fits the child better, leak in general has a lesser effect on the CPAP delivered. However, we did notice that the green/N4901 cannula did not follow the normal trajectory of increase in pressure like the other cannulas (Figure 3). The experiment was repeated multiple times with similar results. We speculate that this could be due to increased pressure through a small cannula dimension which could be a cause for this un-explained result.

The RAM cannula is easy to use and keep in place like the high-flow nasal cannula, which may have better tolerability when compared to a full face CPAP mask[33-35]. It has the advantages of not completely occluding the child's face which occurs when employing a full face/mouth CPAP mask, causing anxiety and further distress in children. This invariably may be the reason sedation is often used -- to help the child tolerate the mask -- an intervention, which by itself, poses significant risk and complications[36]. The HFNC interface is similarly easy to apply, but some critics have concerns with its use due to the unknown amount of pressure that a high flow rate can deliver[37-39]. The RAM cannula may help to bridge this gap by taking advantage of the ease of use and tolerability of HFNC, combined with the reliability of using full-face- or nasal-mask CPAP with little to none of the disadvantages. Anecdotally, we have observed a trend in our unit, as well as with our transportation teams, a global adoption of the RAM cannula, presumably due to the ease of use. In our personal experience, we have seen that it is clinically more tolerable to a full face mask, and with minimal loss of the set CPAP, as shown in our study, we anticipate that it could be used as an alternative to HFNC or full-face mask CPAP for some children coming to the ICU in need of an escalation in respiratory support and ICU care.

The primary limitation of this study is that it was not performed in pediatric patients but rather in models that simulated pediatric airways. However, we believe that the essential mechanics of the pediatric respiratory system are well represented by this model. The relationship between set CPAP and the pressure delivered to the lungs in an actual clinical situation is dependent on many uncontrollable factors, which is why NIV, in general, and NIV through nasal prongs are exercises in rough estimates at best. The anatomy of our lung model does not exactly resemble the airway anatomy of the pediatric patient. However, our intent was not to try to duplicate the pediatric upper airway anatomy and the way variable anatomy may affect delivered CPAP, but rather to evaluate the effect of leaks on the level of CPAP delivered using the RAM cannula. We assumed that the size of the leak would mimic what we see clinically despite the differences in anatomy. The leak compensation option on the PB840 and Servo-i ventilators are designed to compensate for leaks in the breathing circuit to maintain CPAP and prevent auto-triggering during NIV and invasive ventilation. It is possible that not using leak compensation for this experiment or using a different ventilator that does not offer leak compensation may have yielded different results. Further study of this issue is warranted.

Conclusion

The use of the RAM cannula to deliver CPAP to pediatric patients may be safe and efficacious. As with full face mask CPAP, RAM CPAP takes advantage of all the ventilator safeguards utilized in CPAP mode. Most importantly, pressure is regulated and prevented from exceeding the set level by more than 1 or 2 cmH_2O and the mean '% leak effect' averaged approximately -25% across all models of RAM cannula and set CPAP levels of 5, 7, and 10 cmH_2O. We observed that measured CPAP was negatively affected by leak and positively affected by higher set CPAP and RAM cannula size, respectively.

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Table 1: Setup and Models

Weight Model	Endotracheal Tube Size	Diameter of nasal 3D model (mm)	Cannula Size (Color)	Circuit Type	Servo-i Setting
0.5 kg	5	3	N4900 (White)	Neonatal	Infant- NIV-Nasal CPAP
1 kg	5.5	3	N4901 (Green)	Neonatal	Infant- NIV-Nasal CPAP
2 kg	6	4	N4902 (Blue)	Neonatal	Infant- NIV-Nasal CPAP
4 kg	6.5	5	N4903 (Orange)	Neonatal	Infant- NIV-Nasal CPAP
8 kg	7	6	N4904 (Yellow)	Neonatal	Infant- NIV-Nasal CPAP
10 kg	8	7	N4905 (Mint)	Pediatric	Adult- NIV-Pressure Control
20 kg	9	7	N4906 (Purple)	Pediatric	Adult- NIV-Pressure Control

Table 2: Lung Model Settings

Model	0.5 kg	1 kg	2 kg	4 kg	8 kg	10 kg	20 kg
Compliance (mL/cmH_2O)	0.5	1	2	5	5	10	15
P100* (cmH_2O)	-2.1	-2.8	-3.5	-4.2	-4	-4	-4
Vt# (mL/kg)	0.9	3.2	7.8	23.2	42	60	90
Resistance (cm H2O/L/s)	200	150	100	50	35	30	20
Inspiratory Time (s)	0.25	0.3	0.35	0.4	0.5	0.5	0.7
Respiratory Rate (breaths/min)	70	60	50	40	35	30	30
Increase (%)	24.2	20	17	13.5	14.5	14.5	14.5
Hold (%)	5	10	12.2	13.2	12	12	12
Release (%)	19.5	20	19.5	17.8	17	17	17
Pause (%)	0	0	0	0	0	0	0

*P100= airway occlusion pressure 0.1s after the start of inspiratory flow

#Vt= tidal volume

Table 3: Mean Measured CPAP With Varying Leaks and Set CPAP With Different Cannula Sizes

	CPAP	**5 (cm H_2O)**	**7 (cm H_2O)**	**10 (cm H_2O)**
Cannula	Leak			
White/N4900	0	3.85	5.35	7.62
	20	3.18	4.67	6.6
	40	2.48	3.58	4.94
	60	1.7	2.36	3.18
Green/N4901	0	5.06	7.13	10.12
	20	4.56	6.44	9.28
	40	3.82	3.85	7.89
	60	2.77	2.77	5.34
Blue/N4902	0	3.76	5.26	7.51
	20	3.04	5.27	5.98
	40	2.3	4.07	4.37
	60	1.44	1.91	3.43
Orange/N4903	0	3.8	5.4	7.8
	20	3.2	4.62	6.4
	40	2.58	3.58	5.16
	60	1.77	2.48	3.48
Yellow/N4904	0	4.9	6.9	9.95
	20	4.45	6.33	8.97
	40	3.65	5.26	7.61
	60	2.68	3.97	5.64
Mint/N4905	0	5.48	7.53	11.62
	20	5.29	7.17	10.39
	40	4.85	6.29	9.35
	60	4.34	5.31	7.3
Purple/N4906	0	5.6	8.16	11.09
	20	5.6	7.52	10.49
	40	4.91	6.68	9.03
	60	3.88	5.12	7.46

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Figure legends

Figure 1: Model Setup

Figure 2: Individual Model Components

Figure 3: Measured CPAP for set cannula size, set CPAP and varying leak (mean+SD)

Figure 4: Set CPAP vs Measured CPAP (mean+SD)

Figure 1: Model Setup

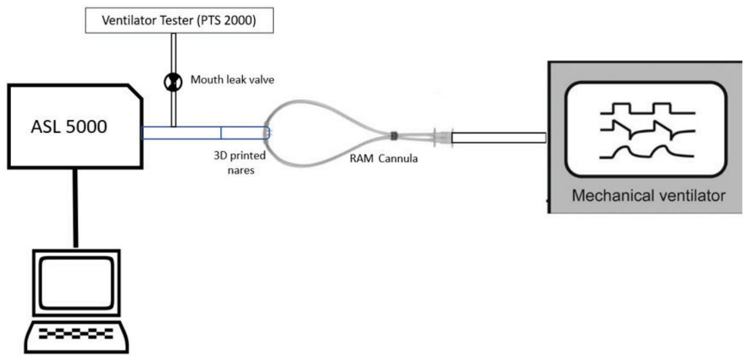


Figure 1: Model Setup

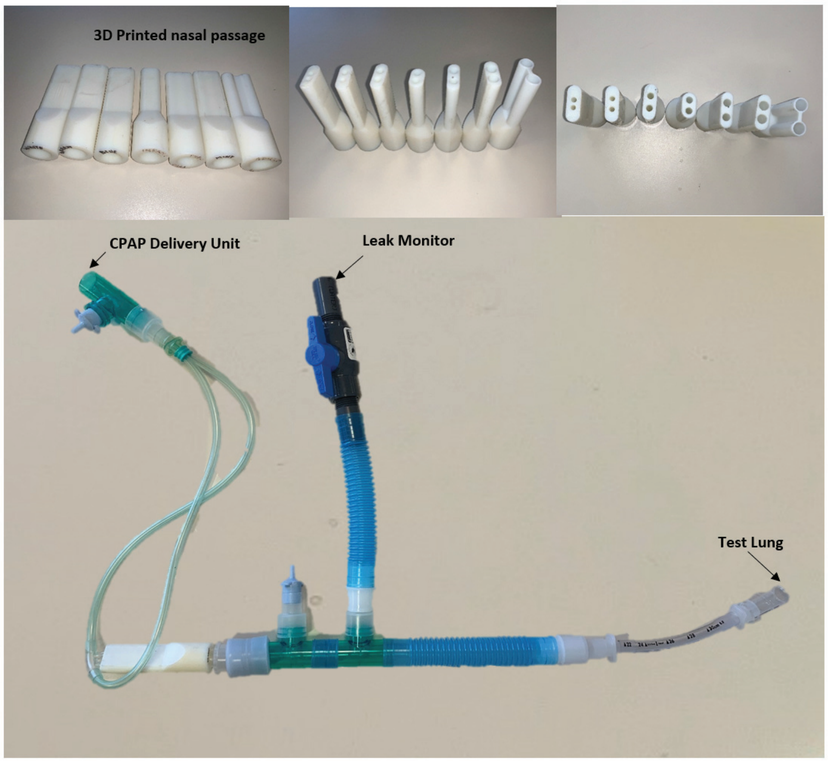
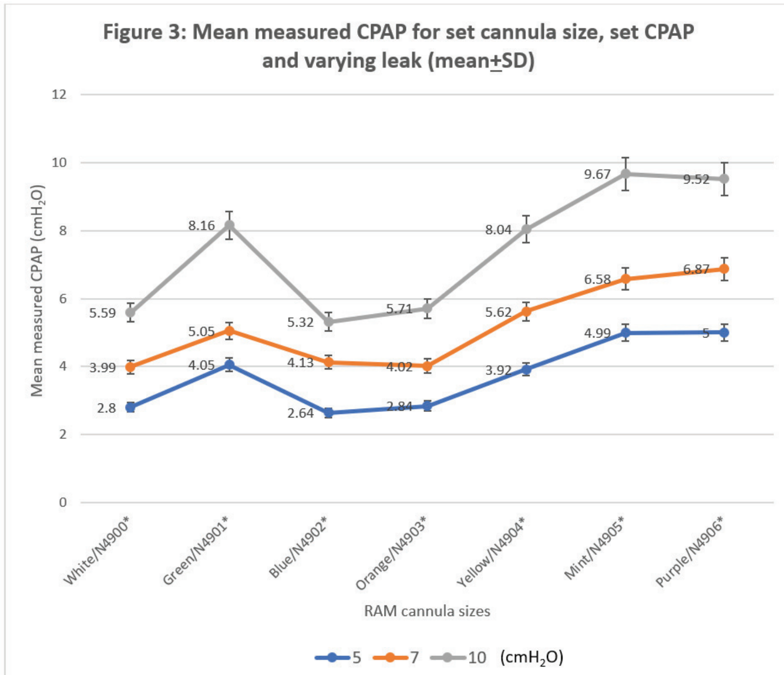
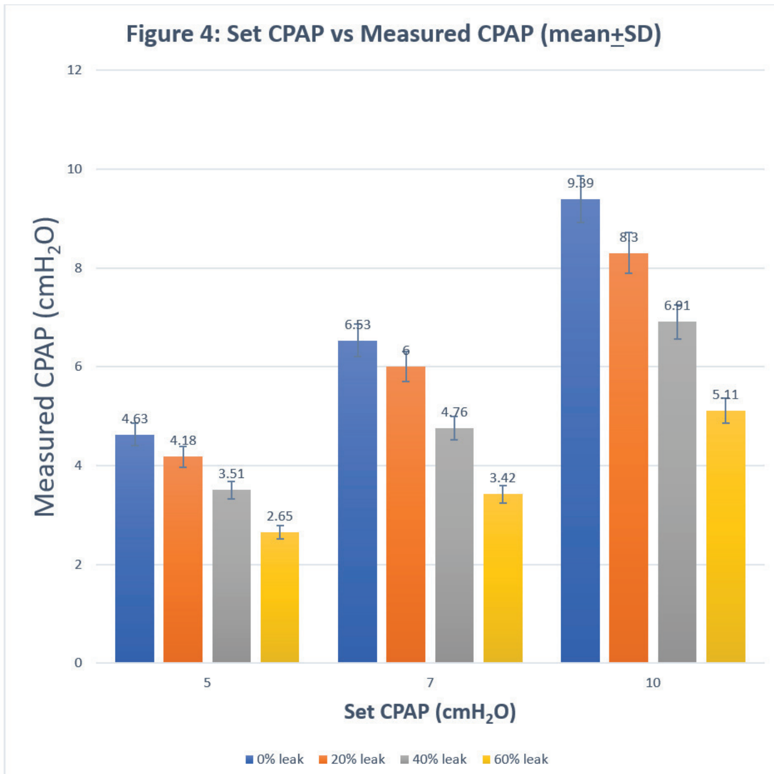


Figure 2: Individual Model Components



Note: Flow rates of 2.5 liters per minute was used for sizes N4900-N4903 and 15 liters per minute for sizes N4904-N4906.

Figure 3: Mean measured CPAP for set cannula size, set CPAP and varying leak (mean+SD)



Note: Data is averaged for all cannula sizes and set CPAP.

Figure 4: Set CPAP vs Measured CPAP (mean+SD)