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Evaluation of a Bubble CPAP System for Low Resource Settings

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Conflict of Interest: Robert DiBlasi has served as a consultant, received research funding, and has been on the speaker’s bureau for Draeger Medical, Bunnell Medical, Vapotherm and Vero Biotech. Michelle Dundek and Ellie Ng are engineers with Vayu Global Health Innovations, a public benefit company that develops low cost bubble CPAP (B-CPAP) systems and other oxygen delivery solutions. The other authors have indicated that they have no potential conflicts of interest to disclose.

Author contributions: Literature search, study design, data collection, data analysis and manuscript preparation were done by the all authors. MD, EN, AB, RD, and JP provided input on the design of studies. AB, JP and RD assisted in acquiring measurements and data analysis. TB oversaw all aspects of this research.

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Abstract

**Background:** Despite its established safety, efficacy, and relative simplicity, CPAP treatment is not widely available for newborns and infants in low- and middle-income settings (LMICS). A novel bubble CPAP (B-CPAP) system was designed to address the gaps in quality and accessibility of existing CPAP systems by providing blended, humidified and pressurized breathing gases without the need for electricity, compressed air, or manual power. This is the first study that tested the performance of the system with a simulated patient model.

**Methods:** In a spontaneously breathing 3D printed nasal airway model of a pre-term neonate, CPAP performance was assessed based on delivered pressure, oxygen level, and humidity at different settings.

**Results:** Preliminary device performance characteristics were within 5% between three separate devices. Performance testing showed accurate control of CPAP and oxygen concentration at all settings with the B-CPAP system. Lung model pressure and oxygen concentration were shown to stay within ± 0.5 cmH₂O and ± 4% of full scale (FS) of the device settings, respectively, with relative humidity levels of >80%.

**Conclusions:** Performance testing of the B-CPAP system demonstrates accurate control of CPAP and oxygen concentration with humidity levels suitable for premature newborns on noninvasive support.

**Key Words:** Bubble CPAP; global health; respiratory distress syndrome; humidification
Introduction

Nearly four million infants die throughout the world each year, with one million dying principally from respiratory insufficiency in low- and middle-income countries (LMICs) that lack respiratory support devices and technologies commonly used in high resource settings. The absent technologies include advanced invasive mechanical ventilators, but they also include relatively simple interventions such as noninvasive ventilation. Nasal continuous positive airway pressure (N-CPAP) is a form of noninvasive ventilation that has been used for almost 50 years in high resource settings. It is associated with lower indicators of lung injury and inflammation, pulmonary growth arrest, and chronic lung disease than invasive mechanical ventilators. When it is made available in low and middle-income countries (LMICS), N-CPAP has been shown to reduce mortality in preterm neonates by 66%. As such, the World Health Organization (WHO) strongly recommends CPAP for newborns diagnosed with respiratory distress syndrome (RDS). The American Academy of Pediatrics also recommends that N-CPAP and other oxygen blending systems are made available for all preterm births; and others have pointed out the potential of N-CPAP to support patients in transit.

Despite its established safety, efficacy, and relative simplicity, N-CPAP treatment is not widely available in LMICs. In India for example, a 2020 survey found that only one-third of district hospital neonatal units have any access to CPAP. There are many barriers to accessing N-CPAP, including cost, need for electricity, need for compressed medical air and blending systems, and availability of skilled human resources for training, maintenance, and patient monitoring. As a result, care providers in LMICs often resort
to improvising nasal bubble CPAP (B-CPAP) systems; approximately one-third of hospitals in the Indian survey using N-CPAP use home-made B-CPAP systems. These systems are made from supplies on hand, typically including a compressed and non-humidified pure oxygen (100%) gas source. They often give poor quality CPAP because the thin nasal cannula they employ are difficult to exhale through,¹⁹, ²⁰ and they lead to prolonged exposure to pure oxygen which can cause damage to the eyes, lungs and brain.

Several low-cost B-CPAP systems have been developed in recent years to address the demand for affordable methods of delivering CPAP.²¹-²⁷ These devices have some significant advantages over previous devices, including successfully eliminating the need for compressed air. However, these more affordable B-CPAP systems still face formidable barriers to adoption in many facilities. They all require continuous electricity to humidify gases or blend air and oxygen, but a 2014 WHO Surgical Assessment Tool survey of approximately 800 low-income hospitals found that only 59% of health care facilities have reliable electricity access.²⁸ In addition, many low-cost CPAP systems do not provide the same quality of CPAP as established, expensive devices. Low-cost CPAP systems often do not include humidification, have large amounts of dead space that cause the patient to re-breathe carbon dioxide and utilize high resistance circuits that have a large imposed work of breathing.¹⁹ Therefore, there remains an unmet need for a system that provides high quality B-CPAP, does not require electricity or compressed air, is easy to use, and is low cost.
Mollazadeh-Moghaddam et al described a low-cost method to blend ambient air and pressurized oxygen without electricity using a unique fixed performance Venturi. An adjustable version of this Venturi was created and combined with a humidifier, low-resistance breathing circuit and water column to create a novel B-CPAP system (Vayu Global Health Innovations, Boston, USA). These descriptive studies in vitro were designed to evaluate the performance of the novel B-CPAP system based on clinically relevant parameters critical to effective CPAP therapy using a realistic, spontaneously breathing patient model.

**Methods**

We designed and conducted studies in vitro in three separate stages. The first stage evaluated pressure, oxygen concentration delivery, and humidity using a specialized temperature and humidity chamber at all device settings for three samples of the bubble CPAP system. These studies evaluated inter-device variability and performance stability and can be found by accessing the online supplement (Supplemental methods). Following this testing, we evaluated delivered pressure and oxygen concentration in a high-fidelity realistic breathing lung model, using appropriate flow settings for low birthweight newborns, who represent the most common patient population requiring CPAP for RDS and surfactant deficiency. A final test evaluated relative humidity levels within a non-heated lung model using a bellows, a 3D model, and a hygrometer. The lab setting was maintained at low ambient humidity to evaluate humidity output without rebreathing of exhaled heated humidity.

**The B-CPAP System**
The B-CPAP system delivers humidified, filtered, pressurized and oxygen-enriched air to the patient (Figure 1A) via secured nasal prongs (Figure 1B). The system requires a 50 psi source of medical grade oxygen with an adjustable flowmeter. Oxygen enters the circuit and passes through an adjustable Venturi (Figure 1C), where it mixes with ambient air to create a source of oxygen-enriched air of adjustable concentration. The mixture is filtered, humidified, and delivered to the patient through short binasal prongs. Exhaled gases exit the system by bubbling out through the water column, which generates CPAP. The amount of pressure delivered to the patient is determined by the depth of submersion of the expiratory tubing in the water column (4-10 cmH₂O). Volumetric flow of the source gas is set to the minimum flow that maintains continuous bubbling throughout the respiratory cycle at the set CPAP level.³⁰

The B-CPAP system Venturi, an adjustable concentration Venturi that can handle operational low flows and relatively thin tubing found in neonatal circuits,²⁹ generates oxygen-enriched air by augmenting the flow of pure oxygen from a cylinder with entrained ambient air. It can be adjusted from 30-100% oxygen by turning the threaded portion to position an indicator along a numbered scale. A nut can be tightened to lock the position, and a swivel connector downstream allows the Venturi to be adjusted during treatment without coiling the tubing. A bacterial viral filter (Great Group Medical Co., Changhua, Taiwan) is positioned downstream of the Venturi and upstream of the humidifier. The bubble-through humidifier comprises a custom molded lid screwed onto a plastic reservoir, and operates passively as the enriched, filtered gas passes through a small volume of water before exiting the chamber and entering the inspiratory limb of
the breathing circuit. Standard 10 mm corrugated tubing connects the humidifier and water column to the nasal prongs (Great Group Medical Co., Changhua, Taiwan). The expiratory limb of the breathing circuit is attached to a downstream filter, which connects to the wand of the custom-designed water column lid. The wand can be rotated to change the depth of submersion, which changes the amount of CPAP pressure delivered.

**Nasal Airway/Lung Models**

Nasal resistance in newborns accounts for nearly half of total airway resistance.\(^3\) As such, we designed a realistic replica of a nasal airway modeled from a computed tomography scan of an infant at 30 weeks of gestation (Figure 2). This model has been described in detail elsewhere.\(^3\) The model did not have an oral airway opening, therefore only closed-mouth conditions were simulated.

The nasal model was attached to two different spontaneously breathing, preterm neonatal lung models for testing. Oxygen and pressure delivery was measured with the ASL 5000 Test Lung (Ingmar Medical, Pittsburgh, Pennsylvania), a digitally controlled, high-fidelity breathing simulator, which utilizes a screw-drive controlled piston and mathematical modeling to simulate size- and disease-specific pulmonary mechanics and is shown in Figure 3. Spontaneous breathing was simulated using preterm neonate normal values given in Table 1. The inspiratory-to-expiratory ratio was held constant at 1:3, and inspiratory effort was adjusted to maintain constant tidal volume (6 mL/kg). The second lung model, a Silastic infant test lung with compliance of 0.47 mL/cm H\(_2\)O and
resistance of 150 cm H₂O/L/s; model 191 (Maquet, Wayne, New Jersey) shown in Figure 4, was used to evaluate humidity levels.

Lung Model Pressure and Oxygen Concentration Testing

The B-CPAP system, nasal model, and lung simulator were set up as shown in Figure 3. A pressurized oxygen gas cylinder connected to a regulator set at 50 psi (not shown) was attached to an adjustable flow meter. This flow meter was connected to the Venturi using oxygen tubing. A calibrated flow sensor (TSI Inc., Shoreview, Minnesota) was inserted between the Venturi and upstream filter to monitor the total flow into the system (i.e. blended air/oxygen flow) and direct readout of the flow was readily visible from an accompanying screen. To obtain desired bias flow, the oxygen flow from the cylinder was titrated until the readout from the sensor matched. A flow of 6 L/min was used because it was the minimum flow that maintained vigorous bubbling throughout the respiratory cycle at all CPAP levels. The TSI flow meter was removed after measuring flow and prior to testing. Nasal prongs (size 1) were inserted snugly into the nasal airway openings of the nasal model. Initially, the Venturi was set to 30% oxygen and the wand in the water column was set to 4 cmH₂O. Once the readout of the oxygen concentration stabilized, 20 breathing cycles were recorded. The same steps were repeated for set CPAP levels of 6, 8, and 10 cmH₂O, and the pressures were also applied at oxygen levels of 40%, 60%, 80%, and 100% at each of the CPAP settings to record data for all setting combinations. Lung model pressures (end-expiratory pressure), oxygen concentration, and tidal volume were measured within the ASL 5000.
Humidity Testing
Humidification performance testing was conducted at a bias flow of 6 L/min and a set CPAP of 5 cmH₂O. The lung model was attached as shown in Figure 4. A hygrometer, the Fisherbrand™ Traceable™ Temperature/Humidity Meter (Thermo Fisher Scientific, USA) was inserted distal to the nasal model to measure the temperature and RH of the gases after they passed through the CPAP system and nasal passages. Breathing was simulated by manually generating breaths, distending and retracting the silastic lung approximately 2 cm in length. Two one-way valves were placed in series to prevent re-breathing and recirculating of exhaled humidity from the lung model. For reference points, the RH of the laboratory ambient air and of the oxygen proximal to the cylinder were recorded and compared to the gas mixture exiting the bubble humidifier.

Data Analysis
The sampled data for each run of 20 breaths was extracted from the ASL 5000 software and saved to a spreadsheet (Excel, Microsoft, Redmond, WA). Mean and standard deviation were calculated for 20 simulated breaths using Matlab (Mathworks, Natick, MA).

Results
Outcomes for delivered end-expiratory pressure (CPAP) and tidal volume based on different CPAP and oxygen concentration settings are shown in Figure 5. Tidal volume remained consistent across all combinations of CPAP and oxygen concentration settings, within ± 0.3 mL of the intended 6 mL volume. Flow remained consistent across all combinations of CPAP and oxygen concentration settings, with values registering 6.0
± 0.25 L/min. CPAP values registered within ± 0.5 cmH₂O of their set CPAP settings across all oxygen levels.

Figure 6 shows measured oxygen concentrations compared to the set percent of oxygen. Measured oxygen concentrations at settings of 30%, 40%, 60%, 80% and 100% fell within ± 1%, ± 2%, ± 3%, ± 4%, and ± 2%, respectively, of full scale (FS) of their intended set-point value. Generally, greater CPAP levels generated slightly greater oxygen concentrations, particularly for the settings of 60% and 80%.

Results from the humidity testing using the non-heated valved lung model are shown in Figure 7. Reference values were observed to be 44.3 ± 0.2% RH for laboratory ambient air, 1.7 ± 0.05% RH proximal to the oxygen cylinder. There were only small differences in RH in the silastic lung model receiving humidified gas through the bubble humidifier at 100%, 60%, and 30% oxygen. At these settings, RH was 87.7 ± 0.4%, 85.8 ± 0.2%, and 81.8 ± 0.2%, respectively. Combined effects from passive humidification and entrainment of ambient humidity, without assistance from heat, provided nearly two-fold greater RH than ambient and substantially greater humidity than gas exiting the oxygen cylinder.

Discussion

The major findings from these studies in vitro with the B-CPAP system show accurate control of CPAP and oxygen concentration, as well as adequate humidity delivery. Pressure and oxygen concentration were recorded well within ± .5 cmH₂O and ± 4%
respectively across all device settings. Relative humidity levels of >80% were achieved without the aid of heat or moisture from actual nasal passageways. CPAP system performance is dependent upon controlling pressure, blending oxygen, and humidifying breathing gases, and the B-CPAP system delivered on all three criteria.

The B-CPAP system maintains positive pressure by submerging the distal end of the breathing circuit in a water reservoir. This method of pressure generation has been used for decades in other bubble CPAP systems. Bubbling in the water column superimposes oscillatory pressure waveforms on top of the CPAP level that may make B-CPAP even more beneficial than other modes of CPAP delivery that do not generate pressure oscillations, such as ventilator driven CPAP.33 Even with these oscillations, the B-CPAP system consistently and accurately delivered various mean CPAP levels throughout the study. Preliminary data (see Supplement) showed measured pressure was within ± 0.4 cmH2O of the set pressure for a range of blended flow rates, indicating that the resistance of the breathing circuit did not significantly affect delivered CPAP. Furthermore, with the lung simulator, pressures were observed to be within ± 0.5 cmH2O of the set value regardless of oxygen concentration being delivered. Therefore, pressure delivery was not impacted by the unique Venturi because the correct pressure was delivered regardless of the Venturi’s setting. Overall, the B-CPAP system delivered pressure well within ± 1.0 cmH2O, a metric consistent with B-CPAP devices that are US FDA cleared.34
Traditional Venturis have not been used with infant CPAP systems before because they cannot generate any flow with back pressure as little as 0.6 cmH2O. A unique Venturi was recently described that can handle the low flows and thin tubing of infant oxygen delivery systems. This is the first published study to show high accuracy oxygen delivery within a spontaneously breathing lung model using a CPAP system that integrates an adjustable version of this unique Venturi. This represents a technological breakthrough because other air-oxygen blending mechanisms in CPAP systems and other oxygen delivery devices for infants all require high-pressure air and oxygen inputs, electricity, compressors, oxygen concentrators, or expensive pneumatic blenders. Because of these barriers, many providers in LMICs currently give patients unblended, 100% oxygen, which can cause Retinopathy of Prematurity (ROP), Bronchopulmonary Dysplasia and neurological injury. The WHO estimates there are 1.4 million blind children worldwide, two-thirds of whom live in LMICs where ROP is a major contributor to blindness, highlighting the need for inexpensive and accurate oxygen delivery mechanisms. We demonstrated consistent and accurate oxygen delivery across all CPAP and oxygen concentration levels in the B-CPAP system for the tested model.

WHO recommends starting CPAP at 30% oxygen and limiting use of higher oxygen concentrations. The B-CPAP system successfully delivered oxygen concentrations from 30-100%. The Venturi was most accurate at the lowest settings, which are the most commonly used. For all oxygen concentration settings, the device delivered a blend of air and oxygen within 4 percentage points of full scale of the setting. This is comparable to the accuracy of commercially available pneumatic blenders (± 3% FS).
that are expensive, complex, and require pressurized air.\textsuperscript{37} Therefore, the B-CPAP system delivered adequate range and accuracy of oxygen concentration settings in the tested model. Additional studies \textit{in vitro} are needed to determine accuracy across all patient sizes by testing the system on larger infant and pediatric models.

The need for heated humidification is clear during mechanical ventilation, where the normal heating and humidifying functions of the nasopharynx are bypassed, but less clear during noninvasive ventilation. Some CPAP systems contain heated humidifiers, while others do not include any supplemental humidification, but instead recommend applying nasal saline drops. Patients on these devices can experience nasal irritation and nose bleeds, indicating that some humidification is appropriate.\textsuperscript{38,39}

WHO and the American Association for Respiratory Care recommend humidification of oxygen delivered at flowrates greater than 4 L/min to prevent drying of nasal mucosae.\textsuperscript{40,41} The question remains whether passive bubble humidification is adequate or heated humidification is required during noninvasive ventilation. Many CPAP systems include an active heated humidifier, but these have drawbacks, including that they can cause condensation to accumulate in the circuit. Condensation may increase infection risk and has been associated with nasal obstruction\textsuperscript{42} and unintended increases in pressure levels.\textsuperscript{32}

There are no defined standards for optimal temperature and humidity levels of CPAP breathing gases. Some data from adults suggest that the minimum absolute humidity is
15 mgH\textsubscript{2}O/ L\textsuperscript{43}, while a heated humidifier commonly used to support neonates with B-CPAP in high resource settings generates 23- 27 mgH\textsubscript{2}O/ L.\textsuperscript{42} The tested B-CPAP system sources humidity both from the humidity present in entrained ambient air and a passive bubble humidifier. Therefore, the amount of humidity generated by the device depends on the temperature and humidity of the environment. Based on preliminary data (see Supplement) the B-CPAP system generated 22.0- 28.6 mgH\textsubscript{2}O/ L in an environment at 30°C and 30% RH, which is comparable to the temperature and humidity levels of hospitals in India and Tanzania. 22.0- 28.6 mgH\textsubscript{2}O/ L is well over the minimum 15 mgH\textsubscript{2}O/ L and is comparable to commercial devices commonly used in high resource settings. Furthermore, we observed relative humidity levels >80% with the bubble humidifier in our cool, dry (44% RH) lab. That level of humidity meets ISO recommended values and is comparable to recently published data on noninvasive devices with active humidifiers applied to neonatal mannequins.\textsuperscript{44} This observation leads to the assumption that exchange of humidity entrained through the Venturi (ambient) and humidifier combined with dried oxygen from the cylinder occurs very rapidly before entering the nasal cavity. Future studies should address whether additional increases in RH by bubble humidifiers is the result of increased water vapor, generation of aerosols, or both.

The B-CPAP system was able to generate all tested flow rates with a 50 psi source of oxygen. Preliminary data (see supplement) showed that the blended flow of air and oxygen out of the Venturi was always greater than the flow of pure oxygen from the external source for oxygen concentrations < 100% due to the addition of entrained
ambient air. This allows the user to conserve oxygen relative to improvised devices that source breathing gases only from pressurized oxygen sources. For example, consider an M tank filled to 2200 psi (7080 liters) that will be refilled when it is 25% full. For a patient that needs 6 LPM of breathing gases and 5 cmH₂O pressure on an improvised B-CPAP system providing 100% oxygen, the tank will last almost 15 hours. For the same patient on the subject B-CPAP system at 30% oxygen, the tank will last 26 hours.

Our study was limited in several regards. Only a pre-term neonatal lung model was used, so further evaluation is needed to determine if the B-CPAP system’s reliable performance translates to larger infants. Furthermore, there is a limit to the extent that data from a mechanical lung simulator can be applied to actual patients. For example, the lung compliance and volume of patients on B-CPAP may change over time, unlike in the lung simulator. Future studies in a dynamically breathing lung model may be useful to determine delivered pressure and oxygen over time. Our study did not consider oral leak and how a leaky seal around the nasal prongs may affect performance. We also only used a set flow of 6 L/min with the neonatal lung model. Understanding how higher flow rates affect performance would be worthwhile since precise control of flow with a meter may not be available in LMICs.

Finally, bench-top studies like this demonstrate efficacy of a device in ideal conditions, but in low resource settings where staff and biomedical engineering support are limited, it is difficult to create ideal conditions. Recent research has emphasized the challenges of implementing B-CPAP treatment in low resource settings. Further studies are
needed to see how effective this novel system is when integrated into healthcare facilities in different contexts.

Conclusion

The novel B-CPAP system is the first infant CPAP device that is simple to use and provides CPAP with humidification and oxygen concentration control without the need for electricity, compressed air, or manual power. The results of this study demonstrate that the B-CPAP system provides CPAP pressures, delivered oxygen concentration precision, and humidification comparable to commercial CPAP devices. The next steps are to build on the results of this study with further bench tests and identify implementation strategies to integrate B-CPAP systems effectively into health systems, optimize provider performance, and support quality care for newborns and infants suffering from respiratory distress.
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Figure Legends

**Figure 1.** The B-CPAP system (A) comprises of: (1) An external pressurized oxygen source, (2) Venturi, (3) Two bacterial and viral filters- one on the inspiratory and one on the expiratory limb, (4) Humidifier, (5) Nasal prongs, (6) Water column with an adjustable wand to control the delivered pressure from 4-10 cm H$_2$O, and (7) Warmer bracket that stabilizes the system and allows it to be placed inside infant radiant warmers. The patient interface (B) comprises of: (1) Hat; (2) Two safety pins, (3) Two rubber bands; (4) Hook tape moustache; and (5) Loop tape strips. The Venturi (C) is the distinguishing feature of the B-CPAP system; it delivers 30-100% oxygen by mixing pressurized oxygen and ambient air.

**Figure 2.** 3D printed nasal airway of preterm infant taken from a 28-week-old subject. Full model is shown on the left (A) and the modular nasal airway is shown on the right (B). The nasal passages and closed oral cavity are clearly shown in B.

**Figure 3.** Test set-up for PEEP and oxygen concentration performance testing.

**Figure 4.** Test set-up for humidification performance testing.

**Figure 5.** Results for PEEP (A) and Tidal Volume (B) for all set CPAP levels and oxygen concentration settings. Each bar indicates the mean value of 20 breaths and the error bars denote standard deviation.
Figure 6. Measured oxygen concentration as a function of Set oxygen concentration to illustrate the deviation from the intended value. Each bar indicates the mean value of 20 breaths and the error bars denote standard deviation. In each group, the different set CPAPs are denoted by different colors.

Figure 7. Relative humidity at each condition. Each bar indicates the mean of either 1 minute of observation or 20 breaths. The error bars denote standard deviation. The first two conditions are reference values to the latter three conditions which are simulated breathing.
Quick Look

Current Knowledge
CPAP has been used for decades to treat newborns and infants with respiratory
distress in high resource settings. Studies have shown that CPAP can reduce mortality
when implemented in low resource settings, but CPAP treatment remains unavailable in
many low resource hospitals due to its cost and other barriers. Several low-cost bubble
CPAP systems have been designed recently to be more accessible, but these systems
all require continuous electricity and can still be prohibitively expensive.

What This Paper Contributes To Our Knowledge
A novel newborn and infant CPAP system has been developed that does not require
electricity, compressed air, or manual power. This study evaluated device performance
in a spontaneously breathing lung model. The device provided pressure, oxygen
concentrations and humidification to an appropriate range and accuracy for newborns
and infants.
Table 1: Lung Model configuration and testing conditions

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<th>Variable</th>
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<tr>
<td>Compliance (mL/cmH₂O)</td>
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<tr>
<td>Resistance (cmH₂O/L×s⁻¹)</td>
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<tr>
<td>Pleural Pressure (cmH₂O)*</td>
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<td>Tidal Volumes (mL)</td>
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<tr>
<td>Respiratory Rate</td>
<td>50</td>
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<tr>
<td>Minute Ventilation (L/min)</td>
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</tbody>
</table>

*Simulated pleural pressures were adjusted to maintain tidal volume of 6 mL at all testing conditions.
Vayu bCPAP system (A) comprises of: (1) An external pressurized oxygen source, (2) Air and oxygen blender, (3) Two bacterial and viral filters- one on the inspiratory and one on the expiratory limb, (4) Humidifier, (5) Nasal prongs, (6) Pressure generator with an adjustable wand to control the delivered pressure from 4-10 cm H2O, and (7) Warmer bracket that stabilizes the system and allows it to be placed inside infant radiant warmers. The patient interface (B) comprises of: (1) Hat; (2) Two safety pins, (3) Two rubber bands; (4) Hook tape moustache; and (5) Loop tape strips. The blender (C) is the distinguishing feature of the Vayu system; it delivers 30-100% oxygen by mixing pressurized oxygen and ambient air.
3D printed nasal airway of preterm infant taken from a 28-week-old subject. Full model is shown on the left (A) and the modular nasal airway is shown on the right (B). The nasal passages and closed oral cavity are clearly shown in B.
Test set-up for PEEP and oxygen concentration performance testing.
Test set-up for humidification performance testing.
Results for PEEP (A) and Tidal Volume (B) for all set CPAP levels and oxygen concentration settings. Each bar indicates the mean value of 20 breaths and the error bars denote standard deviation.
Measured oxygen concentration as a function of set oxygen concentration to illustrate the deviation from the intended value. Each bar indicates the mean value of 20 breaths and the error bars denote standard deviation. In each group, the different set CPAPs are denoted by different colors.
Relative humidity at each condition. Each bar indicates the mean of either 1 minute of observation or 20 breaths. The error bars denote standard deviation. The first two conditions are reference values to the latter three conditions which are simulated breathing.