Nasal Cannula, CPAP, and High-Flow Nasal Cannula: Effect of Flow on Temperature, Humidity, Pressure, and Resistance

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Abstract

Background: *Delivery of warm, humidified, supplemental oxygen via high-flow nasal cannula has several potential benefits; however, the high-flow range may not maintain humidification and temperature and in some cases may cause excessive expiratory pressure loading.*

Objective: *To compare the effect of flow on temperature, humidity, pressure, and resistance in nasal cannula (NC), continuous positive airway pressure (CPAP), and high-flow nasal cannula (HFNC) in a clinical setting.*

Methods: *The three delivery systems were tested in the nursery using each instrument's recommended specifications and flow ranges (0-3 L/min and 0-8 L/min). Flow, pressure, temperature, and humidity were measured, and resistance was calculated.*

Results: *For all devices at 0-3 L/min, there was a difference ($p<0.01$) in temperature (NC 35.9°C > CPAP 34.5°C > HFNC 34.0°C), humidity (HFNC 82% > CPAP 77% > NC 57%), pressure (HFNC 22 cmH_2O > NC 4 cmH_2O > CPAP 3 cmH_2O), and resistance (HFNC 636 cmH_2O/L/sec > NC 270 cmH_2O/L/sec > CPAP 93 cmH_2O/L/sec) as a function of flow. For HFNC and CPAP at 0-8 L/min, there was a difference ($p<0.01$) in temperature (CPAP 34.5°C > HFNC 34.0°C) in humidity (HFNC 83 % > CPAP 76 %), pressure (HFNC 56 cmH_2O > CPAP 14 cmH_2O) and resistance (HFNC 783 cmH_2O/L/sec > CPAP 280 cmH_2O/L/sec) as a function of flow.*

Conclusions: *Gas delivered by HFNC was more humid than NC and CPAP. However, the higher pressure and resistance delivered by the HFNC system may have clinical relevance, such as increased work of breathing, and warrants further in vivo studies.* (Biomedical Instrumentation & Technology; 2011:1:69–74).

Introduction

Nasal cannula (NC) with supplemental oxygen is often used to transition infants from mechanical ventilatory support and continuous, positive end expiratory pressure using nasal prongs (CPAP) support to room air. In these cases, the gas flow with nasal cannula is generally at 2 L/min or less. Conventional nasal cannula in neonates provides unheated, humidified gas. Attempts to deliver warm gas via nasal cannula using available systems have resulted in an unacceptable amount of condensation in the tubing.

Delivery of unheated gas via nasal cannula has several potential adverse consequences. Maintaining normal body temperature in the face of increased convective heat loss when receiving unheated gas may lead to an increase in metabolic rate and the conversion of life sustaining substrates to acidic metabolic by-products. Kopelman and Holbert[1] reported increased nasal secretions, mucosal injury, and coagulase-negative staphylococcal sepsis in extremely low-birthweight infants who were receiving unheated humidified gas via nasal cannula. Kopelman[2] also reported two infants who developed upper-airway obstruction secondary to mucosal injury from receiving unheated, humidified gas. In addition, Greenspan et al[3] demonstrated in premature infants that resuscitation with unhumidified gas at room temperature resulted in adverse airway responsiveness as compared to warmed, humidified gas resuscitation.

In an attempt to circumvent several of these aforementioned problems, high-flow nasal cannula have been developed to deliver high-flow, warm, humidified gas via nasal cannula. For neonates, the recommended gas flow rate is 1 to 8 L/min. However, the consequence of high-flow rate in infants may cause excessive expiratory loading which may result in inadvertent end-distending pressure and potential pulmonary injury. Pulmonary over-distention can cause air leak and activation of the Herring-Breuer reflex in which feedback response by stretch receptors limits inspirations and results in apnea. Locke[4] demonstrated that delivered oxygen and end-distending pressure varied depending on breathing patterns, cannula size, and infant size. Locke showed that there was unregulated positive end-distending pressure and altered breathing patterns in preterm infants receiving flow rates of 0.5 to 2 L/min via nasal cannula. Sreenan[5] also demon-

	Internal diameter (mm)	Outer diameter (Tip) (mm)	Prong length (mm)
Nasal Cannula (NC)			
Tubing length – 7 feet	1.6	1.85	3
CPAP –9F	3.5	4.0	3
CPAP – 10.5F	4.0	4.5	3
CPAP – 12F	4.5	5.0	3
HFNC – premature Tubing length – 7 feet	1.27	1.52	7.62
HFNC – infant Tubing length – 7 feet	1.6	1.85	7.62

Table 1. Cannulae dimensions and specifications. (All data based on manufacturer's specifications and verified by our measurements.)

strated that flow rates of 1 to 2.5 L/min via nasal cannula generated end-distending pressure similar to CPAP at 6 cm H_20. The flow needed to generate the end-distending pressure was proportional to the size of the baby.

Although high-flow nasal cannula devices are designed to deliver warm humidified gas via nasal cannula, the recommended high-flow rates are a matter of concern for infant application. With these issues in mind, the purpose of this study is to compare temperature, humidity, pressure, and flow-resistance measurements taken during respiratory gas delivery with conventional NC, CPAP, and HFNC in a neonatal intensive care setting.

Methods

Using continuous gas flow, temperature, humidity, and pressure were measured at the distal end of each cannula from three devices: a conventional nasal cannula connected to a non-heated bubble humidifier (Salter Labs, Arvin, CA), a flow generator CPAP (Viasys, Yorba Linda, CA), and a HFNC (Vapotherm, Inc. Annapolis, CA). As shown in Figure 1, measurements were made in a warmed isolette (Air Shields C-100 Incubator, Hatboro, PA). An infant nasal cannula (Salter Labs, Arvin, CA; http://salterlabs.com/store/downloads/48.pdf) was used with conventional nasal cannula device, INCA infant nasal prongs (Cooper Surgical, Trumbull, CT; http://www.coopersurgical.com/Documents/INCA%20Brochure.pdf) 9Fr, 10.5Fr, and 12Fr were used with the CPAP device, and the premature and infant Vapotherm nasal cannulae (Vapotherm, Inc., Annapolis, MD) were used with the Vapotherm unit. It should be noted that although the 9Fr, 10.5Fr, and 12Fr were tested with the CPAP device and both the premature and infant Vapotherm nasal cannulae were tested, the results are presented for the 10.5 Fr INCA infant nasal prongs and the infant Vapotherm nasal cannula, since inter-cannulae variation was small as a function of the tested flow range. The dimensions for all of the cannulae are presented in Table 1.

The distal end of the cannula and a lung simulator (laboratory developed hood; a 2.5 liter box with a 0.5 cm venting hole and a container of water inside) were placed inside an isolette warmed to 37°C. The lung simulator's temperature in the warmed isolette and humidity from the container of water reflects the temperature (37°C)

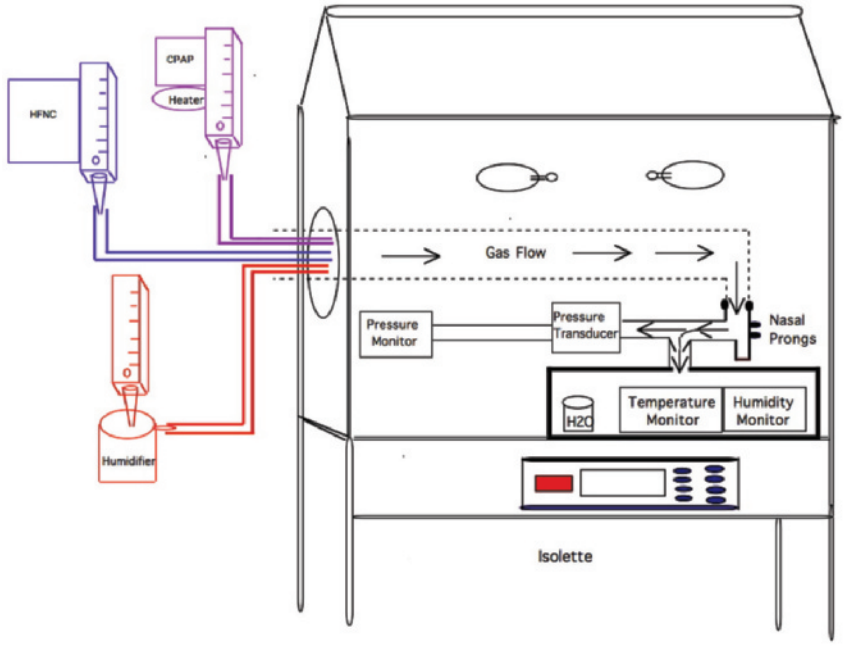

Figure 1. Schematic of system test apparatus used in the neonatal intensive care unit. The schematic illustrates how all three devices (NC, CPAP, and HFNC) were tested; however, each device was independently tested.

	NC	CPAP	HFNC
Flow Ranges	1-3 L/min	1-8 L/min	1-8 L/min
Device Set Temperature	24.9 °C	36.2°C	39°C

Table 2. Flow ranges and temperature settings.

and humidity (100% saturation) of an infant's airway/lungs and was developed to establish a uniform thermal, humidification, and pressure load across all devices. The vent was used to simulate a constant leak across all devices when tested over the recommended flow ranges. A temperature and humidity sensor/monitor (Fisher Scientific Traceable Temperature and Humidity Monitor; serial-number ISO 17025) was placed inside the lung simulator. A "Y" connector was inserted into the cannula wall opposite the nasal prongs. One end of the "Y" connector was connected to the cardiorespiratory monitor (Hewlett Packard; Model 78801B; pressure range calibrated for 0–150 mmHg), and the other end was inserted into the lung simulator.

Flow ranges of medical gas (220 C and < 5% humidity) were 0–3 L/min for the nasal cannula and 0–8 L/min for CPAP and Vapotherm as per manufacturer's specifications. (See Table 2.) In the flow range of 0–3 L/min, the flow rate was increased in 0.5 L/min increments. In the flow range of 0–8 L/min, the flow rate was increased in 1 L/min increments. Thirty minutes after each flow rate change, simultaneous measurements of temperature, humidity, and pressures were made. Gas flow was validated using a rotameter (Cole-Parmer; EW32457-46; http://www.coleparmer.com/catalog/product_view.asp?sku=3246152&pfx=EW). Resistance to gas flow across the individual nasal prongs was calculated by dividing upstream pressure by gas flow.

Analysis

Temperature, humidity, pressure, and resistance were analyzed as a function of flow. All three devices were compared at flow rates of 0–3 L/min. CPAP and HFNC

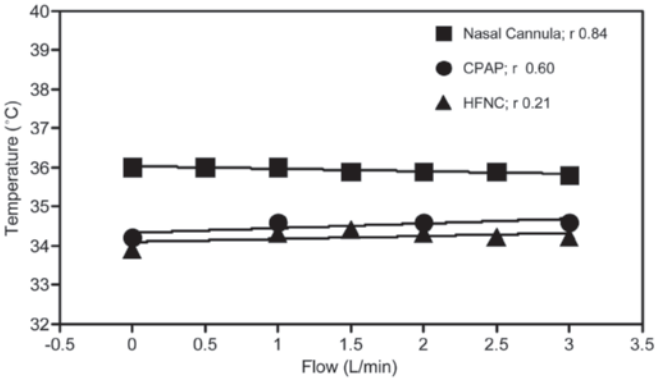

Figure 2a. Temperature-Flow Relationships

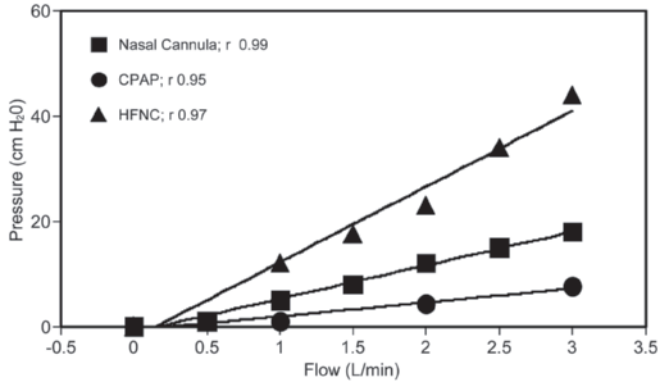

Figure 2c. Pressure-Flow Relationships

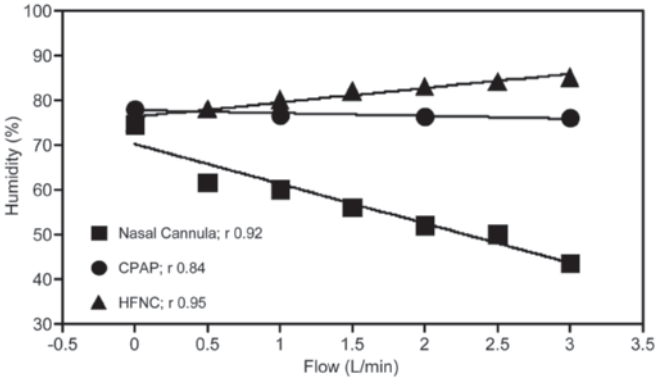

Figure 2b. Humidity-Flow Relationships

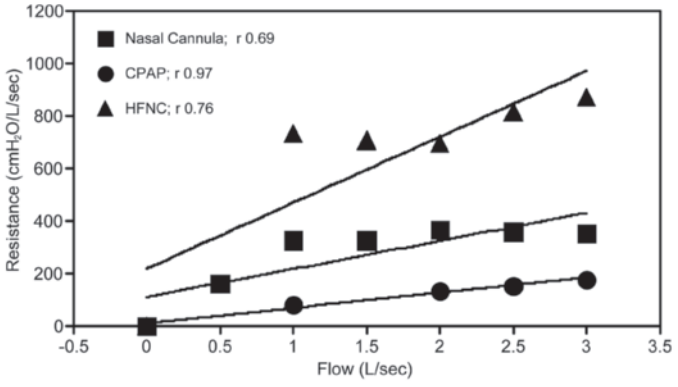

Figure 2d. Resistance-Flow Relationships

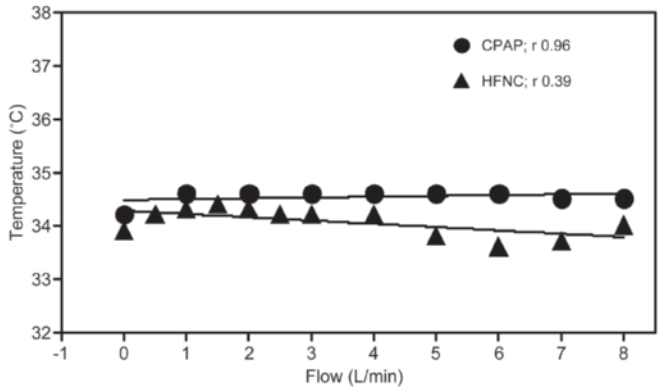

Figure 3a. Temperature-Flow Relationships

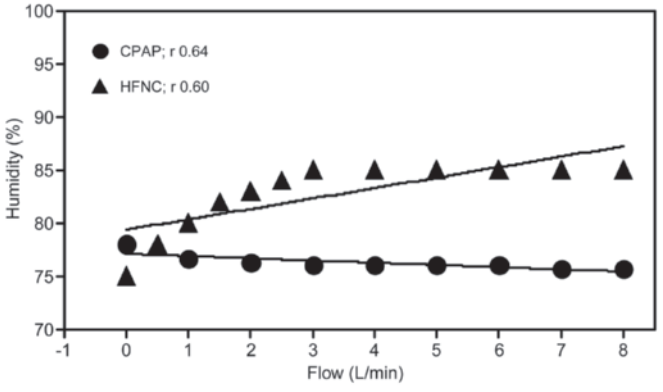

Figure 3b. Humidity–Flow Relationships

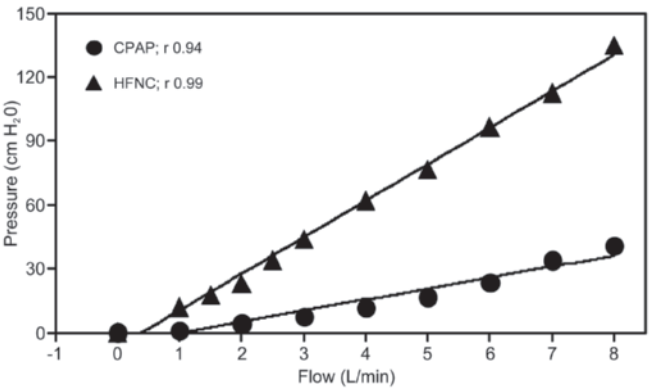

Figure 3c. Pressure-Flow Relationships

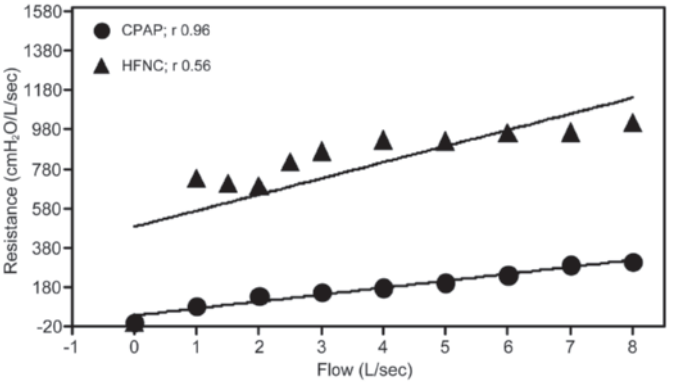

Figure 3d. Resistance-Flow Relationships

were compared at flow rates of 0–8 L/min. These data were statistically analyzed using regression analysis and ANOVA. Post-hoc analysis using Bonferroni was used to determine differences between devices. Data are reported as means and ±SD.

Results

There were no differences in temperature, humidity, pressure, and resistance within each device as a function of cannula size. The relationships of temperature, humidity, pressure, and resistance versus flow for all three devices at 0–3 L/min and for CPAP and HFNC at 0–8 L/min are shown in Figures 2a-d and 3a-d.

When comparing all three devices at flow ranges of 0–3 L/min, there was a significant difference ($p<0.05$) in temperature, the NC temperature of 35.9±0.13°C > CPAP temperature of 34.5±0.25°C > HFNC temperature of 34±0.41°C. With increasing flow rates, the conventional NC delivered significantly less ($p<0.01$) humidified gas of 57±9.8%, compared to CPAP humidity of 77±1.0% and HFNC humidity of 82±3.5%. There was no significant difference in humidity between CPAP and HFNC. When pressures were measured at a "Y" connector inserted into the cannula wall opposite the nasal prongs, the HFNC had significantly ($p<0.01$) higher pressures across all flows. Specifically at 3 L/min, we found that HFNC= 34±4.0 cmH_2O, NC = 18±1.0 cmH_2O and CPAP = 7.71±0.8 cmH_2O. There was no group difference in pressure between NC and CPAP. When comparing all three devices, resistance calculations resulted in a significant difference ($p<0.01$) as a function of increasing flow rates. More specifically at 3 L/min, HFNC = 816±92 cmH_2O/L/sec, NC= 367±19 cmH_2O/L/sec, and CPAP= 154±16 cmH_2O/L/sec.

Comparison of temperature, humidity, pressure and resistance over a flow range of 0–8 L/min using CPAP and HFNC were made. CPAP mean temperature of 34.5±0.19°C was significantly higher ($p<0.01$) than HFNC mean temperature of 34±0.45°C. Humidity provided by HFNC was significantly higher ($p<0.01$) at 83±3.1% than CPAP humidity of 76±0.81%. Similar to the lower flow rates, HFNC pressure and resistance were

dependent on flow and significantly greater ($p<0.01$) than CPAP at high flows. For example at 8 L/min, mean pressure of HFNC = 135±18 cmH_2O and CPAP = 41±0.79 cmH_2O. Also at 8 L/min, mean resistance of HFNC = 1015±137 cmH_2O/L/sec and CPAP = 309±5.89 cmH_2O/L/sec.

Discussion

This study characterizes the effect of gas flow on temperature, humidity, pressure, and resistance profiles of three different respiratory support systems under well controlled *in vitro* conditions (fixed thermal, humidification, and respiratory load). This *in vitro* model was designed to evaluate the pressure and resistive load delivered by the three devices, and the effect of the temperature and humidity load on the airway's milieu at specific flow conditions in a typical neonatal intensive care setting.

The pressure in the newborn's airways depends on the pressure or resistive load of the respiratory support device and the effort generated by the infant. Since resistive loading can impact on lung volume, breathing patterns, and gas exchange, the resistive load that the infant would experience was calculated from the pressures measured at specific flow conditions for each device. Similarly, each device exerts a thermal and humidification load on the infant. The temperature and humidity condition experienced by the infant depends on the thermal and humidity load of the device and the thermal and humidity condition of the airway. These *in vitro* studies were conducted for safety reasons prior to clinical studies, since these data have relevance for clinicians toward optimizing non-invasive respiratory support in neonates.

Nasal cannula generates a pressure by a continuous flow of unheated humidified gas. A flow-driver continuous positive airway pressure (CPAP) device generates a variable flow that is heated and humidified, and maintains a constant pressure using injector jets directed towards each nasal prong producing a Bernoulli effect. This system produces a fluidic flip with each expiratory breath causing the gas flow to flip to the expiratory limb. This phenomenon is known as the Coanda effect. In contrast to the other devices, the Vapotherm HFNC delivers a continuous flow of warm, humidified gas by transpiration of water vapor across a membrane.

One of the functions of the upper respiratory tract is to deliver warm, humidified, particle free gas to the alveoli. During inspiration, there is a transfer of heat and water from the respiratory tract mucosa to the gas by means of convection and evaporation. On expiration, heat and water vapor return to the respiratory tract mucosa from the alveolar gas. This process is designed to protect the lung and conserve body heat. Under normal conditions, there is loss of water and kilocalories of heat in the expired gas. When cold, dry air is inspired, there is an increase in the metabolic rate and oxygen consumption, and additional loss of kilocalories. Similarly, if the air inspired is humidified and above body temperature the neonate will gain heat and increase metabolic rate and oxygen consumption.

When comparing all the devices at 0–3 L/min, the temperature of the nasal cannula was significantly higher than CPAP and HFNC. This significance was due to a higher starting temperature at baseline and was not due to the specific gas delivery system. The initial temperature of each respiratory device was dependent on several factors including material properties of the specific device, heat sources, and conduction/convection exchange with the environment. The gas for the NC was taken directly from the hospital's central source and perhaps environmental changes may have influenced this temperature differently than the other devices. However, as flow increased, the temperature of the NC decreased from 36°C to 35.8°C. The tubing of the nasal cannula extended from the unheated bubble humidifier to the entry-way of the warm isolette allowing for convective heat loss to the room (ambient temperature of 23–25°C). The potential clinical result of this heat loss is a greater expenditure of calories in the neonate. The temperatures of both CPAP and HFNC increased, from 34.2°C to 34.6°C and from 33.9°C to 34.2°C respectively with increasing flow rate. This effect was also seen at the higher flows with temperature increasing as flow increased in both CPAP and HFNC. Whereas the heating systems of both CPAP and HFNC increased the gas temperature, it did not exceed body temperature. The delivery of warm gas provides an environment where energy is conserved, growth is improved, and a normal metabolic rate is maintained.

Any type of neonatal respiratory support requires humidification to protect the airways from inflammation, necrosis, and muco-ciliary injury. Relative humidity is the ratio of water vapor in the air to the amount of water vapor that would be present in the gas at saturation and is expressed as a percentage of saturation. The relative humidity of a gas fully saturated with water vapor at any temperature is 100%. When a gas that is fully saturated comes in contact with a warm environment, such

as a heated respiratory circuit, the relative humidity will decrease.

In this study, humidity decreased from 75% at zero flow to 43% at 3 L/min in the nasal cannula. This might be explained by the difference in temperature of the bubble humidifier at room temperature (23–25°C) and the temperature at the prongs of the nasal cannula in the warmed isolette (37°C). There was also a small decrease in humidity in CPAP device from 78% at no gas flow to 76% at 3 L/min and 8 L/min. This is most likely due to the gas contacting the heated wire in the circuit. Conversely, the humidity in the HFNC system increased with increasing flow rate. The humidity was 75% at zero flow rate and increased to 85% at 3 L/min and 8 L/min. This is most likely due to this specific HFNC's transfer membrane technology.

In this *in vitro* study, the pressures measured increased linearly with increasing flow. The HFNC pressures were significantly higher than CPAP and conventional NC. The pressure measured with HFNC increased from 12 cmH_20 at 1 L/min to 34 cmH_20 at 3 L/min and to 135 cmH_20 at 8 L/min. The pressure measured with the CPAP prongs increased from 1 cmH_20 at 1 L/min to 7.7 cmH_20 at 3 L/min and to 41 cmH_20 at 8 L/min. The pressure measured with the conventional NC was 5 cmH_20 at 1 L/min and 18 cmH_20 at 3 L/min. Similar findings were found for the calculated resistance. Studies have demonstrated that end-distending pressure can be delivered via nasal cannula with flow rates less than 2.5 L/min.[4, 5] Concerns of expiratory loading, pulmonary over-distention, and altered breathing patterns from these unregulated, end-distending pressure delivered via the lower flow conventional NC should make clinicians cautious when using higher flow rates.[6]

At first glance, the use of HFNC for oxygen delivery to the newborn and preterm infant seems like an improved intervention with better thermal and humidity control of inspired gas.[7] However, the high pressures and resistance to airflow measured *in vitro* may affect the infant's respiratory pattern and its effect *in vivo* should be evaluated before the HFNC is readily adopted for smaller infants. In light of the results presented herein, when gas flows are in excess of 1–2 L/min, it is necessary to match infant airway orifices, cannula size, and flow such that the infant is not given inadvertent end-expiratory pressure and compromised with respect to work of breathing. More specifically, we should have systems in place which would detect and possibly prevent these occurrences under a variety of clinical conditions. ■

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