Lung Recruitment and Breathing Pattern During Variable Versus Continuous Flow Nasal Continuous Positive Airway Pressure in Premature Infants: An Evaluation of Three Devices

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ABSTRACT. Objective. To determine whether lung volume changes and breathing pattern parameters differ among 3 devices for delivery of nasal continuous positive airway pressure (CPAP) in premature infants.

Methods. Thirty-two premature infants receiving nasal CPAP for apnea or mild respiratory distress were enrolled. Birth weight was (mean ± standard deviation) 1081 ± 316 g, gestational age 29 ± 2 weeks, age at study 13 ± 12 days, and fraction of inspired oxygen (FIO2) at study 29 ± .1. Three devices, applied in random order, were studied in each infant: continuous flow nasal CPAP via CPAP prongs, continuous flow nasal CPAP via modified nasal cannula, and variable flow nasal CPAP. After lung recruitment to standardize volume history, changes in lung volume (ΔVL) were assessed at nasal CPAP of 8, 6, 4, and 0 cm H2O using calibrated direct current-coupled respiratory inductance plethysmography.

Results. ΔVL was significantly greater overall with the variable flow device compared with both the nasal cannula and CPAP prongs. However, ΔVL was not different between the cannula and the prongs. Respiratory rate, tidal volume, thoraco-abdominal asynchrony, and FIO2 were greater with the modified cannula than for either of the other 2 devices.

Conclusion. Compared with 2 continuous flow devices, the variable flow nasal CPAP device leads to greater lung recruitment. Although a nasal cannula is able to recruit lung volume, it does so at the cost of increased respiratory effort and FIO2. Pediatrics 2001;107:304–308; nasal CPAP, lung volume changes, preterm infants, respiratory inductance plethysmography.

ABBREVIATIONS. CPAP, continuous positive airway pressure; ΔVL, change in lung volume; RIP, respiratory inductance plethysmography; DC, direct current; FIO2, fraction of inspired oxygen; VT, tidal volume; AC, alternating current; RR, respiratory rate; VE, minute ventilation; SD, standard deviation.

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The use of continuous positive airway pressure (CPAP) in premature infants was first described by Gregory et al1 in 1971. CPAP may benefit preterm infants with respiratory distress by recruiting alveoli and stabilizing functional residual capacity.2,3 In infants with obstructive apnea, it may help splint the upper airway.4,5 Currently available nasal CPAP devices (nasal CPAP) use a variety of prong designs and deliver CPAP via either continuous or variable gas flow. To our knowledge, there are no data comparing nasal CPAP devices in their ability to recruit lung volume in preterm neonates. Reliable information about lung recruitment during nasal CPAP is useful both for the clinical management of infants and for comparison of efficacy of the various methods available for its administration.

Our main objective was to compare changes in lung volume (ΔVL) and breathing pattern parameters with 3 nasal CPAP devices that are currently used clinically in premature infants.

METHODS

Premature infants weighing <1800 g at birth who were receiving nasal CPAP for apnea or mild respiratory distress and were otherwise medically stable were eligible for enrollment. The protocol was reviewed and approved by the institutional review board of Cooper Hospital/University Medical Center. Informed consent was obtained from a parent or guardian before testing. Each infant was evaluated on each of the 3 devices, applied in random order as designated on prepared cards stored in sealed envelopes, and opened at the time of study. Three nasal CPAP devices, as described below, were evaluated.

Continuous Flow Nasal CPAP Using Nasal Prongs

The nasal prongs used were Inca nasal CPAP prongs (Ackrad Laboratories, Cranford, NJ). They were attached via ventilator tubing to an infant positive pressure ventilator set in CPAP mode. Continuous flow of 6 L/minute was used and was not changed during the study. The prong size used was the largest prong that fit the infant’s nares without blanching the surrounding tissue. As is conventionally done using this method of nasal CPAP, the amount of airway pressure applied was varied by adjusting the CPAP setting on the ventilator, which varies the resistance at the exhalation valve.

Continuous Flow Nasal CPAP Using a Nasal Cannula

This device, commonly used in our nursery before this study, was fashioned by connecting a 2.5-mm endotracheal tube adapter to an infant-sized nasal cannula (prong internal diameter: 1.5 mm; Salter Laboratories, Arvin, CA). The device could then be attached to any conventional infant ventilator set in CPAP mode. As with the nasal prongs, a continuous flow of 6 L/minute was used in all infants and was not changed during the study. Also similarly, the
amount of CPAP delivered was varied by changing the CPAP setting on the ventilator.

**Variable Flow Nasal CPAP**

The variable flow device used was the Aladdin/Infant Flow nasal CPAP system (Hamilton Medical, Reno, NV; manufactured by BMV Ltd, Brighton, UK; currently distributed by SensorMedics Corp, Yorba Linda, CA as the Infant Flow Nasal CPAP system). The amount of CPAP delivered with this device is changed by varying the amount of gas flow. The largest prongs that fit easily into the nares were used in each infant.

**Instrumentation**

Infants were fed just before instrumentation. Respiratory inductance plethysmography (RIP) bands were then fitted around the chest and abdomen (SensorMedics Corp). The RIP equipment was direct current (DC)-coupled to record static ΔVL (Somnostar; SensorMedics Corp). An esophageal balloon catheter (Neonatal Esophageal Balloon Catheters; Ackrad Laboratories, Cranford, NJ) was positioned in the lower esophagus for estimation of pleural pressure. Appropriate positioning of the esophageal catheter was confirmed by noting a reproducible pressure tracing that closely tracked airway-opening pressure when the airway was occluded. Air leaks from the mouth were detected using a thermistor (BreathSensor; Nellcor Puritan Bennett, Eden Prairie, MN) and its output was continuously recorded (EdenTrace II Plus; EdenTec, Eden Prairie, MN). Only data with no air leak at the mouth were used. If necessary, the infant’s mouth was gently closed during data collection. Respiratory rate, heart rate, and oxygen saturation were continuously monitored during study on the infant’s bedside monitor. Fraction of inspired oxygen (FiO2) was recorded at start of study and was adjusted when necessary to maintain oxygen saturation between 90% and 96%.

**Data Acquisition and Analysis**

All infants were studied supine and while resting quietly. After placing the RIP bands around the infant’s chest and abdomen, and before initiating the nasal CPAP protocol, baseline airflow and pressure were measured using facemask pneumotachography (Neonatal Flow Sensor 7218 [dead space: .8 mL]; Novametrix, Wallingford, CT). Esophageal (transpulmonary) pressure and airflow flows were measured with the Ventraq system (Novametrix). From a series of 10 to 15 leak-free breaths, airway flow was integrated to calculate tidal volume (VT). These breaths were then matched with the corresponding RIP breaths to calibrate the latter.6,7 Esophageal pressure, flow, and volume data were used to obtain baseline lung mechanics data as well as to calibrate the RIP.

Each nasal CPAP device was then applied to the infant in random order. With each device, CPAP was first increased over 10 breaths to obtain baseline lung mechanics data as well as to calibrate the RIP equipment. The time lag between chest and abdominal movement and resulting width of the Lissajous loop can be quantified by the phase angle (θ in degrees), which is proportional to the degree of thoracoabdominal asynchrony.

**Sample Size Calculation**

Sample size calculations were based on finding a clinically significant ΔVL between any 2 of the 3 devices. On the assumption that a difference of 20% would be clinically significant, and using a .05 significance criterion for testing mean differences and a desired power of 80% to 85%, the required sample size was between 26 and 32.9

**Statistical Analysis**

ΔVL, θ, VT, VE, and RR data were analyzed as mixed linear models in a randomized block factorial design, where devices and nasal CPAP levels were considered fixed effects and participants were treated as random blocks.10 Differences in FiO2 were analyzed using the Wilcoxon rank sum test. Least square, pair-wise mean comparisons were used to test for differences between devices, within nasal CPAP levels, and devices-within-nasal CPAP levels. Satterthwaite approximations were used to adjust for the effects of missing cells. Analyses were performed using the mixed procedure in SAS, Version 6.12 (SAS Institute Inc, Cary, NC).

**RESULTS**

Measurements were successfully obtained in 32 of 35 recruited infants. A summary of their demographics and baseline clinical parameters is provided in Table 1.

**Lung Recruitment (ΔVL)**

ΔVL at the 3 different nasal CPAP levels relative to nasal CPAP = 0 are shown in Fig 2. ΔVL decreased with decreasing nasal CPAP support for all 3 devices. The ΔVL was similar for both continuous flow devices. However, ΔVL was significantly larger overall with the variable flow device (P < .001).

**Breathing Pattern (VT, RR, and VE)**

Tidal volumes did not differ among the groups at any nasal CPAP level. Respiratory rate, and, therefore, VE, was significantly higher with the cannula, at all 3 nasal CPAP levels, than with the other 2 devices (Fig 3).

**Breathing Efficiency (θ and Oxygen Requirement)**

Thoracoabdominal asynchrony as determined by RIP phase angle (θ) is shown in Fig 4. No significant differences were found between θ with any nasal CPAP level.

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**TABLE 1.** Patient Characteristics (n = 32; Mean ± SD)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birth weight (g)</td>
<td>1081 ± 316</td>
</tr>
<tr>
<td>Gestational age (wk)</td>
<td>29 ± 2</td>
</tr>
<tr>
<td>Weight at study (g)</td>
<td>1139 ± 278</td>
</tr>
<tr>
<td>Age at study (d)</td>
<td>13 ± 12</td>
</tr>
<tr>
<td>FiO2 at study</td>
<td>.29 ± .10</td>
</tr>
<tr>
<td>Previous days on ventilator</td>
<td>7 ± 11</td>
</tr>
<tr>
<td>Baseline CCl (ml/cm H2O)</td>
<td>3.26 ± 2.42</td>
</tr>
<tr>
<td>Baseline Rlu (cm H2O/L/s)</td>
<td>54.5 ± 38.0</td>
</tr>
</tbody>
</table>

CCl indicates lung compliance; Rlu, lung resistance.
CPAP level for the continuous flow nasal prongs compared with the variable flow device. However, $\theta$ was significantly higher for the cannula, compared with both the other devices ($P < .001$). Percent oxygen required to maintain saturation between 90% and 96% increased from baseline (before study) by an average of 7% during study with the cannula, compared with both the other devices. Oxygen changes from baseline were small and similar for the variable flow device and the continuous flow nasal prongs (Fig 5).

**DISCUSSION**

Few comparative studies of nasal CPAP devices have been published. In particular, we are unaware of any studies that compare lung recruitment with different nasal CPAP devices as they are currently being used in infants. The main objective of this study was to compare the efficacy of 3 distinct devices—2 continuous flow devices and 1 variable flow device—in recruiting lung volume at various nasal CPAP levels.

Factors determining the effectiveness of any nasal CPAP device include its associated work of breathing, flow characteristics, ease of application, and the comfort level of the infant once the device is in place. Continuous flow nasal CPAP is increased or decreased by varying the resistance to exhalation at the exhalation valve on an infant ventilator. Nasal prongs are commonly used to provide continuous

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**Fig 2.** Comparison of the 3 devices: $\Delta V_L$ (mean ± standard deviation [SD]) as a function of nasal CPAP level. NC indicates nasal cannula; VF, variable flow device; NP, nasal prongs ($P < .001$ VF vs both NC and NP).

**Fig 3.** Comparison of the 3 devices: respiratory rate (mean ± SD), as a function of nasal CPAP level. NC indicates nasal cannula; VF, variable flow device; NP, nasal prongs ($P < .001$ NC vs VF; $P = .001$ NC vs NP).

**Fig 4.** Comparison of devices: phase angle ($\theta$; mean ± SD), as a function of nasal CPAP level. NC indicates nasal cannula; VF, variable flow device; NP, nasal prongs ($P < .001$ NC vs VF and NP).

**Fig 5.** Comparison of devices: $\Delta FIO_2$ from baseline level before study (mean ± SD), as a function of nasal CPAP level. NC indicates nasal cannula; VF, variable flow device; NP, nasal prongs ($P < .001$ NC vs VF and NP).
flow nasal CPAP. Concerns exist, however, about increased work of breathing with nasal prongs, compared with face mask CPAP. Additionally, nasal prongs often become dislodged making care of these infants difficult. Locke et al. demonstrated that inadvertent CPAP can be provided with flow through a nasal cannula. Because nasal cannulas are easy to apply and keep in place, their use had become popular in our neonatal intensive care unit to provide nasal CPAP. This cannula system had not been investigated, and the amount of CPAP actually generated was not clear.

The variable flow nasal CPAP device, in contrast to the continuous flow devices, generates CPAP at the airway. It uses jet flows at high velocity, which can entrain gas to assist inspiration on demand and keep the CPAP level constant. On exhalation, the design of the nasal prongs results in gas flow being shunted through an expiratory outlet rather than continue toward the nares, which can increase expiratory work. Two physical model studies of the variable flow device have been published. Moa et al. compared it with a continuous flow system using a lung model and found that the variable flow device showed less variation in mean airway pressure and external workload. Using a simulated breathing apparatus, Klausner et al. compared work of breathing via nasal prongs with the variable flow system and a commonly used continuous flow device. They concluded that the imposed work of breathing with the variable flow system was approximately one fourth that of the continuous flow system. We are aware of only one clinical study comparing a variable flow device with a continuous flow device. Akuwalia et al. compared the variable flow system with nasal CPAP delivered by an endotracheal tube inserted into one nostril. In a crossover design in 20 infants over a total study time of 8 hours, no differences were found in FiO2, respiratory rate, heart rate, blood pressure, or comfort score between devices.

To evaluate lung recruitment with the 3 nasal CPAP devices, we applied DC-coupled RIP to monitor static lung volume changes. Inline pneumotachography cannot be used to measure lung volume changes once a nasal CPAP device is applied to the infant, and changes in breathing synchrony cannot be assessed with pneumotachography. Respiratory inductance plethysmography, however, is a noninvasive technique for obtaining real-time data on breathing patterns. Accurate calibration of RIP using a face mask with pneumotachograph has been demonstrated in both lambs and premature infants. DC-coupled RIP allows for a constant baseline so that ΔVi can be measured. These changes can then be converted to volume (in mL) based on previous calibration by facemask pneumotachography. The sum of the rib cage and abdominal motion equals the tidal volume, and the phase angle between the rib cage and abdominal motion indicates the degree of paradoxical breathing. An increase in paradoxical breathing may indicate an increased work of breathing. Additionally, Locke et al. have shown that in infants with respiratory insufficiency, increasing CPAP results in a decreasing phase angle that is directly and significantly correlated with changes in esophageal pressures.

Our results indicate that the variable flow nasal CPAP system recruits lung volume better than both continuous flow devices. The θ (hence breathing synchrony) obtained with the continuous flow nasal prong system was, surprisingly, similar to that obtained with the variable flow system despite significantly higher lung recruitment with the latter. There are 2 possible, albeit related, explanations for this intriguing finding. First, the decrease in θ with lung recruitment (or nasal CPAP) may be nonlinear. Second, the decrease in θ with recruitment may change or possibly reverse when the lungs are either overdistended (decreased compliance) or above an optimal lung volume. The presence or absence of these conditions is not available from our data, which only show ΔVt from baseline (on nasal CPAP = 0).

The decreased variability in the mean airway pressure during nasal CPAP provided with the variable flow device compared with conventional nasal CPAP systems is perhaps the critical factor leading to the increased lung recruitment with this system. Another factor that alters the efficacy of any nasal CPAP delivery system is the airway leak around the prongs. Because the prongs are mechanically in parallel with the lungs, a larger leak around them results in lower effective nasal CPAP or less recruitment. The use of relatively larger prongs is possible with variable flow systems, both because of the design of the delivery system and the prongs themselves. When the nasal CPAP level is reached at the proximal airway (nares), the inflow from the device is shunted away from the infant. The prongs are made of a thin, soft material, which may flare out during gas inflow, thus increasing the effective internal diameter and decreasing the leak around the prongs. In contrast to conventional nasal CPAP, the wider ID and thinner walls of the prongs coupled with no gas inflow during exhalation all may effectively reduce the imposed work of breathing because of the mechanical device.

Differences in flow rate inherent between the devices may also affect lung recruitment. Although variable flow devices by definition vary CPAP attained by varying the flow rate, actual flow delivered to the nares of the infant has not been assessed. Much of the flow with these systems is shunted away from the infant and out the expiratory limb of the CPAP circuit.

Continuous flow nasal CPAP via the modified nasal cannula recruited lung volume equally to the nasal CPAP prongs, but at a very high cost: RR, θ, and FiO2 all increased significantly with the modified nasal cannula. In the study by Locke et al., no CPAP was generated with a nasal cannula similar in size to the one we used; however, they did not increase the flow rate beyond 2 L/minute. CPAP provision with the cannula as used in our nursery may possibly occur not only because of the high flow rates used but also because of the design of the cannula base, which often covers much of the nares and may thus obstruct expiration. These findings with the modi-
LUNG RECRUITMENT WITH VARIABLE VERSUS CONTINUOUS FLOW NASAL CPAP

We go from anticipation to anticipation, not from satisfaction to satisfaction.”

—Samuel Johnson