

Analysis of distal airway pressure changes in a simulation model of continuous positive airway pressure (CPAP).

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Citation

A Orozco-Gutierrez, R Estrada-Velazquez, C Gil-Rosales. *Analysis of distal airway pressure changes in a simulation model of continuous positive airway pressure (CPAP)*. The Internet Journal of Pediatrics and Neonatology. 2010 Volume 13 Number 1.

Abstract

Background: Nasal continuous positive airway pressure (CPAP) is commonly used to treat respiratory failure in newborns with excellent results; however, pneumothorax is frequently reported, varying in frequency from 1.4% to 10.3%. **Methods:** In this study, we used a lung simulator to determine the cause of this variability by measuring the pressure in the CPAP system and in the interior of one balloon to simulate the lung, with repeat measurements with the nasal prongs sealed and unsealed. In addition, crying was simulated by blowing through a hole that simulated the mouth. **Results:** We found that when the nasal prongs were used, unsealed simulator distension existed. However, the pressure remained at zero when the nostrils were sealed, indicating that the pressure inside the simulated lung was equal to that inside the system. Simulated crying increased the pressure 4-fold. **Conclusions:** We conclude that the seal in the nostrils is a factor for the effectiveness of the procedure and increases the risk of pneumothorax, as well as alter the results of studies on nasal CPAP. Nostril seals should be considered for future studies on the efficacy and safety of nasal CPAP.

INTRODUCTION

Continuous positive airway pressure (CPAP) is one of the most popular techniques described to treat newborn respiratory failure; it has been used since 1971 when Gregory and his colleagues demonstrated that orotracheal CPAP with an anesthesia bag improved oxygenation in preterm infants with respiratory distress. Subsequently, different devices were developed to provide CPAP [1-5]. In subsequent years, mechanical ventilation replaced CPAP as the most common form of ventilatory support. However, in the past several years, CPAP has been shown to have some important advantages over mechanical ventilation, including lower risk of lung injury [6-10].

In the last three decades, in parallel with the evolution of different forms of ventilation, ventilatory goals have evolved. Initially, the goal was to reduce mortality, and in the 1980s, the goal was to reduce neurological damage. In the 1990s, the goal was to prevent lung damage, and currently, the goals are to minimize lung injury and complications of mechanical ventilation [11].

CPAP is one of the strategies used to achieve the above objectives. In recent years, the acceptance of CPAP has increased and several articles assessing the efficacy and safety of the procedure have been published [12-23]. However, there are only a few studies regarding the physiological basis of CPAP [24,25], and little is known about how to best manage patients [26]. This lack of physiological knowledge has led to conflicting clinical results and the development of a great number of dispositives for the everyday treatment of newborns [27-30].

BACKGROUND

It has been accepted that the severity of lung disease is related to gestational age. In severely immature newborns, higher oxygen gradients are needed, therefore increasing the need for mechanical ventilation and consequently increasing the risk of lung damage [31].

Despite the variety of interfaces available to apply CPAP [32,33], nasal prongs are the most common method, with reports suggesting that nasal prongs should be as wide as possible to reduce resistance and fit the nostril snugly without air leakage or tissue damage [34].

Although nasal CPAP is a widely accepted ventilatory

strategy [35-38], there are some unclear aspects regarding its application. The delivered intra-prong pressure in bubble CPAP is assumed to be represented by the submersion depth of the expiratory tubing [39]. However, Chilton and Brooks [40] and De Paoli et al [41] reported a reduction of about 50% in pharyngeal pressure in infants with open mouths.

The intensity of bubbling appears to have no effect on oxygenation and CO₂ in some studies [31], but others mention it as an important determinant of oxygenation.(25)

Moreover, it was found that prong pressure during nasal CPAP delivery is variable and depends on the interaction of submersion depth and flow amplitudes [42]. Another concern that has recently arisen regarding the use of nasal CPAP is the presentation of pneumothorax as a frequent complication [43, 44]. We found no studies that evaluated pressure changes associated with crying or hippus, even though increases in intrathoracic and intra-alveolar pressure in combination with CPAP may be the perfect combination for cause pneumothorax.

The COIN and SUPPORT trials have both demonstrated that CPAP can be used in the smallest babies with high success rates (44) (46), but the COIN trial showed a slightly increased incidence of pneumothorax in the CPAP group. This could be attributed to the fact that the COIN trial used a CPAP of 8 as opposed to a CPAP of 5-6 used in the SUPPORT trial.

The frequency of pneumothorax associated with the use of CPAP in very low birth weight children in various studies varied from 1.6%-10.3% and mortality varied from 6.5% [46] to 48% [31].

HYPOTHESIS

We hypothesized that sealing the nasal prongs to the nostrils alters airway pressure during physiological phenomena such as crying and mouth opening.

MATERIAL AND METHODS

A lung simulator was developed using a T-tube in which the proximal hole simulated the function of the nostrils and was where the prongs were placed. The lateral hole simulated the function of the mouth, and a cap was placed to simulate opening or closure. A flexible latex balloon was connected to the distal port to simulate lung function. To simulate crying, ambient airflow was placed in the mouth hole.

This simulator was connected to a bubble CPAP system. We measured the pressure in the system with a pressure gauge placed at the nasal tip. At the distal end of the latex balloon a hole was made, and another gauge was placed to measure pressure inside the balloon. The measurement results were corroborated using a Portex disposable Manometer (Smiths Medical) and a pressure gauge integrated into a neonatal ventilator model 750 Bear Cub (Bear Medical Systems . (Figure 1).

We applied flow to the CPAP system to obtain pressure on the gauge of 5 cm of water, and bubbles in the bottle of water were also placed at 5 cm of submersion, obtaining adequate expansion of the balloon. Then, we observed the expansion of the balloon and measured the pressure in the distal gauge, comparing it with the pressure registered in the CPAP system. The determination was repeated with the side hole cap placed (mouth closed), removing the plug (mouth open), and with a flow of air through the side hole (simulating valsalva like maneuver).

The study was performed with the unsealed prongs in the proximal hole (unadjusted tip) and with the prongs sealed to simulate adjusted prongs; in both cases, we studied the response with the side hole closed (mouth closed), opened (open mouth), and air flow intermittently passed through the hole to simulate crying, obtaining repeated measurements to simulate different intensities of crying with flow rates of 1, 3, 5, and 10 l/min.

RESULTS

NASAL PRONGS WITH LEAK

With 5 cm of H₂O applied outside the nasal tip, we obtained an adequate expansion of the balloon, but the pressure inside the balloon remained at 0. When we removed the side cap (mouth opened) the pressure did not change inside the balloon or in the nasal prongs, and the expansion of the balloon is maintained.

When we introduced air through the side hole, the pressure did not change inside the balloon or outside the tip with any of the used air flow rates (Table 1).

NASAL PRONGS WITH SEAL.

The study was repeated as described above, except for placing the prongs through a plastic fabric, providing a tight

seal. When 5 cm of H₂O was applied in the prongs with the side hole closed (mouth closed), expansion of the balloon was adequate, and the pressure in the balloon was increased to 5 cm of water, equal to that of the system.

With the removal of the cap to simulate an opened mouth, balloon expansion was maintained, and the pressure in the balloon fell to 0, similar to findings observed when the prongs were used without a seal (Table 2).

When intermittent lateral pressure was introduced at a flow rate of 10 l/min to simulate valsalva like maneuver, the pressure increased to 20 cm of H₂O in the distal gauge, and the balloon over distended. This increase was not reflected to the same extent in the proximal gauge (Figure 3).

Figure 1

Fig.1 .- The system used to evaluate nasal CPAP placed on the proximal orifice of the system. Note the lateral hole simulating the mouth, the latex balloon simulating the distal airways, and the two gauges (schematic representation).

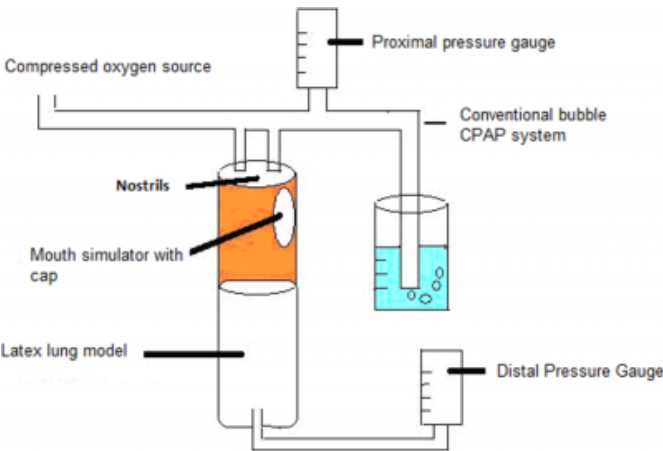


Figure 2

Table 1 .- Results of the determinations of pressure and expansion in the simulator with a set of unsealed nasal prongs.

Nasal prongs with leak	Closed lateral hole (mouth closed)	Open lateral hole (mouth opened)	Lateral air flow (valsalva like maneuver)
Simulated phenomenon			
Balloon expansion	good	good	good
Proximal pressure	5	5	5
Distal pressure	0	0	0

Figure 3

Figure 2 .- Behavior of the system with unsealed prongs. Note the proximal pressure of 5 cm with distal pressure of 0 with expansion of the balloon. The lateral cap is placed to simulate a closed mouth.



Figure 4

Fig 3 .- Inflation of the balloon, simulating the lung when pressure is applied intermittently in the system and the prongs are sealed. Note that the distal pressure is greater than that reported in the proximal gauge.



Figure 5

Table 2 .- Results of the determinations of pressure and expansion in the simulator with a set of sealed nasal prongs.

Nasal prongs without leak	Closed lateral hole (mouth closed)	Open lateral hole (mouth opened)	Lateral air flow (valsalva like maneuver)
Simulated phenomenon			
Balloon expansion	excellent	good	excessive
Proximal pressure	5	5	5
Distal pressure	5	0	20

DISCUSSION

In our study, the system with leakage at the nasal prongs produced an increase in volume and expansion of the balloon without increasing the pressure within the lung simulator, and the pressure inside the balloon did not change in the open mouth or crying simulations. This allowed us to maintain a constant intrapulmonary volume.

Our work verifies the results obtained by Khan et al [47], who showed that when there was appreciable nares-prong leakage, distal pressure decreased and was not reflected by measuring the pressure in the CPAP circuit. They did not examine the pressure increases secondary to common physiologic phenomena in the newborn that received CPAP.

In 2007, Halter et al [48] postulated that alveolar instability caused the appearance of areas of alveolar collapse, alveolar wall edema, leukocyte infiltration, and difficult diffusion of gases. This study did not find a significant release of cytokines and proteases, which suggests that the mechanism of lung injury is mechanical and not chemical; therefore, when lung volume is maintained without pressure splinting, alveolar instability is prevented in the airways, lowering the inflammatory response in the lung. This finding may explain the excellent results in terms of the reductions in bronchopulmonary dysplasia reported since 1983. [6]

Traditionally, all studies have used pressure gauges as close as possible to the nasal prongs as a measure of intrapulmonary pressure [49,50]; according to our results the pressure near the nasal prongs is different of intrapulmonary pressure both pressures are different.

It is generally accepted that pressure drops when the patient open his or her mouth. However, this change is irrelevant if the nasal prongs have leaks.

Sealing the nasal prongs is very important for delivery CPAP more precisely. With a tight seal around the prongs, the system is closed and the pressure in the balloon equals the pressure near of the nasal prongs, producing a more efficient alveolar-arterial gradient; however, if the child open his or her mouth, the pressure decreases, and the system behaves similarly as unsealed prongs, maintaining only expansion of the balloon with a pressure of 0.

When an infant introduces air into the system and performs a

valsalva like maneuver (keeping the mouth closed), the balloon expansion is sudden and forced, increasing up to 400%. (5 cms. H₂O to 20 cms H₂O) , This increase is only partially reflected in the gauge of the CPAP system in which we use as standard monitor, which casts doubt on the effectiveness of routinely used monitoring systems and suggests that the pressure monitoring systems employed may have a limited value to prevent CPAP-associated damage.

When the nasal prongs are sealed, intrapulmonary pressure will be equal to the pressure of the system, which will allow adequate lung expansion; oxygen alveolar-arterial gradient increases, and therefore improved oxygenation. If the mouth is open, this pressure effect is lost and results in constantly fluctuating intrapulmonary pressure. The changing alveolar-arterial gradient will lead to changes in oxygenation. However, as distention is maintained, so is alveolar stability, explaining the reduction of chronic lung damage.

This work explains results published in 2009 [11] that evaluated tracheal CPAP based on the original system of Gregory. In this work, the patient was intubated, and the risk of pressure surges was eliminated. The latex bag in the CPAP system created a closed elastic high-volume system that absorbed the pressure increases and maintained alveolar stability and a stable alveolar-arterial gradient.

CONCLUSIONS

The use of nasal CPAP has been widely disseminated and has been shown to be an effective procedure for treating premature infants with respiratory distress with similar efficacy as mechanical ventilation. It is a very well accepted and safe mode of management of lung disease. The nasal prong seal and secondary intrapulmonary pressure changes affect the efficacy and safety of nasal CPAP. Minimizing leakage around the prongs helps deliver CPAP more precisely. Very small children might need more aggressive pulmonary support with more stable and high pressures, whereas in older children or those with mild lung disease, volume increases may be sufficient to maintain the respiratory homeostasis and alveolar stability. Changing airway pressures with varying nasal prong sealing explains the variability in efficacy and safety observed in prior studies and can be influenced by local routines and uncontrolled events (techniques for fixing the prongs, prong

size, nasal mucosal edema, nasal bleeding and blood clots and crusts, cleaning techniques). Nasal prong sealing is an important factor that influences airway pressure and must be taken into account during clinical trials to ensure more uniform results.

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