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Ventilatory effects of nasal continuous positive airway pressure

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ABSTRACT: Nasal continuous positive airway pressure (nCPAP) improved arterial oxygenation in patients with sleep apnoea as well as those with acute pulmonary processes such as *Pneumocystis carinii* pneumonia. Despite an expanding pool of clinical information, little if any attempt seems to have been made to see whether nCPAP alters ventilatory patterns. The effect of nCPAP was assessed by respiratory inductance plethysmography in 14 healthy males. nCPAP reduced respiratory rate (14.3±1.47 to 9.7±1.98, p<0.0001) but increased tidal volume (0.483±0.090 to 0.602±0.140 *l*, p=0.01). Accordingly, minute ventilation decreased (6.91±1.20 to 5.64±0.93 *l*·min^{-1}, p=0.0002). Duty cycle (TI/TTOT) decreased from 0.43±0.04 to 0.35±0.05 s during nCPAP (p<0.0001). Mean inspiratory time and mean expiratory time increased with nCPAP (1.79±0.19 to 2.20±0.41 and 2.44±0.38 to 4.27±1.07 s, respectively, p<0.02), but there were no significant changes in mean inspiratory flow rate or partitioning of rib cage and abdominal/diaphragmatic contributions to tidal volume. We conclude that nCPAP effects ventilatory pattern in a manner similar to that described for expiratory threshold loading; that is, by decreasing respiratory frequency and minute ventilation. nCPAP does not appear to stimulate healthy subjects to increase their level of ventilation.

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Methods

Fifteen healthy, nonsmoking male volunteers ages 24–37 yrs (mean 29 yrs) were studied. While all were health care professionals, none were aware of the purpose of the study, nor were any results made available to them until studies were completed.

Rib cage and abdominal excursions were recorded using respiratory inductance plethysmography (RIP) under two conditions: a) wearing a nasal continuous positive airway pressure (CPAP) mask with zero CPAP (control), and b) wearing a nasal CPAP mask along with CPAP at 10 cmH_2O. For each subject, a suitably sized transducer inductance coil was placed around the rib cage, just below the axilla, and a second respiband was positioned at the umbilicus above the iliac crest. The location of the coils was marked on each subject and checked regularly to insure that their positions did not change.

Subjects were studied in the supine posture, with eyes closed, in a quiet environment. The nCPAP masks were placed over the nose with the velcro straps tightened in the usual manner. In the control condition, to limit dead space, the centre piece of the nCPAP mask was removed, leaving an open port. A portable nCPAP unit (Respironics SleepEasy II) was used to generate a pressure of 10 cmH_2O. Subjects were asked to breathe through the nose in as quiet and relaxed way as they could. Carbon dioxide was monitored continuously via an infrared CO_2 analyser (Gould-Godart Capnograph Mark III) using a sampling port at the nasal mask. Ventilatory pattern was recorded using RIP for 10 min under each experimental condition. All experiments were done in the same order (0 cmH_2O, then 10 cmH_2O).

Changes in functional residual capacity (FRC) were evaluated in 5 subjects. Under each condition, after a period of stable tidal respirations, subjects were asked to take a maximal inspiration. Six inspiratory capacities were recorded in such a manner with and without nCPAP at 10 cmH_2O. The difference in mean inspiratory capacity was assumed to represent the change in FRC.

Variables recorded were: rib cage contribution to tidal volume, abdominal contribution to tidal volume, tidal volume (VT), inspiratory time (TI), expiratory time (TE), duration of breath (TTOT), percent contribution to tidal volume from the rib cage and abdomen, and end-tidal CO_2. All breaths were analysed. Minute ventilation was calculated from the product of the mean respiratory rate and mean tidal volume. Mean inspiratory flow was calculated from tidal volume/inspiratory time (VT/TI).

The least squares method of calibration for respiratory inductance plethysmography (RIP) was chosen, since measures of tidal volume compartmental contributions to tidal volume have been shown to be more accurate using this technique when ventilation is examined in different

the subjects in both standing and supine postures. Rib cage and abdominal deflections from at least 3 representative breaths in each of the 2 postures were recorded on a multichannel recorder and separate compartmental amplification factors were calculated from simultaneous spirometric measures of tidal volume using simultaneous equations. Calibration of the RIP was verified subsequently by comparing the sum of the rib cage and abdominal deflections with tidal volume measured by spirometry. The calibration procedure was repeated if tidal volume measured by RIP and spirometry differed by more than ±10%.

At the conclusion of the studies, tidal volume by RIP was measured against tidal volume by spirometry. The data were not accepted if there was a difference between the two methods of greater than 10%.

The data are presented as means±SD. Paired t-tests were used to determine the statistical significance between the mean observed values.

dead space in the mask, that there was any significant CO_2 rebreathing.

Respiratory rate slowed significantly from a mean of 14.3±1.47 breaths per min to 9.7±1.98 breaths per min ($p<0.0001$), while tidal volume increased from a mean of 0.483±0.090 *l* to 0.602±0.140 *l* ($p=0.01$) with nCPAP. Overall, minute ventilation decreased from a mean of 6.91±1.20 $l \cdot min^{-1}$ to 5.64±0.93 $l \cdot min^{-1}$ ($p=0.0002$). The change in ventilatory patten is illustrated in the example shown in figure 1.

The mean increase in FRC with nCPAP was 1.07±0.69 *l* ($p<0.05$). While nCPAP increased FRC in all 5 subjects, the increase was variable among subjects (range 0.29–1.88 *l*), although fairly consistent within the same subject.

Duty cycle (T_I/T_{TOT}) decreased from 0.43±0.04 to 0.35±0.05 with nCPAP ($p<0.001$). Mean inspiratory time and mean expiratory time increased with nCPAP (1.79±0.19 to 2.20±0.41 s and 2.44±0.38 to 4.27±1.07 s,

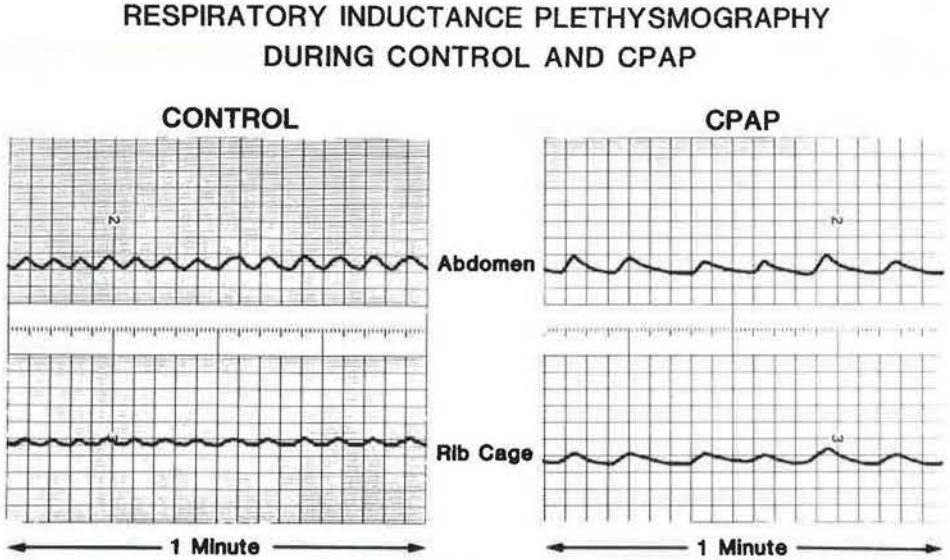

Fig. 1. – Ventilatory pattern as measured by respiratory inductance plethysmography during control and nasal continuous positive airway pressure (CPAP). The vertical axis represents volume and the horizontal axis represents time.

Results

Of the fifteen subjects studied, one experienced difficulty co-ordinating his breathing with the nCPAP device and complained of discomfort. After a number of attempts, the studies on this subject were discontinued and no data gathered from the subject have been included in the analysis. The other fourteen subjects tolerated nCPAP very well, although some noted minor facial discomfort associated with wearing the mask.

The mask in the control state had an open port over the nose with the surrounding dead space measuring approximately 50 ml. The mask dead space is similar when used for applying CPAP. In every subject, end-tidal CO_2 was monitored in the nCPAP mask. There was no trend towards a rising carbon dioxide tension during any study, hence it is unlikely that by virtue of added

respectively, $p<0.02$), although mean expiratory time increased to a much greater degree. There was no significant change in mean inspiratory flow rate (270±43 $ml \cdot min^{-1}$ (control) *vs* 276±45 $ml \cdot min^{-1}$ (nCPAP)).

Partitioning of rib cage and abdominal/diaphragmatic movement was respectively 39±16% and 61±16% of the control tidal volume. No significant difference were noted with nasal CPAP (rib cage = 44±17%, abdomen/diaphragm = 56±17%).

Discussion

The principle of increasing the end-expiratory pressure of spontaneously breathing subjects in order to improve their oxygenation has attracted the attention of respiratory physiologists for over 40 years. Oxygen masks

were strapped tightly to the face of World War I Air Force pilots in the hope of preventing hypoxia at high altitudes, and in 1938, BARACH *et al.* [2] demonstrated face mask positive pressure breathing in the treatment of acute pulmonary oedema. In the 1960s endotracheal positive end expiratory pressure (PEEP) was introduced for the treatment of acute pulmonary oedema [3] and more recently, nCPAP was used for neonates with respiratory distress [4, 5]. Nasal CPAP has now become the subject of widespread attention since SULLIVAN [6] proposed its use in adults with obstructive sleep apnoea.

In the treatment of obstructive sleep apnoea, daytime symptoms, frequency and severity of nocturnal oxygen desaturations and apnoea indices all improve dramatically [7]. The flow of air delivered to the nasal mask appears to act as a "pneumatic splint" which prevents upper airway occlusion by separating the tongue and soft palate from the posterior pharyngeal wall [6]. In its expanding role, nCPAP has recently been shown to improve arterial oxygenation in *Pneumocystis carinii* pneumonia [8] and postoperative atelectasis refractory to standard physiotherapy [9]. While the efficacy of nCPAP is gaining widespread recognition, it is unclear precisely how the application of continuous positive airway pressure to the nose might change the pattern of breathing. We wanted to isolate changes entirely due to nCPAP from the changes in ventilatory patterns that inevitably accompany the lung disease or disordered control of breathing for which nCPAP is prescribed. Accordingly we studied healthy young men, monitored their ventilatory patterns noninvasively, and found a significant decrease in respiratory rate and minute ventilation when nCPAP was applied. Tidal volume, inspiratory time, expiratory time, and FRC increased, and Ti/Ttot decreased. Mean inspiratory flow rates and the partitioning of rib cage and abdominal/diaphragmatic contributions to tidal volume were apparently uninfluenced by nCPAP. The changes in breathing frequency and minute ventilation were qualitatively similar to those that have been described with positive pressure breathing and with expiratory threshold loading applied to the mouth. Positive pressure breathing in rabbits, cats, and dogs has been shown to decrease breathing frequency and minute ventilation and increase tidal volume [10]. In experiments in anaesthetized cats, BISHOP [11] showed that both continuous positive pressure breathing and expiratory threshold loading depress breathing frequency, minute ventilation and tidal volume, while FINKLER [12] documented reductions in breathing frequency and minute ventilation and increases in tidal volume when expiratory threshold loads of 10 cmH_2O were applied. By contrast, negative pressure breathing increased minute ventilation [13].

The application of nCPAP may act as if it was an application of a mechanical load to the upper airway. Resistive loading alone decreases the ventilatory responses to hypercapnia, hypoxia, and to rhythmic dynamic exercise [14–18]. Such studies in healthy subjects in many ways reflect the changes that occur in spontaneous intrinsically loaded situations such as severe airways obstruction [19, 20]. While our findings with nCPAP appear to be new observations, they were on the whole consistent with observations by others, using other forms of mechanical loads. ZECHMAN [21] examined the separate effects of inspiratory and expiratory resistive loads in healthy subjects. He observed that respiratory frequency and minute ventilation fell, tidal volume rose, and the changes were mainly associated with the impedance of expiratory flow. In these and other studies with similar results, the slowing of breathing frequency appeared to be due to the prolongation of expiratory time with expiratory loads and to inspiratory time with inspiratory loads [10, 21, 22].

Positive pressure breathing, expiratory threshold and expiratory resistive loading all increase FRC [12, 22, 23]. Although an increased tidal volume is a consistent finding in studies of expiratory threshold and resistive loading, variable changes in tidal volume with positive pressure breathing have been reported [10, 23, 24]. The reason for this is unclear, yet in this and other studies of expiratory loading, tidal volume is preserved despite diaphragmatic shortening secondary to an elevated FRC. This appears to reflect increased diaphragmatic activity secondary to changes in afferent activity from diaphragmatic muscle spindle and tendon organ receptors [23, 24]. As tidal volume was not diminished in our study, it may not be surprising that there was no significant change in the pattern of thoraco-abdominal motion despite an elevate FRC.

We wondered whether the finding that nCPAP decreased overall minute ventilation could be explained by activation of a vagally mediated volume reflex or by upper airway receptors. Functional residual capacity was increased in our study, but the Hering-Breuer reflex is thought to be weak if not absent in man [25]. In animals, upper airway mechanoreceptors appear to influence ventilatory control [26]; however, in tracheostomized humans, positive pressure changes applied to the oropharynx, isolated from the lower airways by a tracheostomy tube, have negligible effects on the pattern of breathing [27]. It is therefore unlikely that upper airway receptors or the Hering-Breuer reflex explain the changes induced by nCPAP. They are more likely explained by mechanical rather than neural factors. Or findings mimic precisely those obtained by POON *et al.* [28] who used a narrow-bore glass tube attached to the mouth to impose an expiratory resistive load: Te, Ti, respiratory frequency and minute ventilation all decreased, Vt increased, and Vt/Ti remained unchanged. POON *et al.* also noted that end-tidal CO_2 remained unchanged and assumed that V_{CO_2} did not increase. The maintenance of a presumably normal $Paco_2$ in the face of a decreased minute ventilation is in both experiments probably secondary to a decrease in the VD/VT ratio because of an increased tidal volume. These findings are in general agreement with our recent observations regarding $Paco_2$ in patients with early ARDS given nCPAP [8].

To best of our knowledge, while extensively and increasingly used in clinical practice, the effect of nCPAP in healthy volunteers has not been thoroughly studied. Nasal CPAP decreased respiratory rate and minute

ventilation while increasing tidal volume and functional residual capacity. Despite its apparent stimulatory effect in patients with sleep related breathing disorders, nCPAP did not appear to stimulate increases in ventilation in healthy awake subjects. Indeed it produced a pattern of ventilation that was similar to an expiratory threshold or resistive load.

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Effets ventilatoires d'une pression positive continue sur les voies aériennes nasales. S. Kesten, A.S. Rebuck.
RÉSUMÉ: Une pression positive continue sur les voies aériennes nasales (nCPAP), augmente l'oxygénation artérielle chez les patients atteints d'apnée du sommeil, ainsi que chez ceux souffrant de processus pulmonaires aigus, comme la pneumonie à Pneumocystis carinii. Malgré une masse croissante d'informations cliniques, peu ou pas d'efforts ne semblent avoir été faits pour déterminer si la nCPAP modifie le type ventilatoire. Les effets de la nCPAP ont été appréciés par pléthysmographie respiratoire d'inductance chez 14 hommes bien portants. La nCPAP a réduit le taux respiratoire (de 14.3±1.47 à 9.7±1.98, $p<0.0001$), mais a gumenté le volume courant (de 0.483±0.090 à 0.602±0.140 *l*, $p=0.01$). De même, la ventilation minute a diminué (de 6.91±1.20 à 5.64±0.93 $l \cdot min^{-1}$, $p=0.0002$). Le temps de mise sous tension (T_I/T_{TOT}) a diminué de 0.43±0.04 à 0.35±0.05 sec. au cours de la nCPAP ($p<0.0001$). Le temps inspiratoire moyen et le temps expiratoire moyen ont augmenté sous nCPAP (de 1.79±0.19 à 2.20±0.41 sec., et de 2.44±0.38 à 4.27±1.07 sec., respectivement, $p<0.02$). L'on n'a pas noté de modification significative du taux moyen de débit inspiratoire ou de la répartition des contributions de la cage thoracique et des parois abdominales et du diaphragme au volume courant. Nous concluons que la nCPAP agit sur le type ventilatoire d'une façon similaire à celle décrite pour le seuil de surcharge expiratoire, c'est-à-dire en réduisant la fréquence respiratoire et la ventilation minute. Le nCPAP ne semble pas stimuler les sujets à augmenter leur niveau de ventilation.
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