TECHNIQUES AND PROCEDURES

Comparison of Carbon Dioxide Rebreathing During Application of Continuous Positive Airway Pressure With 3 Types of Nasal Mask

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A comparison is made between the end-tidal fractional concentration of carbon dioxide ($F_{ET}CO_2$) obtained during application of varying levels of continuous positive airway pressure (CPAP) with a prototype mask (from Carburos Metálicos) and $F_{ET}CO_2$ obtained with 2 commonly used nasal masks (Profile Lite and ComfortClassic from Respironics). The nasal $F_{ET}CO_2$ was measured on 3 consecutive days in 11 healthy volunteers, 12 patients with severe obstructive sleep apnea-hypopnea syndrome, and 12 hypercapnic patients. A different mask was randomly assigned on each day and the $F_{ET}CO_2$ was measured after 3 minutes of CPAP at 4, 5, 6, 8, 10, 15, and 20 cm H_2O. Although in all cases a progressive reduction in $F_{ET}CO_2$ was observed with increasing CPAP, the effect was greatest with the prototype mask at all pressures. In the 3 different study groups the pressures obtained with the prototype mask were similar to those generated by the CPAP machine. In conclusion, the lower concentration of nasal CO_2 obtained using the prototype mask suggests that it causes less rebreathing.

Key words: *Nasal mask. Continuous positive airway pressure. Sleep apnea. Mechanical ventilation. Rebreathing. CO_2.*

Comparación de la reinhalación de anhídrido carbónico originada por 3 mascarillas nasales durante la aplicación de CPAP

Se describe la fracción *end-tidal* de anhídrido carbónico ($F_{ET}CO_2$) originada con una mascarilla prototipo (Carburos Metálicos) durante la aplicación de diferentes niveles de presión positiva continua en la vía aérea (CPAP) y se compara con la desarrollada por 2 mascarillas nasales de uso habitual (Profile Lite y ComfortClassic, Respironics). En 11 voluntarios sanos, 12 pacientes con síndrome de apneas-hipopneas obstructivas durante el sueño de carácter grave y 12 enfermos hipercápnicos, se midió, de forma aleatoria en 3 días sucesivos, la $F_{ET}CO_2$ nasal después de 3 min de CPAP a 4, 5, 6, 8, 10, 15 y 20 cmH_2O con cada una de las mascarillas. Aunque en todos los casos se logró una reducción progresiva de la $F_{ET}CO_2$ al incrementar la presión, ésta fue mayor con la mascarilla prototipo, para cualquier nivel de presión. En los 3 grupos del estudio las presiones alcanzadas en la mascarilla prototipo fueron similares a las generadas por la máquina de CPAP. En conclusión, la menor concentración de anhídrido carbónico nasal durante la aplicación de la mascarilla prototipo induce a pensar que origina una menor reinhalación.

Palabras clave: *Mascarilla nasal. CPAP. Apneas del sueño. Ventilación mecánica. Reinhalación. CO_2.*

Introduction

Recent years have seen increasing developments in the use of nasal masks for ventilation, both for the provision of continuous positive airway pressure (CPAP) and for intermittent positive pressure ventilation. At the same time, obstructive sleep apnea-hypopnea syndrome (OSAHS) is considered a first degree social health problem due to its high prevalence[1] and increasing awareness of the cardiovascular morbidity with which it is associated.[2-5] Despite the fact that resources for the diagnosis and treatment of OSAHS are limited in Spain,[6] the use of CPAP is likely to increase in the near future. Although to a lesser extent, the use of nasal masks for intermittent positive pressure ventilation has also increased considerably, particularly in patients with chronic hypercapnic respiratory failure of varying etiology.[7-10]

As a consequence, there is increasing interest in certain technical considerations associated with the use of nasal masks, such as monitoring of leaks,[11] the possibility of rebreathing due to equipment failure,[12] and the fit and tolerability of the masks.[13] Specifically, as with any mask used for provision of CPAP, it must be confirmed prior to use that air leaks are rare and that

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carbon dioxide (CO_2) rebreathing is minimal within the range of pressures used.[13,14]

A high-quality nasal mask (CM prototype, Carburos Metálicos, San Sebastian de los Reyes, Madrid, Spain) has been produced in Spain for use with CPAP equipment in the treatment of OSAHS. To date, a single study has been performed in which it was verified that the leak flow in the prototype mask was sufficient to prevent excessive CO_2 rebreathing.[15] The next step in the validation process requires determination of the percentage of residual exhaled CO_2 during provision of positive airway pressure.

The aim of this study was to describe the end-tidal fractional concentration of CO_2 ($F_{ET}CO_2$) during application of varying levels of CPAP using the prototype mask in healthy individuals, patients with OSAHS, and patients with hypercapnia caused by chronic respiratory failure, and to compare the results with those obtained with commonly used nasal masks.

Method

The study population contained 3 groups: healthy subjects, patients with severe OSAHS, and hypercapnic patients. Healthy volunteers were defined as nonsmokers, without respiratory symptoms in the European Community for Coal and Steel questionnaire,[16] without prior history of known respiratory or cardiovascular disease, and with normal spirometry results. Patients were included in the severe OSAHS group if they presented excessive daytime sleepiness (Epworth score >10) and an apnea-hypopnea index of more than 30 measured by cardiorespiratory polygraph. The hypercapnic group contained patients with a $PaCO_2$ of more than 45 mm Hg breathing room air and prior diagnosis (>6 months) of chronic respiratory failure due to neuromuscular disease or chest wall disease, chronic obstructive pulmonary disease, or hypoventilation syndrome.

Exclusion criteria were as follows: prior diagnosis or evidence of bullae in conventional chest radiographs, presence of other associated respiratory diseases, any heart disease, glaucoma, or the presence of clinical instability or treatment changes in the previous 2 weeks.

The sample size was estimated on the basis of a previous study in which increases of more than 1.5% from a mean baseline $F_{ET}CO_2$ of 4.5% were considered clinically significant.[17] To detect changes of that size with an α error of .05 and a β error of .95, at least 10 subjects were required in each study group. All participants gave signed informed consent and the study was approved by the hospital's ethics committee for clinical research.

Baseline spirometry was performed in all subjects using MasterScreen 4.2 equipment (Jaeger, Würtzburg, Germany) according to the recommendations of the American Thoracic Society[18] and using the reference values of the European Community for Steel and Coal.[19]

Analysis of CO_2 rebreathing was performed on 3 consecutive days and on each day a different mask was randomly assigned from the prototype mask and 2 commonly used masks with expiratory ports: the Profile Lite and ComfortClassic (Respironics Inc, Pittsburgh, Pennsylvania, USA). After a 30-minute rest period, the subjects were placed in decubitus, at which time the nasal mask was fitted and checked for air leaks. The mask was connected to a CPAP REMstar Pro apparatus (Respironics) via a 2-meter corrugated tube. CPAP was applied with an ascending regimen of 4, 5, 6, 8, 10, 15, and 20 cm H_2O over a period of 3 minutes for each pressure level. During administration of CPAP it was directly confirmed that patients breathed with their mouth closed and maintained a regular breathing pattern with a breathing rate always below 30 breaths/min.

$F_{ET}CO_2$ was measured continuously through a nasal prong using an infrared absorption analyzer (Oscar II, Datex, Helsinki, Finland; range, 0%-10%; accuracy, 1%; response rate, 75 ms). The analyzer was calibrated prior to measurement of each sample with a bolus of pure nitrogen and another of gas containing 4% CO_2, 16% oxygen, and 80% nitrogen. The pressure generated for CPAP in the prototype mask was measured using a DWD pressure transducer (Jaeger) and a Screenbox analog to digital converter (Jaeger) connected to the mask via a luer-lock port. CO_2 and pressure signals were continuously recorded in real time using the LabVIEW program (National Instruments, Austin, Texas, USA) at a sampling rate of 100 MHz. For the analysis, $F_{ET}CO_2$ and mask pressure achieved in the final 20 seconds of each step in CPAP were considered.

Statistical Analysis

Data are shown as mean (SEM). Comparisons between masks were performed by analysis of variance (ANOVA) for repeated measures, considering sequence of application as a covariable, followed by post-hoc Bonferroni test for multiple comparisons (SPSS version 11.0, SPSS Inc, Chicago, Illinois, USA). Values of *P* below .05 were considered statistically significant.

Results

General characteristics of the recruited subjects are shown in Table 1. The study was performed in 11 healthy subjects, 12 patients with severe OSAHS (apnea-hypopnea index, 49.3 [11.6]; mean nighttime

TABLE 1
General Characteristics of the Subject Groups*

	Controls (n=11)	OSAHS (n=12)	Hypercapnic (n=12)
Sex, % men	82	100	50
Age, y	44 (2)	63 (2)†	65 (3)†
Height, cm	170 (3)	166 (2)	160 (3)‡
Weight, kg	75 (5)	83 (4)	85 (5)
BMI, kg/m^2	25.6 (3.5)	30.0 (4.8)	33.0 (4.5)‡
Active smokers, %	0	0	18‡,§
FVC, L	4.50 (0.40)	3.63 (0.21)	2.14 (0.17)†,‖
FVC, % theoretical	110 (3)	103 (4)	77 (7)†,§
FEV_1, L	3.71 (0.28)	2.81 (0.27)	1.42 (0.12)‡,‖
FEV_1, % theoretical	111 (4)	99 (6)	67 (10)‡,§
FEV_1/FVC, %	83 (2)	77 (4)	67 (6)

*Data are shown as means (SEM).
FVC indicates forced vital capacity; FEV_1, forced expiratory volume in the first second; BMI, body mass index; OSAHS, obstructive sleep apnea-hypopnea syndrome.
†*P*<.001 compared with the control group.
‡*P*<.05 compared with the control group.
§*P*<.05 compared with OSAHS group.
‖*P*<.001 compared with the OSAHS group.

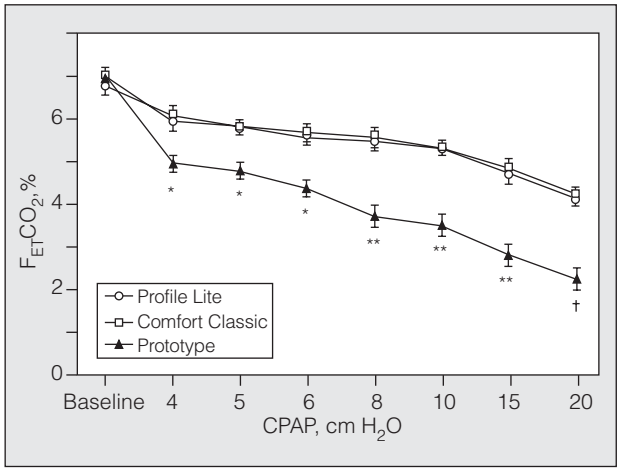

Figure 1. $F_{ET}CO_2$ at different levels of CPAP used in all subjects. Points correspond to means adjusted for the covariable sequence and the whiskers to the standard error of the mean. *P<.01 compared with the other masks at a similar CPAP level. **P<.001 compared with the other masks at a similar CPAP level.

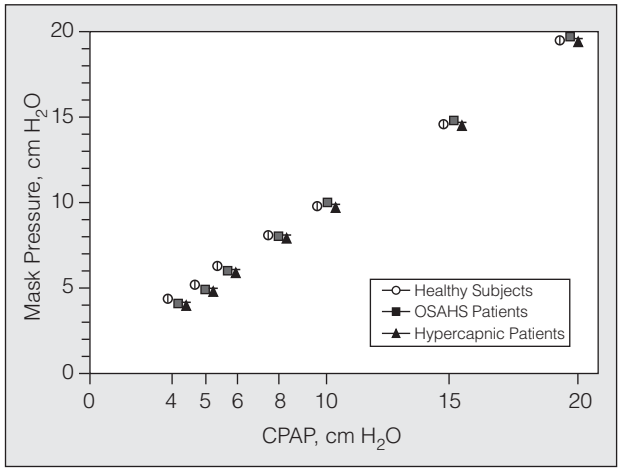

Figure 2. Pressures achieved in the prototype mask during application of CPAP in the 3 study groups. OSAHS indicates obstructive sleep apnea-hypopnea syndrome.

arterial oxygen saturation [SaO_2], 90% [2%]; minimum nighttime SaO_2, 74% [11%]), and 12 hypercapnic patients ($PaCO_2$, 51 [4] mm Hg; PaO_2, 62 [6] mm Hg; pH, 7.41 [0.03]). The OSAHS and hypercapnic groups were made up of individuals who were older than the healthy volunteers. The hypercapnic group presented a higher body mass index than the healthy subjects and also contained a higher number of active smokers than either of the other 2 groups. In addition, forced vital capacity (FVC) and forced expiratory volume in the first second (FEV_1) were lower in that group than in the others, both in terms of absolute values and as percentages of the reference value.

The $F_{ET}CO_2$ following application of the different levels of pressure in all patients is shown in Figure 1. A progressive reduction was achieved with increasing CPAP with all 3 masks, and the effect was already apparent at 4 cm H_2O (P<.001 by multivariate ANOVA). However, at any pressure level, the reduction of $F_{ET}CO_2$ was greater with the prototype mask than with either of the other 2 (Figure 1). The response of $F_{ET}CO_2$ in each of the groups is shown in Table 2. Compared with the 2 conventional masks, the prototype mask achieved a more marked reduction in $F_{ET}CO_2$ above 4 cm H_2O in the hypercapnic group and above 8 cm H_2O in the other 2 study groups.

The pressures achieved in the prototype mask with application of CPAP were similar in the 3 study groups (Figure 2). No significant differences were observed between the pressure provided by the CPAP machine and the pressure inside the mask. Only the pressure developing in the mask with the application of 6 cm H_2O from the ventilator was higher in the control group (6.3 [0.1] cm H_2O) than in the OSAHS (6.1 [0.0] cm H_2O; P=.032) and hypercapnic (6.1 [0.0] cm H_2O; P=.017) groups.

Discussion

Our study confirms that the prototype nasal mask appropriately transfers pressure generated by CPAP equipment in different groups of subjects and generates

TABLE 2
End Tidal Fraction of CO_2 in the Different Study Groups*

Group	Mask	Baseline	CPAP, cm H_2O						
			4	5	6	8	10	15	20
Controls	Profile Lite	6.3 (0.2)	5.9 (0.2)	5.7 (0.3)	5.4 (0.2)	5.3 (0.3)†	5.2 (0.3)‡	4.3 (0.3)†	3.7 (0.3)‡
	ComfortClassic	6.6 (0.2)	5.8 (0.2)	5.7 (0.3)	5.7 (0.2)	5.6 (0.3)‡	5.1 (0.3)‡	4.6 (0.3)‡	3.7 (0.3)‡
	Prototype	6.8 (0.2)	5.0 (0.3)	5.0 (0.3)	4.9 (0.3)	3.8 (0.4)	3.7 (0.3)	2.9 (0.4)	1.8 (0.3)
OSAHS	Profile Lite	6.2 (0.3)	5.7 (0.2)	5.6 (0.3)	5.4 (0.3)†	5.4 (0.3)‡	5.2 (0.4)†	4.7 (0.4)	4.1 (0.4)
	ComfortClassic	6.4 (0.3)	5.5 (0.2)	5.4 (0.3)	5.3 (0.3)	5.3 (0.3)†	5.0 (0.4)†	4.8 (0.4)†	4.4 (0.4)†
	Prototype	6.4 (0.3)	5.0 (0.3)	4.8 (0.3)	4.2 (0.4)	3.7 (0.4)	3.5 (0.4)	3.3 (0.4)	3.9 (0.4)
Hypercapnic	Profile Lite	7.7 (0.3)	6.5 (0.4)†	6.1 (0.4)†	5.9 (0.4)†	5.8 (0.4)†	5.6 (0.4)‡	5.1 (0.4)§	4.7 (0.4)§
	ComfortClassic	7.9 (0.3)	6.4 (0.4)†	6.3 (0.4)§	6.1 (0.4)†	5.8 (0.4)‡	5.8 (0.4)‡	5.1 (0.4)§	4.5 (0.4)‡
	Prototype	7.8 (0.4)	4.9 (0.4)	4.6 (0.4)	4.2 (0.5)	3.7 (0.5)	3.6 (0.5)	2.2 (0.4)	2.0 (0.4)

*Results are shown as means adjusted for the covariable sequence (SEM).
$F_{ET}CO_2$ indicates end-tidal fraction of CO_2; CPAP, continuous positive airway pressure; OSAHS, obstructive sleep apnea-hypopnea syndrome.
Comparison between masks for the same level of CPAP: †P<.05 compared with the prototype mask; ‡P<.01 compared with the prototype mask; §P<.001 compared with the prototype mask.

less CO_2 rebreathing than other masks that are currently in use. These findings highlight the importance of mask choice both in treatment with CPAP and in noninvasive ventilation.[8] Unlike ventilation through intubation or tracheostomy tubes, CPAP and noninvasive ventilation both involve open systems. The discontinuity between the respirator and the airway has important implications and may account in some cases for the ineffectiveness of the treatment due to leaks or a poor seal between the edges of the mask and the patient's skin.

A nasal mask must therefore meet a basic series of criteria in order to be acceptable. Its design and structure should guarantee that it is airtight and rigid, with a low flow resistance and minimal dead space.[8] Furthermore, it must be easily positioned, comfortable, odorless, and adaptable, as well as available in a variety of sizes.[8,20] In an effort to reduce pressure on the patient's face and prevent sores, various materials such as gel or silicone are used in the manufacture of masks to soften the contact with the skin. Finally, economic considerations must not be forgotten, since price is often a decisive factor in choosing a mask.

In addition to leaks, the possibility of rebreathing represents one of the main problems associated with provision of CPAP or noninvasive ventilation using nasal masks. In CPAP, patients breathe through a tube that connects the machine to a nasal mask with an exhalation port. Under normal conditions, the pressure generated by the CPAP machine creates a flow of fresh air through the tube that washes exhaled CO_2 out through the exhalation port and minimizes rebreathing. However, it should be noted that the exhalation port also alters the pressure achieved inside the mask, since ports with a high resistance reduce the flow necessary to generate pressure in the mask. There is a greater risk of rebreathing when the machine is switched off,[17] when low CPAP pressures are applied, or when the flow generated by the machine is reduced by an increase in the resistance of the tubing (a situation that is quite rare) or the exhalation port, the latter being more common and dependent upon the structural characteristics of the port.

Regarding the possibility of rebreathing, the results of this study confirm that provision of CPAP with any of the 3 masks analyzed successfully achieves a progressive reduction in $F_{ET}CO_2$ with increasing pressure. In addition, the results confirm that for the same pressure, the reduction in $F_{ET}CO_2$ is greater with the prototype mask than with the other 2 masks analyzed (Figure 1). In our opinion, this finding simply reflects a higher leak flow through the exhalation port of the prototype mask than through those of the other 2 masks. In a previous study, leak flow through the expiratory port of the prototype mask was compared with that obtained with 2 Respironics ports similar to those used in the Profile Lite and ComfortClassic masks.[15] The leak flow was collected in a Serres suction canister and transferred to a rotameter for measurement of the flow. It was confirmed that at pressures of 10 to 20 cm H_2O the expiratory port of the prototype mask generated a leak flow of 4 L/min more than the others.[15]

It is also worth noting, however, that the generation of a larger leak does not alter the pressure that develops inside the prototype mask. In fact, in this study, no significant differences were observed between the pressure provided by the CPAP machine and the pressure inside the prototype mask (Figure 2). In contrast, Ferguson and Gilmartin[14] reported that with a Plateau exhalation port, similar to the ports incorporated in the Profile Lite and ComfortClassic masks, the pressure achieved in the mask was 1 to 3 cm H_2O less than that set by the ventilator. This difference in behavior probably means that those types of port offer greater resistance than does the port used with the prototype mask. In fact, in the study of Farré et al[17] it was confirmed that the Plateau and Whisper Swivel exhalation ports (Respironics) have a higher resistance, which at high flow rates can reach 50 cm H_2O.

The effect of the nasal mask used to provide CPAP differed slightly between the different study groups (Table 2). In patients with chronic hypercapnic respiratory failure, the prototype mask achieved a greater reduction in $F_{ET}CO_2$ at lower pressure levels than in the other 2 groups. In addition to the limitations associated with the sample size, which was estimated to detect global differences and not only at low pressures, it is possible that the larger amount of CO_2 exhaled by the hypercapnic patients was more sensitive to the effect of CPAP, even at very low pressures.

Our data confirm that type of mask and exhalation port affect the level of CO_2 rebreathing. Among other things, that finding is particularly relevant to the old controversy over the appropriateness of using conventional or made-to-measure masks.[8,21] Although it is irrefutable that masks made specifically to fit the facial characteristics of the patient are useful when continuous ventilation is required or when altering the point of skin contact of the mask, it may be that the leak flow of the exhalation port is not always well controlled. On the other hand, incorporation of the exhalation port in the respirator circuit instead of integrating it in the mask appears not to be an optimal solution, given that this has been shown to generate greater CO_2 rebreathing.[22]

In conclusion, this study shows that a prototype nasal mask produced in Spain generates less rebreathing of CO_2 during provision of CPAP than do other masks commonly used in this country. Apart from considerations of cost, the local availability of one or another type of mask is important for day-to-day clinical practice. Despite the fact that there is currently a large variety of nasal masks available on the market, with a wide range of sizes and designs, the prevailing policy towards this market sector in the Spanish national health system leads to geographical restrictions on their availability.

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