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BRIEF REPORT

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Bilevel positive airway pressure ventilation: factors influencing carbon dioxide rebreathing

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Abstract *Purpose:* Use of bilevel positive airway pressure (BLPAP) ventilators for noninvasive ventilation (NIV) is an established treatment for both acute and chronic ventilatory failure. Although BLPAP ventilator circuits are simpler than those of conventional ventilators, one drawback to their use is that they allow variable amounts of rebreathing to occur. The aim of this work is to measure the amount of CO_2 reinsufflated in relation to the BLPAP ventilator circuit in patients, and to determine predictive factors for rebreathing. *Methods:* Eighteen adult patients were ventilated on pressure support, either by intubation or with mask ventilation, during a weaning period. The mean inspiratory fraction of CO_2 (tidal $FiCO_2$) reinsufflated from the circuit between the intentional leak and the ventilator was measured for each breath. The influence of end-tidal CO_2 concentration ($ETCO_2$), respiratory rate (RR), percentage of inspiratory time (T_i/T_{TOT}), application of expiratory positive airway pressure (EPAP), and inspiratory tidal volume on magnitude of tidal $FiCO_2$, as well as the influence of intubation versus NIV, were studied by univariate comparisons and logistic regression analysis. *Results:* In a total of 11,107 cycles, tidal $FiCO_2$ was $0.072 \pm 0.173\%$. Of fractions measured, 8,976 (81%) were under 0.10% and 2,131 (19%) were over 0.10%, with mean values of $0.026 \pm 0.027\%$ and $0.239 \pm 0.326\%$, respectively. $ETCO_2$, EPAP, NIV versus intubation, and RR had significant predictive value for tidal $FiCO_2$ >0.10%. *Conclusions:* BLPAP ventilators present a specific rebreathing risk to patients. However, that risk remains modest, even in intubated patients, provided that EPAP is applied.

Keywords Bilevel positive airway pressure ventilation · Carbon dioxide · Expiratory positive airway pressure · ICU · Rebreathing

Introduction

Bilevel positive airway pressure (BLPAP) ventilation was introduced in 1990 [1, 2]. BLPAP ventilators are relatively inexpensive and much simpler than conventional ventilators [2]. They offer good performance [3], are currently used to deliver noninvasive ventilation (NIV) in various settings at home or in intensive care units (ICU) [4–9], and have occasionally also been used in intubated or tracheostomized patients [10].

The BLPAP circuit consists of single-limb tubing for inspiration and expiration, including a passive intentional

leak port located either at its distal end or on the mask [11]. During expiration, exhaled gases leave the circuit through the leak port but may also more or less fill the circuit beyond the port and then become part of the following delivered tidal volume (VT). This defines an additional rebreathing process specific to BLPAP ventilation.

Rebreathing risk has already been studied and only negatively related to the level of expiratory positive airway pressure (EPAP) [12–14]. Since CO_2 rebreathing increases the drive to ventilate and the work of breathing [12, 15, 16], it is important to clarify this risk.

Our aim was to assess the actual risk of additional rebreathing and its predictive factors in patients receiving BLPAP ventilation in ICU.

Materials and methods

This observational study was performed during routine care in a 15-bed adult ICU. Ethical approval was obtained from the local institutional review board. Patients gave informed consent and the study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Patients

Eighteen consecutive patients who required mechanical ventilation were studied during their weaning period. All patients were stable and conscious. They were either still intubated or under NIV using an inflatable air cushion oronasal Tyco™ mask (Mallinckrodt DAR, Mirandola, Italy).

Ventilator and settings

The BLPAP ventilator (Vision®; Respironics Inc., Murrysville, PA, USA) was used in pressure support mode. This ventilator is routinely utilized in our ICU either for NIV or in intubated patients during the weaning trial when the necessity for postextubation NIV is anticipated. It allows one to set the inspiratory fraction of oxygen (FiO_2), displays flow, pressure, and volume curves, and is alarm-equipped. The circuit consists of a single limb for inspiration and expiration with an exhalation port at its distal end (Respironics Whisper Swivel device, Murrysville, PA, USA). Ventilator settings were those routinely used. Inspiratory positive airway pressures (IPAP) were chosen to deliver VT of 8–12 ml/kg. In case of intrinsic positive end-expiratory pressure (PEEPi), detected on the ventilator screen, EPAP was adjusted to obtain zero end-expiratory flow without exceeding 9 cmH_2O. For patients with no PEEPi, 4 cmH_2O EPAP (the lowest possible with that ventilator) was applied. FiO_2 was adjusted to maintain oxygen saturation from 90% to 95%.

Measurements

One recording, lasting from 20 to 45 min, was obtained from each patient using the Biopac® MP 100 apparatus (Biopac Systems Inc., Santa Barbara, CA, USA). Calibrated pressure, airflow, and CO_2 (aspirating capnograph device) were sampled at a position 2 cm away from the port, between the exhalation port and the patient. The delay representing transit time from the sample point to the analyzer was measured beforehand. Signals were recorded at a frequency of 200 Hz.

Analyses were made breath by breath, after phasing CO_2 curves with flow and pressure, using Biopac® AcqKnowledge® 3.7 software. The beginning and end of each inspiration were defined at the points where flow crossed the zero line. For each breath, inspiratory positive airway pressure (IPAP), EPAP, inspiration time (T_i), expiration time (T_e), respiratory rate (RR), inspiratory tidal volume (VT_i) as the integral of the surface under the inspiratory flow, and end-tidal CO_2 concentration ($ETCO_2$) were measured. The ratio of $T_i/(T_i + T_e)$, called T_i/T_{TOT}, was calculated. The volume of CO_2 delivered from the circuit at each breath was calculated by integrating the CO_2 flow curve, defined as the product of inspiratory airflow and CO_2 concentration curves [17]. Mean inspiratory fraction of CO_2 for each tidal volume (tidal $FiCO_2$), expressed as a percentage, was defined as: inspired volume of CO_2/VTi × 100. An estimation of the additional dead space volume (VDadd) from each previous expiration accumulated in the circuit between the port and the ventilator was assessed as: VTi × tidal $FiCO_2/ETCO_2$.

Statistical analysis

Data are reported in count and proportion, or as mean ± standard deviation (SD), as appropriate. Each breath was classified according to tidal $FiCO_2$ (exceeding or within 0.10%). Univariate comparisons were performed using the unpaired Student t test for continuous variables, and a χ^2 test for categorical variables. Logistic regression analysis, with tidal $FiCO_2$ as the binomial dependent variable and parameters, both of which were significantly different by univariate analysis and clinically relevant as independent factors, were performed to find the best fitted model. Odds ratio (OR) and 95% confidence interval (95% CI) were determined. Differences were considered significant when $P < 0.05$.

Table 1 Breath characteristics for all cycles and according to rebreathing

Parameters	All cycles (n = 11,107)	Cycles with tidal $FiCO_2$ ≤0.10% (n = 8,976)	Cycles with tidal $FiCO_2$ >0.10% (n = 2,131)	Tidal $FiCO_2$ ≤0.10% versus >0.10% P value
Tidal $FiCO_2$ (%)[a]	0.072 ± 0.173	0.026 ± 0.027	0.269 ± 0.326	<0.001
VDadd (ml)[a]	7.1 ± 21.1	2.4 ± 3.2	26.7 ± 42.6	<0.001
$ETCO_2$ (%)[a]	4.13 ± 0.97	4.09 ± 1.00	4.50 ± 0.65	<0.001
RR (bpm)[a]	27.2 ± 9.6	25.7 ± 8.6	33.1 ± 11.1	<0.001
T_i (s)[a]	1.06 ± 0.48	1.09 ± 0.46	0.95 ± 0.52	<0.001
Te (s)[a]	1.55 ± 0.89	1.61 ± 0.86	1.32 ± 0.97	<0.001
T_i/T_{TOT} (%)[a]	41 ± 7	41 ± 7	44 ± 6	<0.001
VT_i (ml)[a]	447 ± 253	456 ± 245	402 ± 281	<0.001
IPAP (cmH_2O)[a]	23.9 ± 6.0	24.4 ± 5.5	21.7 ± 7.3	<0.001
EPAP (cmH_2O)[a]	7.3 ± 1.8	7.5 ± 1.7	6.5 ± 2.0	<0.001
Cycles INT/NIV[b]	8,275/2,832	6,454/2,522	1,821/310	<0.001

Tidal $FiCO_2$, mean CO_2 fraction for inspiratory tidal volume; VDadd, additional dead space volume due to the BLPAP circuit; $ETCO_2$, end-tidal CO_2 concentration; RR, respiratory rate; bpm, breath per minute; T_i, inspiratory time; T_e, expiratory time; T_i/T_{TOT}, $T_i/(T_i + T_e)$ ratio; VT_i, inspiratory tidal volume; IPAP, peak inspiratory pressure; EPAP, expiratory positive airway pressure; INT, intubation; NIV, noninvasive ventilation

[a] Data expressed as mean ± SD

[b] Data expressed as number of cycles

Table 2 Odds ratio to predict tidal $FiCO_2$ (cutoff 0.10%)

Predictor parameters	OR	95% CI	P value
$ETCO_2$	3.09	2.84–3.37	<0.001
RR	1.19	1.18–1.20	<0.001
T_i/T_{TOT}	1.00	0.99–1.01	0.81
EPAP	0.55	0.53–0.57	<0.001
VTi	1.00	1.00–1.01	<0.001
NIV versus INT	0.70	0.57–0.85	<0.001

Tidal $FiCO_2$, CO_2 fraction for inspiratory tidal volume; OR, odds ratio; CI, confidence interval; $ETCO_2$, end-tidal CO_2 concentration; RR, respiratory rate; T_i/T_{TOT}, $T_i/(T_i + T_e)$ ratio; EPAP, expiratory positive airway pressure; VT_i, inspiratory tidal volume; INT, intubation; NIV, noninvasive ventilation

Results

The 18 patients (13 males, mean age 54 ± 19 years) had been mechanically ventilated for 8.2 ± 6.6 days. Eleven patients (61%) were intubated and seven (39%) were under NIV. A total of 11,107 respiratory cycles were analyzed. Of the cycles measured, 8,976 (81%) had $FiCO_2$ below 0.10% and 2,131 (19%) had $FiCO_2$ exceeding 0.10%.

Values and univariate comparisons are presented in Table 1. Results of the logistic regression analysis are presented in Table 2. Four parameters had good predictive value for tidal $FiCO_2$ exceeding 0.10%: high $ETCO_2$, low EPAP, intubation, and high RR.

Discussion

In this study, we accurately measured the additional CO_2 rebreathing from the circuit, specifically induced with BLPAP ventilation. Our results underline the reality of a modest amount of rebreathing under a BLPAP ventilator in the clinical setting. Furthermore, we report for the first time the respective contribution of the different possible factors associated with CO_2 rebreathing in ICU.

We have compared a large number of individual breaths, split into two groups according to a low or higher rebreathing with a cutoff of tidal $FiCO_2$ at 0.10%. The comparison of individual breaths, rather than for example patients, is appropriated since the amount of rebreathing may depend on numerous factors, such as VT, EPAP, and timing of the respiratory cycle (RR and T_i/T_{TOT}). Most of these exhibit large variations (in the same patient) on a breath-by-breath basis during spontaneous breathing with pressure support. The choice of the cutoff is based on the consideration that such a value corresponds to 0.8 mmHg when the atmospheric pressure is 760 mmHg. Even if apparently low, 1 mmHg is enough to stimulate ventilation during pressure support ventilation [15, 16].

According to logistic regression analysis, we observed four pertinent factors that correlate with the magnitude of rebreathing. First and foremost was high $ETCO_2$, which correlates with increased possibility that tidal $FiCO_2$ will exceed 0.10%. Since $ETCO_2$ approximately corresponds to the concentration of CO_2 filling the circuit it is quite normal that, as $ETCO_2$ increases, so does tidal $FiCO_2$. Second, high EPAP correlated with increased likelihood that tidal $FiCO_2$ will be below 0.10%. This confirms previously published data which show that EPAP up to 8 cmH_2O may be necessary to eliminate rebreathing [13] and that low EPAP promotes significant rebreathing able to stimulate ventilation and increase the work of breathing [12]. Third, the type of connection is an important predictive factor, since less rebreathing takes place in the

course of NIV compared with translaryngeal intubation. Incidental leakage occurring at the skin–mask junction will decrease rebreathing from the circuit dead space, including the volume of the mask. Such a risk of leakage does not exist with intubation, provided the cuff is adequately inflated. In the same way, amplified leakage via the oral cavity during nocturnal nasal mask ventilation explains the uselessness of a non-rebreathing exhalation valve during BLPAP ventilation [14]. Fourthly, high RR was also a predictive factor for rebreathing in this study. Its influence has not been pointed out before. It may be related to the fact that too short a duration of expiration will be insufficient to completely flush expiratory gas from the circuit. In addition, VTi was also statistically significant, with an OR very close to 1 without clinical importance, whereas T_i/T_{TOT} had no influence on rebreathing.

The general findings of our study might be applied to all other BLPAP devices, circuits, exhalation ports, and interfaces, with the magnitude of additional rebreathing inversely proportional to the surface of the port and its distance from the patient [11].

We conclude that BLPAP ventilation actually presents a modest specific risk for rebreathing due to circuit leakage particular to the BLPAP ventilator design. That risk applied to about 10% and 20% of breaths, provided EPAP is applied, in NIV and with intubation, respectively. These data also show that BLPAP ventilation may be reasonably used in intubated patients. Recommendations to decrease the amount and incidence of rebreathing are use of EPAP (4–8 cmH_2O) and avoiding a rapid RR.

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