Reliability of Tidal Volume in Average Volume Assured Pressure Support Mode

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BACKGROUND: Remote monitoring is increasingly used in patients who receive home mechanical ventilation. The average volume assured pressure support mode is a target volume pressure preset mode that delivers a given tidal volume (VT) within a range of controlled inspiratory pressures. In a mode such as this, it is important to verify that the VT value retrieved from the ventilator SD card is accurate. METHODS: A lung model was set with C (Compliance) 0.075 L/cm H2O and Rl (Inspiratory resistance)-Re (Expiratory resistance) 15–25 cm H2O/L/s (model 1) or with C 0.050 L/cm H2O and Re 6 cm H2O/L/s (model 2) and 6 cm H2O effort. Three home-care ventilators (A40, PrismaST30, and Vivo40) were set to average volume assured pressure support mode with 0.3 and 0.6 L VT each at PEEP 5 and 10 cm H2O, and were connected to the lung model with and without unintentional leak. The reference airway pressure and flow were measured by a data logger. VT was expressed in body temperature and pressure saturated. We assessed the difference in VT between the ventilator SD card and a data logger relative to set VT and factors associated with its magnitude. RESULTS: For A40, PrismaST30, and Vivo40, the adjusted mean VT differences between the ventilator SD card and the data logger were -0.053 L (95% CI -0.067 to -0.039 L) (P < .001), -0.002 L (95% CI -0.022 to 0.019 L) (P = .86), and -0.067 L (95% CI -0.007 to 0.127 L) (P = .03), respectively. The partial Spearman correlation coefficients between the ventilator SD card and a data logger were 0.89 (P < .001), 0.59 (P < .001), and 0.78 (P < .001), respectively to the ventilators. The relative variations in measured VT from the set VT were 16.0, -12.0, and 6.7% for the ventilator SD card, and were -2.5, -7.5, and -27.2% for the data logger, respectively. The discrepancy in ventilator between SD card and data logger were influenced by PEEP for the PrismaST30 ventilator, unintentional leak for the Vivo40 ventilator and PEEP, unintentional leak, and underlying disease, the effect of each depending on the levels of the other factors, for the A40 ventilator. CONCLUSIONS: In the 3 home-care ventilators, the ventilator SD card underestimated VT. Factors involved in this difference differed among the ventilators. Key words: home mechanical ventilation; bi-level; average volume assured pressure support mode; noninvasive ventilation.

Introduction

Caregiver experts in some countries recommend that domiciliary noninvasive ventilation (NIV) for patients with chronic respiratory failure should be initiated on the basis of invasive (arterial blood gas) or noninvasive (capnogra-
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Quick Look

Current knowledge

Caregivers involved in home ventilation use data retrieved from the internal card of the ventilators to adjust settings. The average volume assured pressure support mode is a target volume pressure–preset mode that delivers a given tidal volume ($V_T$) within a range of controlled inspiratory pressures. We compared the $V_T$ given by using the internal card of 3 home-care ventilators to a data logger reference device.

What this paper contributes to our knowledge

$V_T$ significantly correlated between the internal card and the data logger but was systematically underestimated by the former. The factors involved in the discrepancy between the internal card and the data logger were different among the ventilators.

Methods

Setup

The experimental setup is schematically represented in Figure 1 and comprised the following items: (1) ASL 5000 Lung Model (Ingmar, Pittsburgh, Pennsylvania); (2) a data logger (Biopac 150; Biopac, Goleta, California) used to collect pressure and flow; (3) 2 pneumotachographs (Hans Rudolph 3830 series pneumotachograph; Hans Rudolph, Pawnee, Kansas) (the pneumotachograph 2 in Fig. 1 was used to perform the measurements presented in the results section); (4) a standardized leak that mimicked continuous nonintentional leak (20 L/min at 15 cm H$_2$O pressure); (5) 3 home care ventilators (A40 [Philips, Amsterdam, the

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Netherlands], PrismaST30 [Weinmann, Hamburg, Germany], Vivo40 [Breas]), validated for use in patients; and (6) a single-limb ventilator circuit (Intersurgical, Fontenay-sous-bois, France). The inclusion criteria of home mechanical ventilators for this study were the following: integrated ventilator SD card, the average volume assured pressure support mode available, and the availability of the device in France. Ventilators characterized as “life support” were excluded from this research.

Protocol

Before the experiments, both the pressure transducer and pneumotachographs were calibrated at room air temperature and pressure. The pneumotachographs calibration consisted in comparing, in the steady condition, the flow measured by the pneumotachographs with the flow from a reference flow meter, which was a rotameter (Houdec glass [Houdec Innovation SAS, Abrest, France]) specially designed for use in air. The ASL 5000 Lung Model was set to mimic COPD (model 1) and obesity hypoventilation syndrome (model 2) (Fig. 1). A fixed inspiratory effort of 6 cm H₂O with a sinusoidal profile was selected (Fig. 1). The frequency of effort was fixed at 12 breaths/min. The muscular effort lasted 16% of total breath duration, followed by a 2% pause and a 40% release time. Henceforth, the total duration of effort was 1 s. The ventilator was set in the pressure preset S (Spontaneous)/T (timed) mode at predetermined settings (Table 1).

For model 1 or model 2, each ventilator was run to target 0.300 and 0.600 L V\textsubscript{T}, each at PEEP 5 and 10 cm H\textsubscript{2}O. Experiments were performed with and without a nonintentional leak (Fig. 1). Recordings were started simultaneously with the ventilator and the data logger. To analyze exactly the same breaths with the ventilator SD card and the data logger, the ASL writings included a single large breath after completion of 30 breaths. This signal was easily recognized by both the ventilator SD card and the data logger. After this signal, 30 consecutive breaths were recorded.

Data Analysis

The last 10 breaths over these 30 breaths were manually analyzed backward from the very last breath in the venti-


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The secondary end point was the assessment of factors involved for each ventilator in the VT difference between the ventilator SD card and data logger. We first computed the relative variation between the target and measured VT (VT set − VT measured)/VT set for the ventilator SD card and the data logger, and expressed this variation as a percentage. This was done to make the computation independent of the size of the VT value. Then, we computed the absolute difference of the relative variation between the data logger and the ventilator SD card as follows:

\[
\frac{(VT_{set} - VT_{data~logger})}{VT_{set}} - \frac{(VT_{set} - VT_{ventilator~SD~card})}{VT_{set}} = \frac{(VT_{ventilator~SD~card} - VT_{data~logger})}{VT_{set}}
\]

If the difference is positive, then the ventilator SD card overestimates VT compared with the VT data logger. The opposite is true if the difference is negative. The role of factors that may be involved in the VT difference between the ventilator SD card and the data logger were underlying disease (model 1 or model 2), nonintentional leak (absent of present), and PEEP level (5 and 10 cm H₂O) was investigated by adjusting a linear model separately for each ventilator. All the factors were included in the model, with their double and triple interactions, which led to 8 coefficients. If the interactions were not significant at the .05 level, then they were discarded from the model one by one, starting from the least significant one. The final model was used to calculate the difference between the VT ventilator SD card and the data logger relative to the VT set for the different combinations of the levels of factors analyzed. The data analysis was performed by using R software (R, R Foundation for Statistical Computing, Vienna, Austria).

Results

VT Over All the Ventilators

Overall measurements of the median values of VT were 0.372 L (0.280, 0.571 L) for the ventilator SD card and 0.473 L (0.350, 0.674 L) for the data logger. The partial Spearman correlation coefficient was 0.46 (0.36, 0.54) (P < .001). The adjusted mean difference between the ventilator SD card and the data logger was −0.074 L (95% CI −0.118 to −0.031 L) (P < .001). Overall, the ventilator SD card underestimated VT (Fig. 2). The median value of the relative difference between the target VT and the ventilator SD card was 6.7% (−10.9%, 13.7%) and was −15.3% (−23.5%, 1.2%) for the data logger, which...
indicated that, as a whole, the ventilator SD card underestimated and the data logger overestimated VT relative to the target set VT. The A40 ventilator seemed acceptable at low VT but systematically underestimated VT to be >0.4 L. The Vivo40 ventilator systematically underestimated VT. The Prisma ST30 underestimated VT in the vicinity of 0.6 L.

VT for Each Ventilator

**A40 Ventilator.** For 160 measurements for the A40 ventilator, the adjusted mean difference between the ventilator SD card and the data logger was −0.053 L (95% CI −0.067 to −0.039 L) (P < .001). The partial Spearman correlation coefficient was 0.89 (0.83, 0.93) (P < .001). The ventilator SD card underestimated VT compared with the data logger (Fig. 2). The relative difference between the target VT and the ventilator SD card was 16.0% (9.0%, 22.6%) and was 2.5% (21.2%, 10.6%) for the data logger, which indicated that both ventilator SD card underestimated the target set VT.

**PrismaST30 Ventilator.** For all 160 measurements with the PrismaST30 ventilator, the adjusted mean difference between the ventilator SD card and the data logger was −0.002 L (95% CI −0.022 to 0.019 L) (P = .86). The adjusted Spearman correlation coefficient was 0.59 (0.44, 0.71) (P < .001). The ventilator SD card underestimated VT compared with the data logger (Fig. 2). The relative difference between the target VT and the ventilator SD card was −12.0% (−12.9, −10.9) and was −7.5% (−15.6, 3.4) for the data logger, which indicated that both ventilator SD card underestimated the target set VT.

**Vivo40 Ventilator.** For all 160 measurements with the Vivo40 ventilator, the adjusted mean difference between the ventilator SD card and the data logger was 0.067 L (95% CI 0.007 to 0.127 L) (P = .03). The partial Spearman correlation coefficient was 0.78 (0.61, 0.87) (P < .001). The ventilator SD card underestimated VT compared with the data logger (Fig. 2). The relative difference between the target VT and the ventilator SD card was 6.7% (0%, 6.7%) and was 27.2% (37.0%, −19.2%) for the data logger, which indicated that both ventilator SD card underestimated, and the data logger overestimated the VT relative to the target set VT.

Factors Involved in the Difference Between the Target and Measured VT

The complete model for each ventilator was simplified according to our statistical strategy (see supplementary materials). Overall, for the PrismaST30 ventilator, only the PEEP level influenced the difference between the ventilator SD card and the data logger, whereas only the nonintentional leak influenced the difference for the Vivo40 ventilator (Table 2). For the A40 ventilator, the PEEP level, nonintentional leak, and the underlying disease in-
fluenced the difference between the ventilator SD card and the data logger, but the effect of each of these factors depends on the levels of the other factors (the interactions were all statistically significant, as shown in the supplementary materials). For the A40 ventilator, the magnitude of underestimation was more important than without a nonintentional leak (Table 2). It was almost −20% for model 1 and −17% for model 2, regardless of the level of PEEP when nonintentional leak was present. When the nonintentional leak was absent, the underestimation was less than −10%. The PrismaST30 ventilator was associated with underestimation at PEEP 5 cm H2O and overestimation at PEEP 10 cm H2O. For the Vivo40 ventilator, underestimation was >10% with and without nonintentional leak.

**Discussion**

The main findings of our bench study were that the ventilator SD card underestimated the delivered VT compared with the data logger taken as the reference and that different factors across ventilators were associated with the magnitude of this difference. To our knowledge, this was the first bench study that compared the average volume assured pressure support mode across these 3 home-care ventilators. As caregivers experts in NIV mentioned, the remote monitoring of respiratory parameters recorded by the built-in ventilator software is a step forward for patients on long-term ventilation at home, and its results should have a role in the decision-making process.4 Our choice of ventilators for the present experiment was driven by the fact that non–life-support ventilators represent the large majority of the devices used to deliver NIV at home.

The main end point of the present investigation on the average volume assured pressure support mode was VT. We did that in line with Pasquina et al11 that emphasized on the direct relationship between alveolar hypoventilation and VT and the VT variability in the pressure preset pressure-limited mode. Both resulted from respiratory mechanics impairment, inspiratory effort intensity, and intentional and nonintentional leaks. Therefore, it is worth investigating VT delivery in the average volume assured pressure support mode.3-7

It should be noted that, even though NIV is the standard of care for patients with COPD in acute hypercapnic ventilatory failure, the beneficial effect of long-term use of NIV in these patients is not supported by the evidence. However, quality of life has been improved by long-term use of NIV in patients with COPD and the patients with obesity hypoventilation syndrome.12,13 The justification of the selected set VT was to match the range of VT used in recent trials on average volume assured pressure support.3-7 For expiratory positive airway pressure, the level of 10 cm H2O is used specifically in patients with respiratory sleep disorders at the same rate as in patients with obesity-hypoventilation syndrome as in overlap syndrome. The average volume assured pressure support mode gives a better VT estimation with a single limb circuit and intentional leak than with a double-limb circuit or an exhalation valve, with appropriate pressure adaptation during nonintentional leaks.15 Apart from VT, the Minute ventilation is another key element in NIV. Minute ventilation depends on the product of the VT and the breathing frequency, which is much easier to calculate. The study by Contal et al10 showed a good correlation between the breathing frequency measured by the test lung and by the ventilator SD card in the fixed pressure preset mode.

The present study found that each of the 3 ventilators underestimated VT, as already pointed out,10,16 in the fixed pressure preset mode. The difference between the ventilator SD card and Biopac 150 for VT measurement was not homogeneous and depended on ventilator and test lung conditions. Of interest for the practitioner in charge of the patient, our study provided factors that were associated with the magnitude of the difference between the ventilator SD card and Biopac 150, each relative to the set VT.

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**Table 2. Coefficients of Error (95% CI) in Every Condition Tested in Each Ventilator**

<table>
<thead>
<tr>
<th>Combination</th>
<th>A40*</th>
<th>PrismaST30*</th>
<th>Vivo40*</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIL + model 1 PEEP 5 cm H2O</td>
<td>−33.0 (−34.6 to −31.4)</td>
<td>−3.3 (−8.4 to 1.7)</td>
<td>−35.3 (−37.7 to −33.2)</td>
</tr>
<tr>
<td>NIL + model 2 PEEP 5 cm H2O</td>
<td>−29.5 (−31.1 to −27.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIL + model 1 PEEP 10 cm H2O</td>
<td>−30.9 (−32.5 to −29.3)</td>
<td>5.2 (2.7–7.8)</td>
<td></td>
</tr>
<tr>
<td>NIL + model 2 PEEP 10 cm H2O</td>
<td>−26.6 (−28.2 to −24.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIL − model 1 PEEP 5 cm H2O</td>
<td>−9.2 (−10.8 to −7.6)</td>
<td>−3.3 (−8.4 to 1.7)</td>
<td>−27.7 (−29.8 to −25.7)</td>
</tr>
<tr>
<td>NIL − model 2 PEEP 5 cm H2O</td>
<td>−13.2 (−14.8 to −11.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIL − model 1 PEEP 10 cm H2O</td>
<td>−17.5 (−19.1 to −15.9)</td>
<td>5.2 (2.7–7.8)</td>
<td></td>
</tr>
<tr>
<td>NIL − model 2 PEEP 10 cm H2O</td>
<td>−9.9 (−11.6 to −8.3)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are percentages.

* p < .001 vs 0.

NIL = nonintentional leak.
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(see supplementary materials). Except for model 1 PEEP 5 cm H₂O and model 2 PEEP 10 cm H₂O both without nonintentional leak, the 6 other combinations challenged the A40 ventilator card compared with the Biopac 150 (Table 2). Only PEEP (5 vs 10 cm H₂O) for the PrismaST30 ventilator and nonintentional leak for the Vivo40 ventilator were associated with the inaccuracy of the ventilator SD card (Table 2). The magnitude of the difference for each significant combination can be found in the supplementary materials. Taken together, these results showed that, as expected, nonintentional leaks and PEEP are the common factors that led to underdelivering VT. Leak compensation can be more efficient with a pressure increase, but the risk of leaks increases.6 Because the data retrieved from the ventilator SD card tended to underestimate the size of VT, the caregiver would be keen to increase VT with the subsequent risk of higher leaks.

This hybrid ventilation mode was expected to overcome the lack of strict VT control with pressure-limited ventilation. Clinical studies on the average volume assured pressure support mode showed contrasting results on sleep quality and efficacy on CO₂ correction. Storre et al3 and Janssens et al4 demonstrated a better nocturnal transthroneously measured partial pressure of carbon dioxide correction. Murphy et al3 found no difference between ST (spontaneous timed) and the average volume assured pressure support modes on diurnal Paco₂. A key issue is the range of driving pressure that results in a better ventilator adaptation during nonintentional leaks or high airway resistances, as shown by Ambrogio et al.6

The present study also showed that, even though the VT delivered was underestimated with the ventilator SD card, it was close to the target VT according to Biopac 150, which may suggest that the prescribed setting was actually delivered. Only clinical studies would be able to demonstrate it. This outcome is crucial because adjustment of VT based on the ventilator SD card measurement is necessary to offer to the patient receiving NIV a better follow-up with more reliable adaptation. Therefore, the accuracy of VT measurement should be part of manufacturers’ specifications. The difference in the results between the Vivo40 ventilator (an older machine) and the PrismaST30 ventilator (the most recent machine) tested in the present study may indicate an improvement in the technology from the manufacturers. However, the algorithm in the PrismaST30 ventilator led to an excessively high VT at the higher PEEP.

Limitations

We did not assess the leaks. Leaks which is another key parameter for NIV efficacy and tolerance evaluation.17 As pointed out by Fauroux et al16 leaks could compromise VT delivery more than the increase in resistance. This is a more-complicated parameter to estimate according to the bench test study by Contral et al,10 due to different manufacturer specifications: the ventilators that were presently investigated measured the amount of both intentional and nonintentional leaks. Other ventilators measure only nonintentional leak, which requires indicating the type of interface.

We used a fixed nonintentional leak but in clinical practice leaks are unstable, and may appear suddenly or progressively, which will not have the same impact on VT measurement. However, it is difficult to induce random nonintentional leaks with variable intensity in a lung model. Furthermore airway resistances fluctuate, particularly in the upper airways during sleep; consequently, the lack of ability to program these modifications on the test lung limits the efficacy evaluation of the average volume assured pressure support mode.

Conclusions

Of the 3 home-care ventilators tested in our study, the ventilator SD card underestimated VT but the correlation with reference value was high. Factors involved in this difference varied among the ventilators.

REFERENCES

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