Laboratory investigations

Measurement of respiratory mechanics using the Puritan-Bennett 7200a ventilator

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This study was designed in order to validate the respiratory mechanical variables measured by the Puritan-Bennett 7200a ventilator equipped with the 30/40 module. Two ventilators were connected to a lung model and submitted to several breathing patterns by modifying the respiratory rate, the tidal volume, the inspiratory flowrate and the model resistance. The inspiratory flowrate ($\dot{V}$), tidal volume (VT), peak inspiratory pressure (P_{max}), plateau pressure (P_{plat}) and PEEP measured by the ventilators were compared with the same variables measured at the connection between the breathing circuit and the lung model. The compliance ($C_{30/40}$) and the resistance ($R_{30/40}$) calculated by the 30/40 module were compared with those calculated by using the variables measured by the reference equipment. Both ventilators made a constant underestimation of $\dot{V}$ by 2.8 and 3.7 $L \cdot min^{-1}$, respectively. The VT was measured with a mean error of less than 10 ml but did not reflect the preselected values in the presence of an intrinsic PEEP. The P_{plat} was overestimated by 7 and 10%, respectively. The same calibration error was observed with P_{max} which was also affected by a pressure gradient due to the resistance of the breathing circuit. Even in the absence of intrinsic PEEP, $C_{30/40}$ presented an error due to the combination of the measurement errors on VT, P_{plat} and PEEP. Finally, $R_{30/40}$ presented a high percentage of error due to the combination of the measurement errors on $\dot{V}$, P_{max}, and P_{plat}, and to a sporadic aberrant selection of $\dot{V}$. Due to these numerous sources of error, the two ventilators studied did not give reliable estimates of resistance and compliance. We do not recommend the use of the optional 30/40 module to measure respiratory mechanics at the bedside.

Cette étude a été réalisée afin de valider les paramètres de mécanique respiratoire mesurés par le ventilateur Puritan-Bennett 7200a muni d'un module 30/40. Deux ventilateurs ont été branchés à un modèle de poumon et soumis à plusieurs conditions ventilatoires en modifiant la fréquence respiratoire, le volume courant, le débit inspiratoire et la résistance du modèle. Le débit inspiratoire ($\dot{V}$), le volume courant (VT), la pression inspiratoire maximale (P_{max}), la pression de plateau (P_{plat}) et le PEEP mesurés par les ventilateurs ont été comparés aux mêmes paramètres mesurés au niveau du branchement entre le circuit respiratoire et le modèle de poumon. La compliance ($C_{30/40}$) et la résistance ($R_{30/40}$) calculées par le module 30/40 ont été comparées à celles calculées en utilisant les paramètres mesurés au moyen de l'appareillage de référence. Les deux ventilateurs ont fait une sous-estimation constante du $\dot{V}$ de 2,8 et 3,7 $L \cdot min^{-1}$, respectivement. Le VT était mesuré avec une erreur moyenne de moins de 10 ml mais, en présence d'un PEEP intrinsèque, cette mesure ne reflétait pas les valeurs présélectionnées. La P_{plat} était surestimée par 7 et 10%, respectivement. La même erreur de calibration était observée avec P_{max} qui était de plus affectée par un gradient de pression dû

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à la résistance du circuit respiratoire. Même en l'absence de PEEP intrinsèque, $C_{30/40}$ présentait une erreur secondaire à la combinaison des erreurs de mesure sur VT, P_{plat} et PEEP. Finalement, $R_{30/40}$ présentait un haut pourcentage d'erreur secondaire à la combinaison des erreurs de mesure sur $\dot{V}$, P_{max}, et P_{plat}, et à une sélection sporadiquement aberrante de $\dot{V}$. A cause de ces nombreuses sources d'erreur, les deux ventilateurs étudiés n'ont pas fourni des estimations fiables de la résistance et de la compliance. Nous ne recommandons pas l'utilisation du module optionnel 30/40 pour mesurer la mécanique respiratoire au chevet du patient.

In intensive care units (ICU), many artificially ventilated patients could benefit from the use of non-invasive methods for the determination of the mechanical properties of their respiratory systems. Although several non-invasive methods[1-10] have been proposed for the measurement of respiratory mechanics, most clinicians still rely on the interrupter technique.[6] For this simple approach, the ventilator must generate a constant inspiratory flow which is abruptly interrupted (Figure 1). An inspiratory pause is then maintained in order to obtain a stable "plateau" pressure. The analysis of this breathing pattern requires only the measurement of five variables: the constant inspiratory flowrate ($\dot{V}$), the expired tidal volume (VT), the peak inspiratory pressure (P_{max}), the plateau pressure (P_{plat}) and the end-expiratory pressure (PEEP). The pressure drop between P_{max} and P_{plat} represents the resistive pressure (P_{res}) and the pressure gradient between P_{plat} and PEEP is the elastic pressure (P_{el}). Dividing P_{res} by $\dot{V}$ gives the inspiratory resistance of the respiratory system (R). Finally, dividing VT by P_{el} gives the static compliance of the respiratory system.

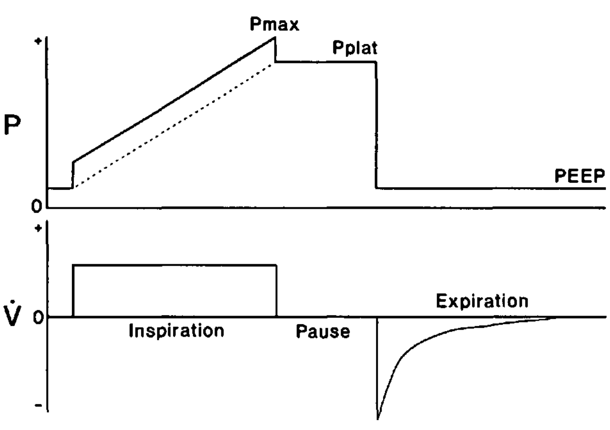

FIGURE 1 Schematic pressure and flow tracings observed during a modified breathing pattern required for the measurement of respiratory mechanics by the interrupter technique.

Electronic flowmeters and pressure transducers are being used in the internal pneumatic systems of several modern ventilators; their measurements are analyzed by a microprocessor controlling several solenoid and pneumatic valves in order to create the selected breathing pattern. This approach not only enables the ventilator to generate a constant inspiratory flow and to maintain an inspiratory pause but also, amongst other things, to correct the inspiratory flow for the compliance of the breathing circuit, to perform the BTPS correction for VT, and to maintain PEEP at the selected level. By the addition of optional electronic components (for example, the Puritan-Bennett 30/40 module), many ventilators can also estimate the compliance and the resistance of the respiratory system automatically by using the interrupter technique. However, the measurement of respiratory mechanics for most of these ventilators has not been validated. As, in our institution, routine automatic measurements of the respiratory mechanics are often made with the Puritan-Bennett 7200a ventilator equipped with the optional 30/40 module, the aim of this study was to validate the respiratory mechanical variables measured and calculated by this ventilator.

Methods

Two ventilators were randomly selected and were studied immediately after a thorough preventive maintenance, performed according to Puritan-Bennett specifications. In order to simulate a wide variety of clinical situations encountered in adult patients, they were then connected to a mechanical lung model and submitted to 54 different ventilatory situations by modifying the respiratory rate (10, 20 or 30 · min^{-1}), the tidal volume (0.5, 1.0 or 1.5 L), the inspiratory flowrate (20, 60 or 100 L · min^{-1}) and the model resistance (7- or 9-mm endotracheal tubes). Of these 54 ventilatory situations, 30 produced a steady-state ventilatory pattern and were considered for further analysis. For the 24 ventilatory situations rejected, either the ventilators were unable to achieve the requested breathing pattern or the mechanical lung model was unable to tolerate the large increase in volume secondary to the presence of intrinsic PEEP.

In these Puritan-Bennett ventilators, the flow measurements are made with three "hot-wire" flowmeters: one for the inspired oxygen flowrate, one for the inspired air flowrate and one for the expired gases. Each of these hot-wire flowmeters is specifically calibrated at the factory and the calibration cannot be re-adjusted by the hospital biomedical engineering technicians. This calibration is verified periodically with a reference calibration analyzer (Timeter RT-200) and, if the observed values are not within the ±15% margin of tolerance accepted by Puritan-Bennett, the whole flowmeter must be discarded. Using a feedback control mechanism, the internal electronic system of the ventilator will adjust the two inspiratory flowrates in order to deliver the selected $\mathrm{FIO_2}$ and the total inspiratory flowrate desired. For this study, as our reference pneumotachometer (*vide infra*) is sensitive to the viscosity of the gas mixture, the inspired fraction of oxygen ($\mathrm{FIO_2}$) was kept at 0.21. Furthermore, as these ventilators can be equipped with at least three different humidifiers, no humidifier was used in the breathing circuit in order to standardize the resistance of the inspiratory limb of the breathing circuit. Finally, a standard Puritan-Bennett breathing circuit with new inspiratory and expiratory filters was used. Any modification to the standard breathing circuit provided by Puritan-Bennett should be studied, as it can result in very different mechanical behaviour.

At the connection between the breathing circuit and the lung model, the pressure was measured with a piezoresistive transducer (Micro Switch 143PC03D) and the flowrate was measured with a pneumotachometer (Fleisch #3). The pressure transducer was calibrated against a water manometer (100 cm glass U-tube filled with distilled water) within ±0.2 cm H_2O. The linearity of the electronic pressure measurements was verified from 0 to 90 cm H_2O. The Fleisch pneumotachometer was calibrated against two "calibration analyzers" (Timeter Instrument Corporation Series RT-200) within ±0.1 $\mathrm{L \cdot min^{-1}}$. The linearity of the electronic flow measurements was verified from −180 to 180 $\mathrm{L \cdot min^{-1}}$. These electronic signals were amplified (Hewlett Packard 8802A), low-pass filtered at 80 Hz (Frequency Devices 902LPF), digitized at a sampling rate of 256 Hz (Data Translation 2801A A/D converter) and stored on the hard disk of a microcomputer.

Using the calibration factors provided by Puritan-Bennett, the analog pressure and flow signals obtained from the ventilator were also digitized and stored on the computer. For clinical use, the expiratory flow signal was already corrected in BTPS by the ventilator assuming expiratory gases at 37°C and fully saturated in water. However, using a lung model with dry gases at room temperature (20°C) for this study, this expiratory flow signal was corrected appropriately before data analysis. In this study, the expiratory flow and volume signals for both the Puritan-Bennett ventilator and the reference pneumotachometer will be expressed in STPD. The variables calculated by the optional 30/40 module (C and R) and displayed on the ventilator front panel were recorded manually. For both the ventilator and the laboratory instrumentation, the flow and pressure signals measured were analyzed ("Asystant+" scientific software) in order to obtain the steady-state $\dot{V}$, V_T, P_{max}, P_{plat} and PEEP. Using these measured variables, the compliance and the resistance were calculated.

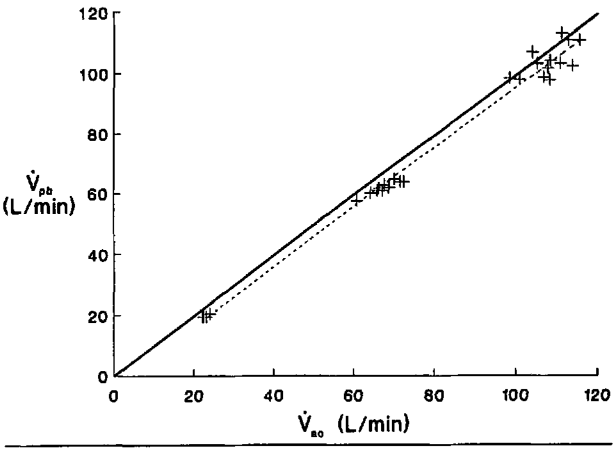

FIGURE 2 Relationship observed between the constant inspiratory flowrate measured by ventilator #2 and the one measured at the connection between the breathing circuit and the lung model. Regression line (dashed) -vs- line of identity (solid).

For each of these measured and calculated variables, the comparisons between the values obtained from the ventilator and those obtained from the reference equipment were made by linear regression. Furthermore, the values of the compliance and of the resistance calculated by the optional 30/40 module were also compared to those obtained by our calculations. For each of these relationships, the least squares estimates of the slope and of the y-intercept were tested against the theoretical values (line of identity: slope = 1 and y-intercept = 0). By analogy to the verification of the calibration of laboratory instruments against a "gold standard" reference, the two statistical hypotheses tested were that the observed slope is equal to the theoretical value of 1 and that the observed y-intercept is equal to the theoretical value of 0. Statistical significance was assumed when $P < 0.05$.

Results

Comparing the constant inspiratory flowrates measured by the two ventilators (#1 and #2) with those measured by the reference pneumotachometer at the connection with the lung model, the slopes of these relationships (0.9993 and 0.9899, respectively) were not different from the theoretical slope value of 1. However, both ventilators underestimated the inspiratory flowrate by 2.8 and 3.7 $\mathrm{L \cdot min^{-1}}$, respectively (i.e., y-intercepts were statistically different from the theoretical value of 0 $\mathrm{L \cdot min^{-1}}$). This absolute error resulted in an important relative error at the inspiratory flowrate of 20 $\mathrm{L \cdot min^{-1}}$. For ventilator #2, as shown in Figure 2, an increased scattering of the data points was observed at 100 $\mathrm{L \cdot min^{-1}}$. Contrary to ventilator #1, ventilator #2 presented an unstable inspiratory flow signal at this high flowrate.

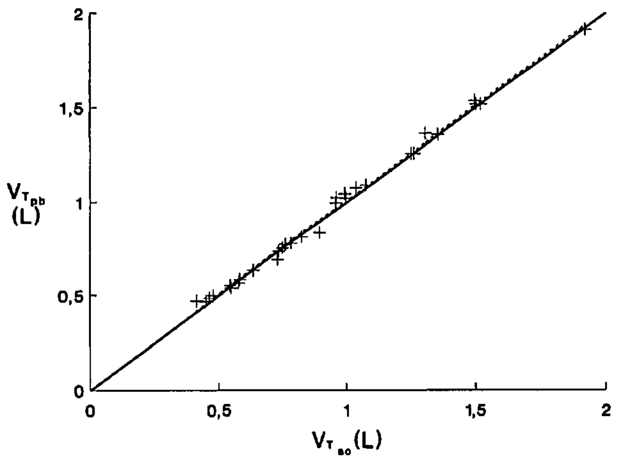

FIGURE 3a Relationship observed between the tidal volume measured by ventilator #2 and the one measured at the connection between the breathing circuit and the lung model. For this comparison, the tidal volume was measured during the breathing cycle modified by the 30/40 module. Regression line (dashed) -vs- line of identity (solid).

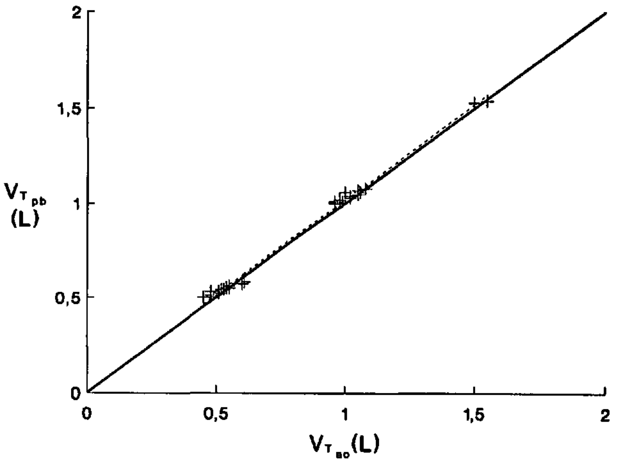

FIGURE 3b Relationship observed between the tidal volume measured by ventilator #2 and the one measured at the connection between the breathing circuit and the lung model. For this comparison, the tidal volume was measured during the steady-state breathing cycle preceding the one modified by the 30/40 module. Regression line (dashed) -vs- line of identity (solid).

The tidal volume (expiratory flow integrated over time) was measured with a mean error of less than 10 ml and no differences were found between the ventilators and the reference equipment. However, as shown in Figure 3a for ventilator #2, the measured VT did not always reflect the preselected values of 0.5, 1.0 and 1.5 L. This initial relationship was observed during the breathing cycle which follows the activation of the optional 30/40 module and which is used by this module for the automatic calculation of compliance and resistance. As the use of the 30/40 module modified the steady-state breathing pattern by inserting an inspiratory plateau followed by a variable expiratory time, we also analyzed the same volume signals during the breathing cycles preceding the activation of the 30/40 module (steady-state conditions). As shown in Figure 3b, the VT obtained were then much closer to the preselected values.

Comparing the plateau pressure measured by the ventilators with that measured by the reference pressure transducer at the connection with the lung model, the slope of these relationships (1.0704 and 1.1026, respectively) was different from the slope of the line of identity. However, the y-intercepts (−0.042 and −0.038 cm H_2O, respectively) were not different from the theoretical value of 0 cm H_2O. In other words, these ventilators overestimated P_{plat} by 7 and 10%, respectively (Figure 4a). This error in the calibration of the pressure transducers was also observed in the measurement of P_{max}, as shown by the slope of the relationships obtained for each preselected inspiratory flowrate (Figure 4b). For each ventilator, the slopes of these three relationships were different from 1 but did not present a difference when compared with the slope observed for P_{plat}. Furthermore, the measurement of this dynamic pressure (P_{max}) was also affected by another source of overestimation: the pressure gradient due to the resistance of the inspiratory limb of the breathing circuit. This phenomenon is reflected by the y-intercepts which are different from 0 cm H_2O. For these two ventilators and at 100 $L \cdot min^{-1}$, this pressure gradient reached 4.78 and 6.04 cm H_2O, respectively. Finally, PEEP was always measured within 1 cm H_2O of the preselected value of 5 cm H_2O.

As a measure of the internal consistency of the Puritan-Bennett system, the compliance automatically calculated by the 30/40 module ($C_{30/40}$) was compared with that calculated using the variables measured by the ventilators (C_{pb}): the observed relationships were not different from the line of identity (Figure 5a). However, comparing $C_{30/40}$ with the compliance calculated using the variables obtained from the reference equipment and using the steady-state VT (C_{ao}), an important scattering of the data points was observed (Figure 5b) and the slopes and the y-intercepts were different from those of the line of identity. For example, as shown in Figure 5b, the following regression equation was obtained with ventilator #2:

$$C_{30/40} = (C_{ao} \cdot 0.7275) + 38.5 \text{ ml} \cdot \text{cm } H_2O^{-1}$$

However, as will be discussed later, this equation depends not only on the ventilatory studied, but also on the presence of an intrinsic PEEP in the lung model and on the random variations of the expiratory time when the 30/40 module is activated.

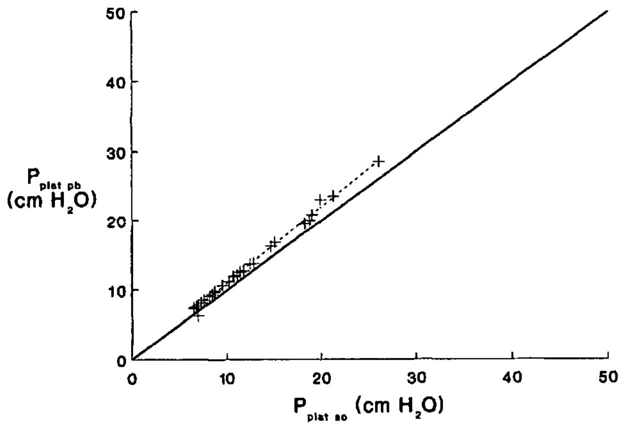

FIGURE 4a Relationship observed between the plateau pressure measured by ventilator #2 and the one measured at the connection between the breathing circuit and the lung model. Regression line (dashed) -vs- line of identity (solid).

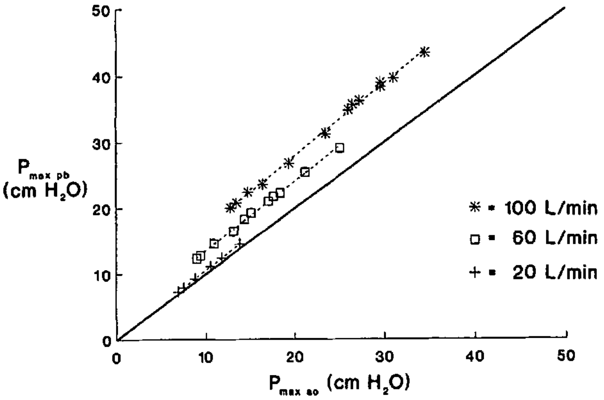

FIGURE 4b Relationships observed at the three inspiratory flowrates studied between the peak inspiratory pressure measured by ventilator #2 and the one measured at the connection between the breathing circuit and the lung model. Regression lines (dashed) -vs- line of identity (solid).

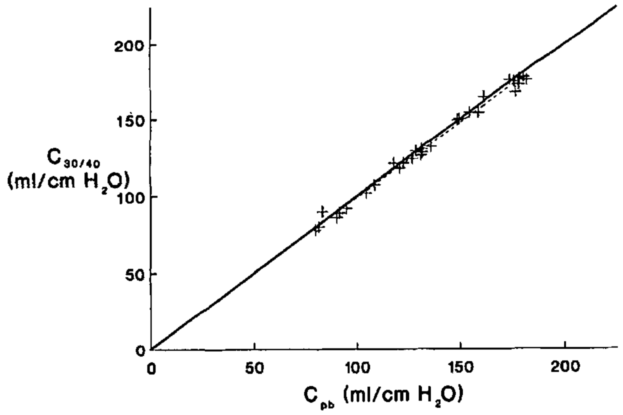

FIGURE 5a Relationship observed between the compliance calculated by the 30/40 module and the one calculated using the variables measured by ventilator #2. Regression line (dashed) -vs- line of identity (solid).

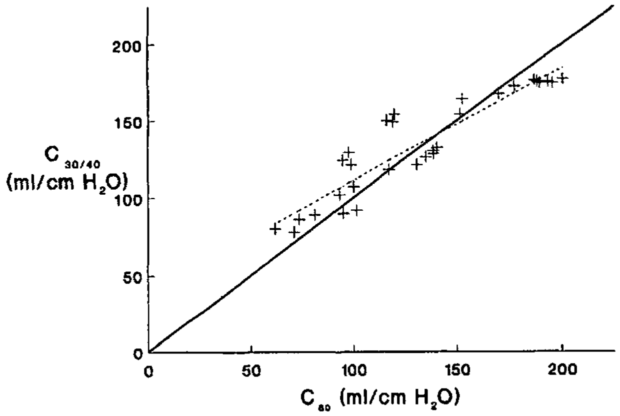

FIGURE 5b Relationship observed between the compliance calculated by the 30/40 module of ventilator #2 and the one calculated using the steady-state variables measured at the connection between the breathing circuit and the lung model. Regression line (dashed) -vs- line of identity (solid).

Again as a measure of the internal consistency of the Puritan-Bennett system, the resistance automatically calculated by the 30/40 module ($R_{30/40}$) was compared with that calculated using the variables measured by the ventilators (R_{pb}): the observed relationships had a slope not different from the slope of the line of identity but they had a slightly negative y-intercept (Figure 6a). Furthermore, some aberrant data points were observed with ventilator #2 when using an inspiratory flowrate of 100 $L \cdot min^{-1}$. For both ventilators, when comparing $R_{30/40}$ with the resistance calculated using the variables obtained from the reference equipment (R_{ao}), a relationship having a slope and a y-intercept significantly higher than those of the line of identity was observed at each inspiratory flowrate studied (Figure 6b).

Discussion

Clinicians may not expect the measurement of respiratory mechanics performed automatically by a ventilator (equipped with such an option) to be as precise as the one made with specialized laboratory equipment. However, from a practical standpoint, many anaesthetists, intensivists and respiratory technicians use such ventilators for the measurement of the respiratory mechanics. Confronted with this situation, we decided to conduct the present study which was not designed to characterize the overall behaviour of the Puritan-Bennett 7200a ventilator but to pinpoint potential pitfalls of the measurement of respiratory mechanics with this ventilator. Similar studies should also be conducted on the other ventilators offering automatic measurement of respiratory mechanics.

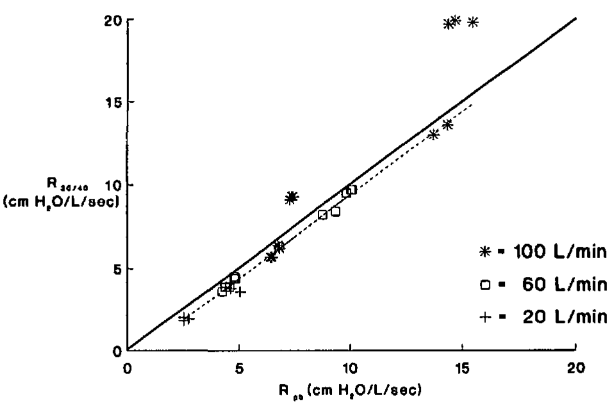

FIGURE 6a Relationship observed between the resistance calculated by the 30/40 module and the one calculated using the variables measured by ventilator #2. The six aberrant data points observed at 100 L · min^{-1} were not used for the regression analysis. Regression line (dashed) -vs- line of identity (solid).

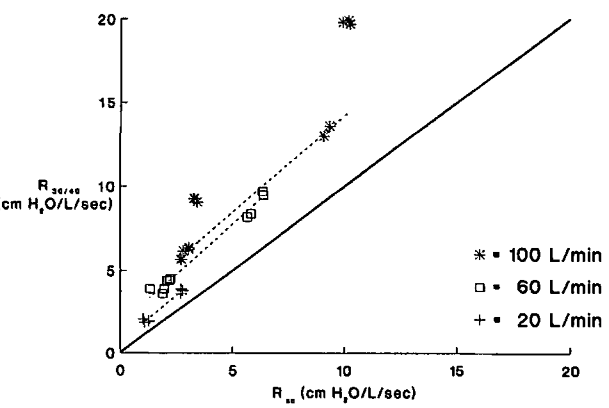

FIGURE 6b Relationships observed at the three inspiratory flowrates studied between the resistance calculated by the 30/40 module of ventilator #2 and the one calculated using the variables measured at the connection between the breathing circuit and the lung model. The six aberrant data points observed at 100 L · min^{-1} were not used for the regression analysis. Regression lines (dashed) -vs- line of identity (solid).

Knowing that the margins of tolerance accepted by the manufacturer during preventive maintenance are ±15% for the inspiratory flowrate and ±20% for the tidal volume, clinicians should already appreciate the level of precision to be expected. Using the analog flow signal provided by the ventilators and analyzing it according to the manufacturer's specifications, we observed a negative offset with both ventilators (2.8 and 3.7 L · min^{-1}). However, the increments in flowrate were measured accurately. In other words, if the absolute error was almost constant, the relative error became important at a low flowrate. At 20 L · min^{-1}, the percentage of error of the measurement of the constant inspiratory flowrate was 14 and 18.5%, respectively. Unfortunately, the initial factory calibration of the electronic flowmeters cannot be corrected by the hospital technicians during the preventive maintenance procedure.

The measurement of VT (i.e., expiratory flow integrated over time) was accurate. However, the VT measured after the activation of the 30/40 module did not always reflect the steady-state VT. This happened in the presence of an intrinsic PEEP and when the duration of the expiratory time was modified by the activation of the 30/40 module. As, after the automatic addition of an inspiratory pause, the duration of the expiratory time was unpredictable, the presence of intrinsic PEEP resulted in a variable expired VT which will later influence the calculation of the compliance. In the user's guide, Puritan-Bennett warns that the presence of intrinsic PEEP must be eliminated before using the 30/40 module. Classically, this can be done by measuring the airway opening pressure after an occlusion performed at end-expiration. But, as a flow signal tracing is provided on the last version of this ventilator (PB7200ae), one can also detect the presence of intrinsic PEEP when a residual end-expiratory flow is observed.

During the preventive maintenance procedure, the margin of tolerance accepted for the pressure measurements is only specified for the verification of the PEEP system. This margin of tolerance ranges from ±8% at 30 cm H_2O to ±20% at 10 cm H_2O. Using the analog pressure signal provided by the ventilators and analyzing it according to the manufacturer's specifications, it was observed that P_{plat} (quasi-static pressure measurement) was overestimated by 7.0 and 10.3%, respectively. No offset (y-intercept ≈ 0) was observed for P_{plat}. However, P_{max} (dynamic pressure measurement) presented not only the same degree of overestimation due to calibration but also a positive offset which was related to the inspiratory flowrate used. As the "airway pressure" is measured inside the ventilator, one can predict that an error will be introduced by the resistance of the breathing circuit (filters and tubes). The measurement of P_{max} could be improved by adding a special tubing between the internal pressure transducer and a connector inserted at the proximal end of the endotracheal tube. Such an optional tubing was offered on an earlier version of this ventilator (PB7200) but, probably in order to reduce the number of branching tubes and the related risk of leaks, Puritan-Bennett prefers to measure the "airway pressure" inside the ventilator, thus adding a considerable pressure gradient related to the resistance of the breathing circuit. Finally, as for the flowmeters, the initial factory calibration of the electronic pressure transducers cannot be corrected by the hospital technicians during the preventive maintenance procedure.

As shown in Figure 5a, the comparison of $C_{30/40}$ and C_{pb} shows that the 30/40 module performed adequate selection of the variables (as measured by the ventilator) and calculation of the compliance. This is a reflection of the good internal consistency of the Puritan-Bennett measuring system. However, as shown in Figure 5b, when $C_{30/40}$ is compared with the compliance calculated using the variables obtained from the reference equipment and using the steady-state VT (C_{ao}), it becomes obvious that the measurement errors made by the ventilator can be important. As mentioned before, the variability of the VT measured during the breathing cycle modified by the 30/40 module is the major source of the scattering of the data points. However, restricting this comparison to the data points not influenced by intrinsic PEEP, the slope of the $C_{30/40}$-vs-C_{ao} relationships was still much lower ($\approx$10%) than the slope of the line of identity due to the errors in the measurement of P_{plat} and PEEP. From a practical standpoint, the automatic measurement of the compliance can present a relatively high percentage of error due to the combination of the errors on VT (manufacturer's tolerance: ±20%), P_{plat} (up to +10% observed) and PEEP (manufacturer's tolerance up to ±20% at 10 cm H_2O). As mentioned by Puritan-Bennett, it is essential to detect the presence of an eventual intrinsic PEEP (*vide supra*).

In general, the 30/40 module performed a relatively adequate selection of the variables and calculations of the resistance: both ventilators presented a $R_{30/40}$-vs-R_{pb} relationship with a slope not significantly different from 1 but with a slightly negative y-intercept. However, for ventilator #2 (Figure 6a), six aberrant data points were observed when the inspiratory flowrate was 100 $L \cdot min^{-1}$. As mentioned before, this ventilator presented a "noisy" flow signal at this high flowrate (turbulence?) and this may have influenced the selection of the appropriate flowrate value by the 30/40 module. Therefore, the internal consistency of the Puritan-Bennett measuring system was sub-optimal for the measurement of flow with ventilator #2. At the bedside, one should observe the flow signal tracing when available (i.e., Puritan-Bennett 7200ae ventilator) in order to avoid using the 30/40 module in the presence of a noisy inspiratory flow signal. But, as shown in Figure 6b, these aberrant data points are only one source of error with the automatic measurement of the respiratory resistance. This measurement can also present a high percentage of error due to the combination of the measurement errors on $\dot{V}$ (manufacturer's tolerance: ±15%), P_{plat} (up to +10% observed) and P_{max}. In fact, for the two ventilators studied, a large part of the error of R was due to the overestimation of P_{max} which is dependent on the inspiratory flowrate (*vide supra*). In the clinical setting, if one accepts the error of the absolute values of the resistance, any comparison between two values can be done only at the same inspiratory flowrate. Finally, any modification to the breathing circuit (tube, filter, humidifier ...) can modify the resistance measured by a Puritan-Bennett 7200a ventilator equipped with an optional 30/40 module.

Due to the numerous sources of error identified, the two Puritan-Bennett 7200a ventilators studied did not give reliable estimates of resistance and compliance and, for the time being, we do not recommend the use of the optional 30/40 module to measure respiratory mechanics at the bedside. This does not imply that other brands of ventilators would perform better for this purpose. Furthermore, this study was limited to the measurement of respiratory mechanics and no conclusion is made about the overall performance of the Puritan-Bennett 7200a ventilator. Finally, one should remember that the measurement of respiratory mechanics with the interrupter technique requires a patient with a relaxed respiratory system. If this is possible under heavy sedation or complete neuromuscular blockade, one must also realize the limitations of this approach for many ICU patients where other approaches may be necessary.[1-10] However, these techniques would require a more sophisticated signal processing and/or the addition of laboratory instrumentation in the breathing circuit.

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