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A new simple method to perform pressure-volume curves obtained under quasi-static conditions during mechanical ventilation

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Abstract *Objective*: To describe a fast, simple method to acquire pressure-volume curves of the respiratory system and to compare this with a classic method in terms of reliability of the data and speed.
Design: Acquisition of pressure-volume curves by low flow inflation technique (P-Vlf) versus the occlusion technique (P-Vst) using the standard equipment of a Cesar ventilator.
Setting: General ICU – Aix en Provence Hospital.
Patients: Ten sedated, curarized patients undergoing mechanical ventilation.
Interventions: P-Vlf curves were acquired by setting the ventilator parameters at f = 5 c./min, duty time Ti/Ttot = 80 %, V_T = 1100 ml, pause time = 0. The pressure and volume data were collected directly on the ventilator screen. P-Vst curves were acquired using an airway occlusion technique. The pressures obtained for the same inflation volumes and times necessary for performance of the two techniques were compared.
Results: The time needed to acquire a P-Vlf curve was 3 min versus 38 min for P-Vst curve. Concordance analysis between the two methods showed a 95 % confidence interval of (–0.5 cm H_2O, + 1.8 cm H_2O) for pressure.
Conclusions: P-Vlf curves are close to P-Vst curves, are much less time-consuming, easy to acquire with Cesar ventilator equipment, and may be used in clinical routine to assess the elastic properties of the respiratory system.

Key words Pressure-volume curves · Low flow inflation technique · Pulmonary mechanics

Introduction

The acquisition of a static pressure-volume curve (P-Vst curve) of the respiratory system (RS) is recommended in intensive care to assess the elastic properties of the RS in patients undergoing mechanical ventilation (MV). P-Vst curve is used as a diagnostic and prognostic tool [1]. Furthermore, interest in this curve has grown over the last years, because its analysis can guide ventilation therapy in some patients with acute respiratory distress syndrome (ARDS) [2–4].

Today two methods to obtain the P-Vst curve are commonly described:

– The "super syringe" method [5, 6], which requires a specific device rarely available in the clinical setting. Moreover, this technique needs the patient to be disconnected from the ventilator and is not routinely used at the bedside.

– The "airway occlusion method" [7] has the advantage of not requiring disconnection of the patient from the ventilator. But this technique, in its original description, requires complex technical equipment to record pressure and volume data . Fernandez et al. [8] showed that it is possible to acquire P-Vst curves using nothing but the standard sensors of the ventilator for pressure and volume measurements. The acquisition of the P-Vst curve, although rich in information, is rarely achieved in the clinical setting because it is time-consuming and tedious, and it is always necessary to transfer the data to a graphic tool in order to visualise the curve.

We describe a simple and very fast method to acquire the static inflation curve of the RS, and compare it to the airway occlusion technique. The comparison will focus 1) on the accuracy and reliability of the data obtained with the new technique and 2) on the time needed to perform the two techniques.

Method and patients

Method

Several intensive care ventilators display a dynamic pressure-volume loop, cycle after cycle on screen. The pressure displayed is the airway pressure (Paw) and the volume is the tidal volume (V_T), so this curve is a dynamic Paw-V_T curve, very different to the static P-V curve (P-Vst curve): Paw is mainly influenced both by the elastic properties of the RS and by the resistive properties of the RS; the inspiratory motion equation is [9]:

$$\text{Paw} = \text{Pel.rs} + \text{Pres.rs} \qquad \text{(Eq. 1)}$$

where Pel.rs is the part of the total pressure applied on the RS to overcome the impedance of the elastic element of the RS, and Pres.rs is the frictional, flow-resistive part of the total pressure needed to overcome the impedance of the resistive element of the RS [10, 11].

Equation 1 can be broken down as follows:

$$\text{Paw} = [(\text{PEEPi}) + (\text{V/Cst})] + (\text{V'.Rrs})$$

where PEEPi is end expiratory recoil pressure of the RS due to an incomplete expiration, Cst is RS static compliance, V' is inspiratory flow and Rrs is RS inspiratory resistance.

Classic methods measure Paw during an interruption of flow (V' = 0) and under these conditions Paw = Pel.rs . If V' is made very low during inflation, the resistive component (V'.Rrs) can become negligible and thus Paw ≅ Pel.rs.

The Paw-V_T curve set by the ventilator assesses the RS mechanical properties only in the range of the inflated volume: a high inflation volume must be chosen to examine a large part of the inspiratory capacity (from end expiratory lung volume (EELV) to total lung capacity (TLC)).

Performance of the methods

Low flow inflation P-V curve (P-Vlf)

The method was performed in sedated, curarized patients undergoing MV (Cesar ventilator, Taema, France). Patients were ventilated in volume-controlled mode, with constant square-wave flow. The ventilator monitoring screen was set to P-V graph and the scale range chosen with due consideration. Before starting the procedure, tracheo-bronchial secretions were carefully aspirated. The upper limit pressure was fixed at 45 cm H_2O, FIO_2 was increased by 30 % for safety reasons, and PEEP, if any, was removed. First an end expiratory pause was obtained by pressing the "hold expiratory" button. While holding this button down, the frequency rate was quickly set to the minimum (f = 5 c./mn), the V_T to 1100 ml (the maximum V_T authorized by the Cesar ventilator is 1200 ml, but being on the top of the screen, the point corresponding to 1200 ml is difficult to measure with accuracy), Ti/Ttot ratio (representing the percentage of time taken by the inflation in the total duration of a cycle) was set to the maximum (80 %), and the end inspiratory pause time (T plateau) was set to zero. The "hold expiratory" button was released and the cycle with the newly set parameters started: at the same time the P-Vlf curve that was displayed on the screen was "frozen". Immediately following, the ventilator parameters (f, V_T, Ti/Ttot, T plateau) were re-set to their values prior to the procedure. Then, on the "frozen" P-Vlf curve, using the adjustable crosshair cursors available on the screen, we measured the pressures (Plf) corresponding to volumes of 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000 and 1100 ml.

For each patient, this measurement was repeated twice with an interval of 20 "normal" respiratory cycles between two measurements, and only the mean Plf values were considered. Then the data pairs were transferred to a graphic spreadsheet (Clarisworks, Macintosh, Apple) where the Plf values were plotted against the corresponding volumes.

Static P-V curve (P-Vst)

The P-Vst curve was acquired using the classic airway occlusion method, described elsewhere [7], in the same patients, under the same conditions; briefly, this method consists of measuring the static pressure (Pst) at the end of a 2-s inspiratory pause, after inflation of volumes of 100, 200, 300, . .. 1100 ml.

The absence of an air leak in the tubing was shown by the achievement of a steady pressure plateau during this end inspiratory pause. PEEPi was measured during an end expiratory pause. Twenty "normal" respiratory cycles were allowed between two occlusion cycles. Here again, measurements were made 3 times and mean values were considered. P-V data pairs were transferred to the same graphic tool to visualise the curve.

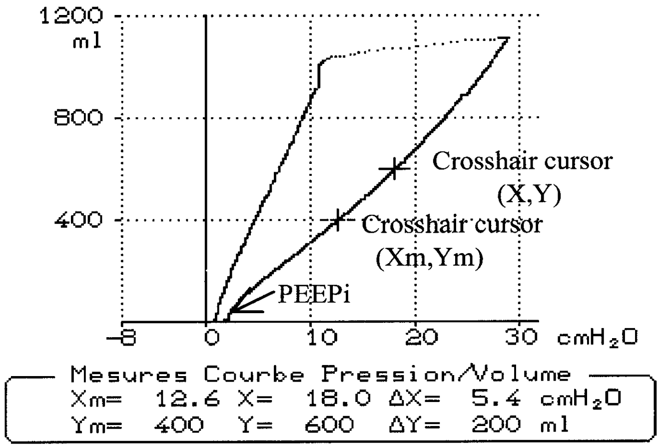
Pressure measurement

Plf measurement

In the P-V graph position, movable crosshair cursors are available on the Cesar monitoring screen, which are able to give accurate coordinates (P-V) for any point of the P-V plot. The crosshair cursors were moved along the "frozen" P-Vlf curve for different volumes (0, 100, 200, . .. 1100 ml), and the corresponding pressures (Plf) were directly read on the ventilator screen (Fig. 1).

Pst measurement

The monitoring screen was set in the pressure-time curve position. After performance of the occlusion cycle, the pressure-time wave was "frozen". The screen vertical Y-scale-measure sliders (Fig. 2) can be moved to the end of the inspiratory pause to measure the plateau pressure value (Pst).



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Mesures Courbe Pression/Volume
 Xm=  12.6 X=  18.0 ΔX=  5.4 cmH2O
 Ym=  400  Y=  600  ΔY=  200 ml
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Fig. 1 Original screen picture of P-Vlf loop. Crosshair cursors are moved along the inflation segment of the loop. P-V coordinates are read directly on the screen

Time measurement

The time necessary to acquire the P-V curves in both techniques was analysed. Since the clinician's wish is to see the P-V graph, usable for analysis, the times compared were those necessary to obtain these graphs: Since, in the low flow technique, the P-V graph is acquired directly on the screen, the chronometer started when the "hold expiratory" button was pressed, and stopped after P-V graph "freezing" (the time taken to do the measurements and transfer the P-V data pairs to the computer was not considered because it is only necessary for comparison of the two techniques, and not to see the curve in routine use). Concerning the occlusion technique, since the visualization of the P-V graph is obtained on the computer screen, the time considered was the time needed to perform each occlusion cycle, plus the duration of the 20 "normal" cycles, plus the time necessary to transfer the data pairs to the graphic tool, and the chronometer was stopped when the P-V graph appeared on the computer screen.

Compliance calculation

RS compliance was calculated as the Δvolume / Δpressure ratio (ΔV/ΔP) of the linear portion of the P-V curve. In order to define this linear portion, the P-Vst curve was divided into 11 segments (0 → 100 ml, 100 → 200 ml, . .. 1000 → 1100 ml), and the ΔV/ΔP ratios were calculated for each segment. The segment with the highest ΔV/ΔP ratio and the adjacent segments whose ΔV/ΔP ratios differed by less than 10% from this highest one, were considered to define the linear portion . A visual estimation of the curve shape validated this definition. The same portion of the curve was used to calculate the compliance of the P-Vlf curve (Clf).

Patients

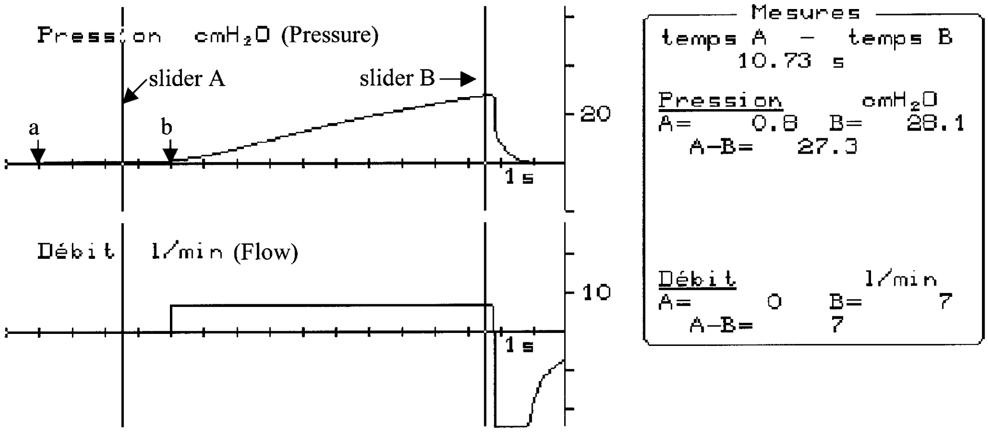
The research protocol was approved by the Ethics Committee of our Institution (Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale). Ten patients admitted onto the ICU for various causes (Table 1), undergoing MV, were studied. All patients had SaO_2 monitoring by pulse oxymetry and invasive arterial blood pressure monitoring. Patients with evidence of hemodynamic instability, severe acute cardiac arrhythmias, non-corrected hypoxemia ($PaO_2/FIO_2 < 200$ mmHg with $PaO_2 < 70$ mmHg) or hypercarbia ($PaCO_2 > 45$ mmHg) or who had exhibited pneumothorax or a broncho-pleural fistula in the last 48 h were excluded from the protocol.

Statistical analysis

Plf and Pst values were compared by concordance analysis [12] and linear regression correlation .Variance analysis on ranks (Friedman's test) was used to detect a "patient's effect" (because several data pairs were not patient-independent but obtained from the same patient) and to detect a "volume effect".

Results

Inflation P-V curves (P-Vst and P-Vlf) were acquired for 10 patients and we obtained 238 P-V data pairs; the Pst and Plf values for an inflation volume of 1100 ml could not be obtained in patient n° 8, because of a po-



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Mesures
temps A   -   temps B
    10.73  s
Pression        cmH2O
A=     0.8   B=    28.1
  A-B=    27.3

Débit             l/min
A=       0      B=      7
  A-B=      7
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Fig. 2 Original screen recording of pressure-time and flow-time waves during low flow inflation. *a*) expiratory pause beginning, *b*) expiratory pause release. Measurements are made on the screen with the sliders

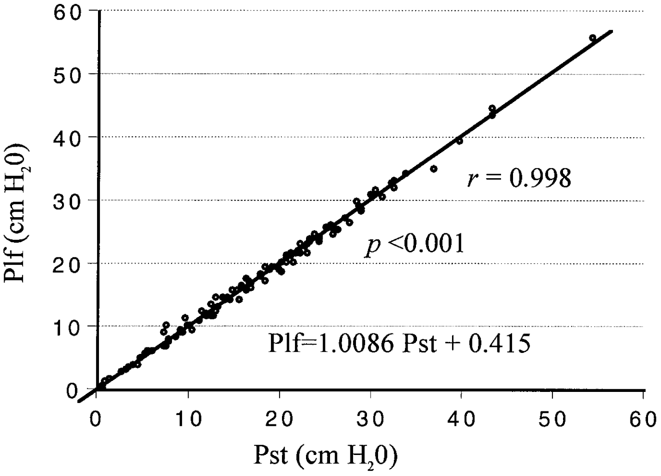

Fig. 3 Correlation between Pst and Plf values. Note that the regression line does not differ from the equality line

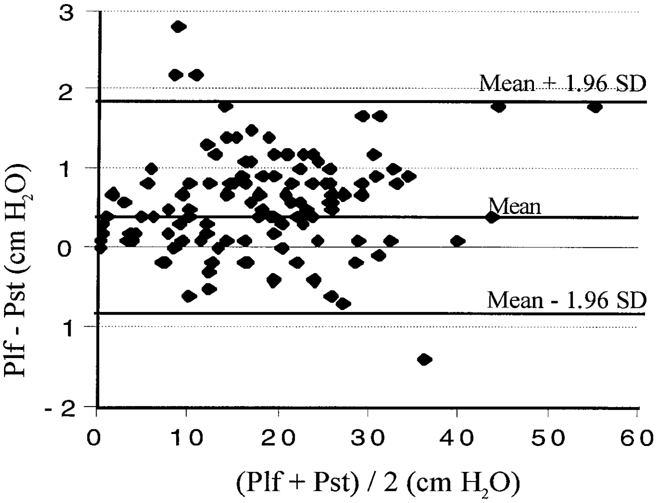

Fig. 4 Agreement test for pressure measurements between the two methods. The 95 % confidence interval ranged from –0.5 cm H_2O to + 1.8 cm H_2O

tentially dangerous high pressure level. No incident or accident occurred during the employment of the two methods: particularly the hemodynamic status remained stable, as did SaO_2. During the P-Vlf curve process, the flow was 7 l/min. The time needed to obtain P-V curves with the two methods was carefully measured: the necessary time was 38 min for P-Vst curve acquisition (30 min, 46 min), 15 s (13 s, 18 s) for one P-Vlf curve and 3 min for the whole P-Vlf maneuver (taking into account the time needed to obtain three measurements).

We compared 119 Pst data samples to 119 Plf data samples, but these samples were obtained in 10 patients so, of course, several data were obtained from the same patient. The result of Friedman's test ($F = 15.31 < \chi^2_9 (95\,\%) = 16.92$; degree of significance = 8.3 %) eliminated a "patient effect" on the data. We used a Friedman's test to verify the accuracy of the method on all volume ranges: the result ($F = 9 < \chi^2_{10} (95\,\%) = 18.31$; degree of significance = 53 %) allowed us to eliminate the presence of a "volume effect". The correlation between Pst and Plf was good ($r = 0.998$; $p < 0.001$) and the regression equation (Fig. 3) (Plf = 1.0086 Pst + 0.415) differs very slightly from the equality line and shows that Plf slightly overestimates Pst systematically. Concordance analysis shows an excellent concordance between Pst and Plf (Fig. 4); it confirms the tendency of the P-Vlf curve to overestimate the P-Vst curve slightly. The test shows that, for a given Plf pressure, the true pressure value differs from –0.5 cm H_2O to + 1.8 cm H_2O with a confidence interval of 95 %.

Static compliance (Cst) ranged from 18.6 ml/cm H_2O to 58.5 ml/cm H_2O (mean Cst = 38.8 ml/cm H_2O). There was no significant difference from Clf, which ranged from 18.05 ml/cm H_2O to 59.7 ml/H_2O (mean Clf = 39.3 ml/cm H_2O).

Discussion

The results of this study show that the P-Vlf curve, obtained during a low flow inflation, is close to the P-Vst curve, and data obtained with this new technique are reliable and accurate enough for clinical use. A constant low flow inflation technique has already been used to acquire P-V curves [13], but it required a sophisticated device to generate and control the low flow rate. Devices such as these are not routinely available at the bedside. Moreover the technique described by these authors required disconnection of the ventilator and imposed long apnea (greater than 60 s, but inflation and deflation P-V relationships were studied). It has been shown [14] that observation of the shape of the dynamic P-V curve on ZEEP, during a constant flow inflation, can provide useful information regarding the elastic properties of the RS. This observation could be an alternative to the P-Vst curve for predicting the effect of PEEP on alveolar recruitment, hemodynamics and gas exchange; but analysis of only the steady-state portion of this dynamic P-V curve is valid, precluding analysis of the initial pressure and volume events, and only the range of the tidal excursion can be studied.

As only inflation flow is controlled, only the inflation limb of the P-V loop is usable. However it has been shown that this inflation limb of the loop is clearly useful in intensive care [15, 16].

The P-Vlf curve tends to overestimate the P-Vst curve slightly; this is probably caused by the presence, even if small, of residual Pres.rs. With the chosen ventilator settings, flow was 7 l/min. These settings were those allowed

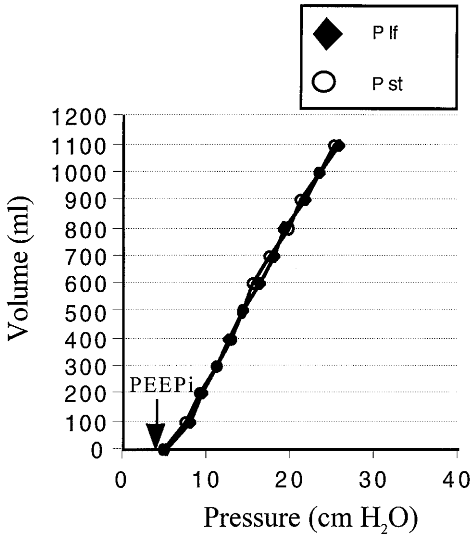

Fig. 5 P-V curves by the two methods in patient n° 7. Note the presence of PEEPi

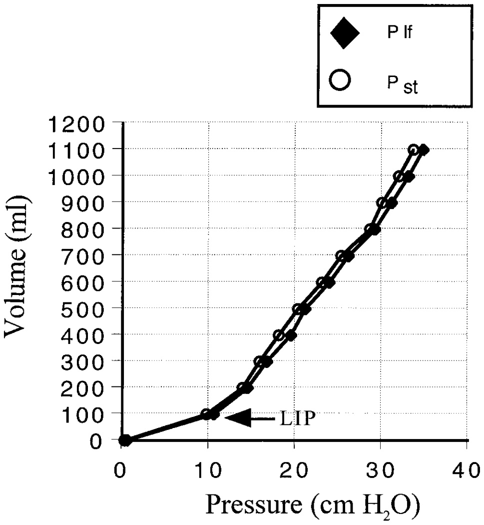

Fig. 6 P-V curves by the two methods in patient n° 10. Note the presence of low inflection point

by the Cesar ventilator and are not rigid: the idea is to inflate a large V_T in order to explore the range of thoraco-pulmonary volumes between EELV and TLC, with a low inflation flow in order to minimise Pres.rs as much as possible. The correct flow rate is not easy to determine: if the flow is very low, the P-V curve is affected by ongoing gas exchange, as the "super syringe" method-generated P-V curves [15]; but too high a flow rate will no longer produce a negligible dynamic pressure component. The chosen V_T (1100 ml) is also ventilator-dependent. In adult patients with normal compliance 1100 ml is usually insufficient to obtain an upper inflection point (UIP), but it is probably a sufficient volume to assess UIP in patients with ARDS: Roupie et al. [3] found an UIP in all patients with ARDS for a lung volume of 850 ± 200 ml above functional residual capacity.

Although the low flow technique described can be performed with most ventilators displaying P-V curves, the method is actually specific to ventilators with on-screen measurement tools and high quality graphic display. We compared several data pairs obtained from the same patient, which could result in statistical error. Friedman's test eliminates such a "patient's effect". Friedman's test was also used to verify if this new method is reliable in all volume ranges: no "volume effect" was found.

P-Vst curves performed with the classic methods exhibit the pressure-volume relationship "step by step", but not the curve progression between two steps, and this constitutes a lack of information. Since the P-Vlf curve is displayed continuously, the inter-step information is not lost: though we did not find a significant difference between the two techniques in the single patient who exhibited low inflection point (LIP) (Fig. 6), Mankikian et al. [13] have reported that a continuous curve is more accurate for determining LIP.

PEEPi can be measured on a P-Vlf curve (Figs. 1, 5). It has been shown that PEEPi can be determined from a "super syringe" technique-generated curve [17]: PEEPi is the isovolumic positive increment appearing at the beginning of the curve, corresponding to the amount of pressure which has to be applied with the super syringe before the RS starts inflating. A computer-controlled occlusion method has also been proposed for measuring the PEEPi on a P-V curve in mechanically ventilated patients [18]. Since PEEPi, with low flow inflation technique, is obtained during an end expiratory occlusion (the expiratory pause while ventilator parameters were changed), PEEPi here reflects the static PEEPi, representing the average PEEPi in a non-homogeneous lung [19]. Most of our patients had normal pulmonary mechanics because we wanted to test this new technique in a general population of ICU patients and not in specific subgroups. Further studies are therefore needed to verify the reliability of the method in patients with very high airway resistance or severe parenchymal dishomogeneity.

The time needed to acquire the P-Vlf curve is markedly less than the time needed to obtain the P-Vst curve. The time necessary to acquire the P-Vst curve can seem to be rather long: this is essentially because, in both techniques, we counted 20 "normal" cycles between two measurement steps. The number of cycles required for lung volume to return to baseline is not clearly established and often not given: 2 [7], 4 [14], 5 [8], and 8–10 [20] cycles were used in previous studies. Ranieri et al. [14] stated that their choice was based on the number of cycles usually required to regain baseline airway opening pressure. In addition, the presence of "slow" compart-

Table 1 General characteristics of the ten patients studied

Patient	Age	Sex	SAPS	Diagnosis	Previous respiratory history	FIO_2	PEEP cm H_2O	Days of ventilation	Outcome
1	52	F	7	Self poisoning	/	0.35	0	1	Alive
2	48	M	17	Pneumonia	COPD	0.45	8	16	Alive
3	46	F	9	Self poisoning	/	0.35	5	1	Alive
4	81	M	20	Myocardial infarction	/	0.6	10	5	Dead
5	47	M	8	Peritonitis	/	0.5	8	2	Alive
6	44	F	9	Self poisoning	/	0.35	0	1	Alive
7	47	F	20	Myocardial infarction	COPD	0.5	6	77	Dead
8	24	F	21	ARDS	/	0.7	12	129	Alive
9	38	F	7	Self poisoning	/	0.35	5	1	Alive
10	34	M	12	Pneumonia	/	0.45	12	32	Alive

ments of the RS have already been described in intubated, paralysed humans [21], and could be frequent in patients with ARDS [22]. Numerous "normal" cycles could be required to resume baseline lung volume in such cases, after inflation of a large V_T. In this study, 20 interstep cycles were allowed to ensure this lung volume goal. The time necessary to acquire P-V curves with four inter-step cycles, as previously described [14], was measured one time, and was found to be 2 min for a P-Vlf curve and 18 min for a P-Vst curve. In all cases, the low flow technique was found to be time saving and this probably constitutes the biggest advantage of this method. Using this technique in clinical routine, it becomes possible to acquire P-V curves very quickly and monitor the evolution of a respiratory disease or the results of the ventilatory therapy adjustments even several times a day.

In conclusion, this study describes a new simple technique for acquiring P-V curves in mechanically ventilated patients, only using the standard equipment of the Cesar ventilator. The method was found to be much less time-consuming than the classic airway occlusion technique, and its accuracy and reliability are sufficient for clinical use. Although further studies are needed in patients with very high airway resistance or severe parenchymal viscoelastic dishomogeneity, the technique with this ventilator can be proposed for studying the elastic properties of the respiratory system at the bedside.

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