Chest wall and lung contribution to the elastic properties of the respiratory system in patients with chronic obstructive pulmonary disease

V.M. Ranieri, R. Giuliani, L. Mascia, S. Grasso,
V. Petruzzelli, F. Bruno, T. Fiore, A. Brienza

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ABSTRACT: Conflicting data are available on the relative contribution of the chest wall (cw) to the intrinsic positive end-expiratory pressure of the total respiratory system (PEEPi,rs) in patients with chronic obstructive pulmonary disease (COPD).

In order to assess the chest wall and lung contribution to the elastic properties of the respiratory system in COPD patients during acute ventilatory failure, using the "interrupter technique", static inflation volume-pressure (V-P) curves of the total respiratory system (rs), lung (L) and cw were obtained in seven mechanically-ventilated COPD patients during application of zero end-expiratory pressure (ZEEP) and different levels (0–15 cmH$_2$O) of PEEP.

On ZEEP, PEEPi,rs was present in all patients (range 10.5–13.1 cmH$_2$O), to which PEEPi,cw and PEEPi,L contributed 17±2 and 83±1%, respectively. The static V-P curves of the rs, L, and cw on ZEEP were concave toward the horizontal axis, indicating that elastance increased with inflating volume. Application of PEEP did not affect lung and chest wall mechanics until PEEP levels exceeding 90% of PEEPi,cw on ZEEP (critical value of PEEP (*P*crit)). At PEEP levels higher than *P*crit, and relative to the V-P curves on ZEEP, we observed that: 1) the V-P curve of the rs showed an initial shift along the curve on ZEEP followed by a downward displacement with inflating volume; 2) the V-P curve of the L was shifted along the curve on ZEEP throughout inflating volume; and 3) the V-P curve of the cw was initially displaced along the curve on ZEEP, whilst a downward displacement appeared at higher lung volume.

In conclusion, our data show that, in chronic obstructive pulmonary disease patients with flow limitation, the increase in pleural pressure does not make a significant contribution to the intrinsic positive end-expiratory pressure of the total respiratory system. However, during tidal ventilation, a substantial increase in elastance of the chest wall is present. The critical values of positive end-expiratory pressure below which there are no changes in chest wall and lung mechanics amount to 90% of the total PEEPi,rs on ZEEP. Positive end-expiratory pressure levels higher than such critical value cause important alterations of the elastic properties of the lung and chest wall.
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Istituto di Anestesiologia e Rianimazione, Università di Bari, Bari, Italy.

Correspondence: V.M. Ranieri
Istituto di Anestesiologia e Rianimazione
Università di Bari
Ospedale Policlinico
Piazza Giulio Cesare, 70124
Bari
Italy

Chronic obstructive pulmonary disease (COPD) is characterized by an increase in airway resistance and a loss of lung elastic recoil. As a result, airflow limitation develops, leading to the presence of dynamic hyperinflation [1, 2] and intrinsic positive end-expiratory pressure (PEEPi).

In a recent study, POLESE and co-workers [3] found that, in mechanically-ventilated COPD patients, the chest wall and lung components of the total respiratory system PEEPi (PEEPi,rs) averaged 16 and 84%, respectively. They therefore concluded that abnormalities of the total respiratory system mechanics mainly reflect alterations of the lung, the contribution of the chest wall being negligible [4]. However, the data of POLESE and co-workers

[3, 4] conflict with the original observations by PEPE and MARINI [1] and with our recent findings [5] suggesting that the chest wall may play a significant role in the mechanical impairment of such patients [6], since PEEPi of chest wall (PEEPi,cw) represents up to 47% of PEEPi,rs [5].

In our study [5] and that of POLESE and co-workers [3] the interrupter technique was used [7, 8] and the respective role of the chest wall and lung mechanics were evaluated only at end-expiratory lung volume (by measuring PEEPi) and at the end of tidal volume inflation (by measuring static elastance). In the present investigation, in order to assess the chest wall and lung contribution to the elastic properties of the respiratory system in COPD

patients during acute ventilatory failure (AVF), the static inspiratory volume-pressure curves of the total respiratory system, chest wall and lung were studied in seven COPD patients during controlled mechanical ventilation (CMV). The study was carried out on zero end-expiratory pressure (ZEEP) and at different levels (0–15 cmH$_2$O) of positive end-expiratory pressure (PEEP).

Methods

Seven COPD patients (5 males and 2 females), admitted to the intensive care unit of the Policlinico Hospital (University of Bari) for management of AVF, were studied. The diagnosis of COPD was confirmed by their history and physical examination, as well as by previous pulmonary function tests. All patients were nasotracheally-intubated and had been mechanically-ventilated with a Siemens Servo Ventilator 900C (Siemens Elema AB, Berlin, FRG) for a mean (±SEM) period of 3±1 days (range 1–6 days). The precipitating causes of AVF and pertinent clinical information are shown in table 1. The investigation was performed in the supine position after sedation (diazepam, 0.1–0.2 mg·kg^{-1} and fentanyl 2–3 µg·kg^{-1}) and paralysis (vecuronium bromide 0.1–0.2 mg·kg^{-1}·h). The baseline ventilatory settings were established by the attending physician according to standard criteria (*e.g.* tidal volume (V_T 10–15 mg·kg^{-1}, respiratory rate (f_R) 12–15 breaths·min^{-1}) (table 2). The protocol was approved by the local Ethics Committee and informed consent was obtained from each patient or next of kin.

Flow (V') was measured with a heated pneumotachograph (Fleisch No. 2; Lausanne, Switzerland) connected to a differential pressure transducer (Validyne MP 45, ±2 cmH$_2$O; Northridge, CA, USA) which was inserted between the y-piece of the ventilator circuit and the endotracheal tube. The pneumotachograph was linear over the experimental range of flow. Equipment dead space (not including the endotracheal tube) was 60 mL. Tracheal pressure (P_{tr}) was measured with a polyethylene catheter (1.5 mm internal diameter (ID)) with multiple side holes, placed 2–3 cm past the carinal end of the endotracheal tube and connected to a pressure transducer (Validyne MP 45, ±100 cmH$_2$O, Northridge, CA, USA).

Table 2. – Baseline ventilatory setting of COPD patients during controlled mechanical ventilation on zero end-expiratory pressure

V_T L	0.83±0.09
V' L·s^{-1}	0.88±0.09
f_R breaths·min^{-1}	16.9±0.92
t_I/t_{tot}	0.27±0.02

Data are presented as mean±SEM of seven patients with chronic obstructive pulmonary disease (COPD). V_T: tidal volume; V': inspiratory flow; f_R: respiratory frequency; t_I: inspiratory time; t_{tot}: total breathing cycle time.

To reduce the effects on the measurements of the compliance and resistance of the system connecting the patients to the ventilator, a single length of standard low compliance tubing supplied with the ventilator was used (2 cm ID, 60 cm long), and the humidifier was omitted from the inspiratory line. The compliance of the system connecting the subjects to the ventilator was 0.4 mL·cmH$_2$O. Special care was taken to avoid gas leaks in the equipment, particularly around the tracheal cuff, which was frequently checked. Oesophageal pressure (P_{oes}) was recorded using a double-lumen nasogastric tube with a thin-walled vinyl balloon (10 cm long, 3.8 cm circumference; Mallinckrodt Inc., Argyle, NY, USA) incorporated in the lower mid-portion of the nasogastric tube and connected to a differential pressure transducer (Validyne MP 45, ±100 cmH$_2$O). This tube-balloon-catheter system allows measurement of P_{oes} in patients requiring nasogastric tube placement [3]. The oesophageal balloon was filled with 1–1.5 mL of air and correctly positioned using the occlusion test [9] immediately before the sedation and paralysis. With the system used to measure P_{tr} and P_{oes} there was no appreciable shift or alteration in amplitude up to 20 Hz.

All the above variables were recorded on an eight-channel strip chart recorder (Hewlett-Packard 7718 A) and on a personal computer *via* a 12-bit analogue-to-digital converter at a sample rate of 100 Hz, for subsequent data analysis. Volume was determined by digital integration of the flow signal.

Except for changes in PEEP and test breaths, the ventilatory settings were kept constant throughout the experiment. PEEP levels of 0, 5, 10 and 15 cmH$_2$O were

Table 1. – Patients characteristics

Pt No.	Age yrs	Sex	FEV$_1$ L	FVC L	F_{I,O_2}	P_{a,O_2}* kPa	mmHg	P_{a,CO_2}* kPa	mmHg	pH*	Precipitating causes of AVF	Days on MV
1	70	M	0.30	1.60	0.4	11.7	88	6.1	46	7.42	Exacerbation COPD	4
2	76	M	0.42	1.29	0.3	10.0	75	6.4	48	7.43	Exacerbation COPD	3
3	71	F	0.30	1.60	0.7	11.6	87	6.0	45	7.47	Bronchopneumonia	2
4	75	F	0.53	1.21	0.5	11.7	88	6.1	46	7.58	Exacerbation COPD	2
5	66	M	0.66	2.54	0.5	13.1	98	5.9	44	7.57	Bronchopneumonia	2
6	48	M	0.73	1.23	0.4	10.1	76	7.3	55	7.44	Exacerbation COPD	3
7	55	M	0.70	2.11	0.5	12.5	94	5.3	40	7.43	Exacerbation COPD	3
Mean	66		0.52	1.65	0.47	11.6	87	6.1	46	7.48		2.7
±SEM	±4		±0.49	±1.33	±0.33	±3.0	±22.5	±1.6	±12.1	±0.18		±2.0

Pt: patient; M: male; F: female; FEV$_1$: forced expiratory volume in one second; FVC: forced vital capacity; F_{I,O_2}: fraction of inspired concentration of oxygen during mechanical ventilation; AVF: acute ventilatory failure; P_{a,O_2}: arterial oxygen tension; P_{a,CO_2}: arterial carbon dioxide tension; COPD: chronic obstructive pulmonary disease; MV: mechanical ventilation. *: data obtained just prior to the study before sedation and paralysis.

applied in random order and maintained for 30–40 min. All measurements of respiratory mechanics were made during the last 5–10 min period of each level of PEEP. The electrocardiogram, heart rate, systemic arterial blood pressure, end-tidal CO_2, and arterial O_2 saturation were continuously monitored. The mean inspiratory oxygen fraction (FI,O_2) was 0.5±0.05 (±SEM). During the study, a physician not involved in the experiment was always present to provide for patients' care.
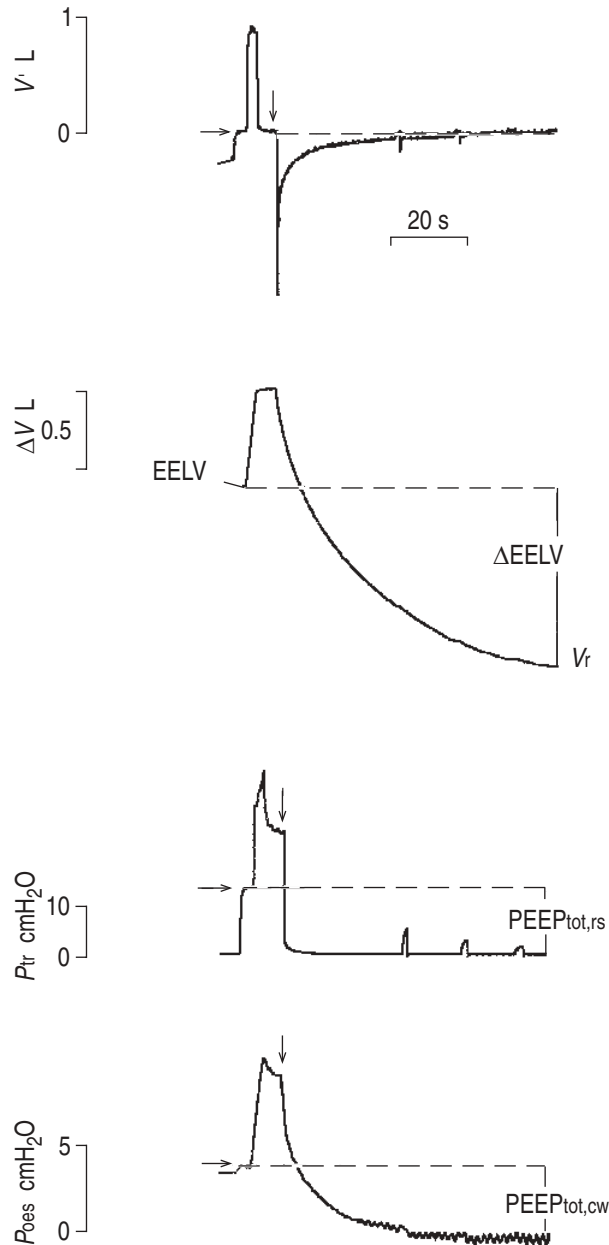

Fig. 1. – Experimental record illustrating the test breath used to determine respiratory mechanics on zero end-expiratory pressure (ZEEP). From top to bottom, tracings represent flow (V'), change in volume (ΔV), tracheal pressure (Ptr), and oesophageal pressure ($Poes$). Horizontal arrow indicates end-expiratory occlusion, whilst vertical arrow indicates end-inspiratory occlusion. EELV: end-expiratory lung volume; Vr: relaxation volume of the respiratory system; PEEPtot,rs: plateau pressure in the respiratory system during end-expiratory occlusion; PEEPtot,cw: plateau pressure in the chest wall during end-expiratory occlusion; ΔEELV: increase in lung volume due to the presence of PEEPtot,rs. See text for further details.

Test breath

During baseline ventilation an end-expiratory airway occlusion (EEO) was performed by pressing the end-expiratory hold knob on the ventilator (fig. 1). In all patients, Ptr and $Poes$ increased following airway occlusion. When an end-expiratory plateau was reached in both Ptr and $Poes$, EEO was released. At the end of the following breath, an end-inspiratory occlusion (EIO) was performed by pressing the end-inspiratory hold knob on the ventilator and was maintained until an apparent plateau was observed in both Ptr and $Poes$ (fig. 1). During the EIO, the patient was disconnected from the ventilator. In this way, when the EIO was released, a complete expiration to the elastic equilibrium (relaxation) volume of the respiratory system (Vr) was allowed. To check whether Vr had been reached, the airway was repeatedly occluded. If, during the occlusion, there was no increase in Ptr, Vr was achieved (fig. 1). After each test breath, the baseline ventilation was resumed until changes in lung volume (ΔV), V', and pressures returned to their baseline values.

Data analysis

Intrinsic PEEP (PEEPi). PEEPi in the respiratory system (PEEPi,rs) and in the chest wall (PEEPi,cw) were measured as the plateau during EEO in, respectively, Ptr and $Poes$ referred to atmosphere. PEEPi in the lung (PEEPi,L) was determined as difference between PEEPi,rs and PEEPi,cw. When PEEP is applied, the pressure measured by EEO is the sum of PEEP set by the ventilator and PEEPi. We termed this pressure "PEEP total" (PEEPtot,rs). In this connection, it should be noted that on ZEEP the end-expiratory pressure applied at the airway opening by the ventilator was slightly positive, amounting to 0.29± 0.06 cmH$_2$O, and hence, also on ZEEP we measured PEEPtot,rs [2]. For reasons of clarity, PEEPi,cw and PEEPi,L on ZEEP and at all levels of PEEP will, henceforth, also be defined as PEEPtot,cw and PEEPtot,L.

Dynamic hyperinflation (ΔEELV). The amount of increase in lung volume due to the presence of PEEPi at each level of PEEP was quantified as the difference between end-expiratory lung volume (EELV) during mechanical ventilation and Vr [5].

Static inflation volume-pressure (V-P) curve. This was measured, as described previously [7], by intermittently performing a series of the above-described test breaths at different inflation volumes that ranged 0.10–0.80 L. Different volumes were achieved by changing the respiratory frequency of the ventilator whilst keeping the inspiratory flow constant at baseline level. The static V-P curves of the respiratory system, chest wall, and lung were obtained by plotting the different volumes against the corresponding pressure values referred to atmosphere at 3–5 s after EIO, which were therefore taken as the static end-inspiratory recoil pressure of the respiratory system (Pst,rs), chest wall (Pst,cw) and lung (Pst,L), respectively. Changes in volume (ΔV) were related to Vr. To estimate absolute static pleural pressure value from measurements of PEEPi,cw and Pst,cw from $Poes$ signal,

a correction was made as follows: assuming that the vertical height of the lungs is about 20 cm, and that the gradient in pleural surface pressure is about 0.25 cmH_2O per cm descent down the lung, the actual values of PEEPi,cw and Pst,cw should be 2.5 cmH_2O more negative than those recorded [9, 10] (taking 10 cm as the bottom level of the lung where the oesophageal balloon is positioned following the occlusion test).

Statistical analysis

Results are expressed as mean±SEM. Regression analysis was performed using the least-square method. Values obtained at different levels of PEEP were compared using the two-way analysis of variance (ANOVA) of repeated-measures. A p-value equal to or less than 0.05 was considered significant. If significant, the values obtained at different levels of PEEP were compared with those on ZEEP using the paired t-test as modified by Dunnett.

Results

PEEPtot,rs was present in all patients ranging 10.5–13.1 cmH_2O. The mean values are provided in table 3 together with those of ΔEELV, which ranged 0.85–1.01 L. PEEPtot,cw and PEEPtot,L represented 17 and 83% of the PEEPtot,rs value, respectively. Figure 2 illustrates the average inflation V-P relationship of the total respiratory system, chest wall and lung on ZEEP. In the range between EELV and baseline VT, the static V-P curves of the total respiratory system, chest wall and lung were fitted to a power equation of the type [2, 7]:

$$\Delta P_{st} = a \cdot \Delta V^b \qquad (1)$$

where coefficient a represents static elastance of the relevant respiratory component at ΔV of 1 L and coefficient b is a dimensionless number that indicates the variation of elastance with inflating volume [11]. For values of coefficient $b < 1$, elastance decreases with inflating volume, whilst it increases for values of coefficient $b > 1$. Values of coefficient $b = 1$ indicate that elastance is constant in the experimental volume range and that, therefore, the V-P relationship is linear rather than curvilinear [11]. The correlation coefficients ranged 0.95–0.99
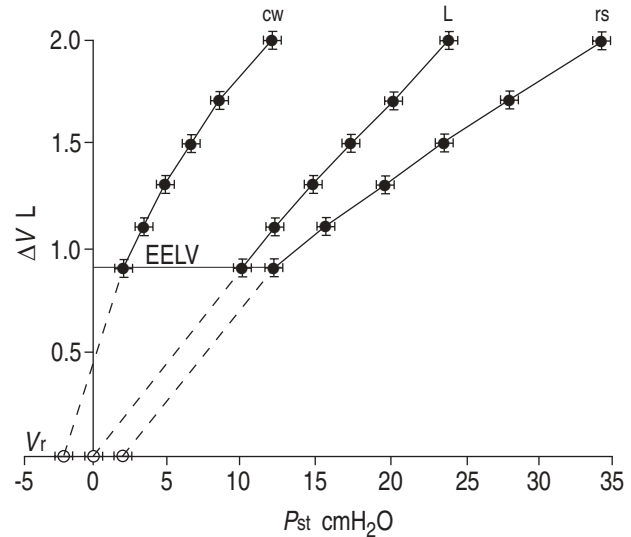

Fig. 2. – Mean static inflation volume-pressure (V-P) curves of the respiratory system on zero end-expiratory pressure. ΔV: changes in lung volume relative to the elastic equilibrium (relaxation) volume of the respiratory system (Vr); Pst: static elastic recoil pressure; EELV: end-expiratory lung volume; rs: total respiratory system; L: lung; cw: chest wall. Solid lines are obtained by fitting Equation (1) to experimental points. Dotted lines connect experimental points at EELV to the absolute pressure values in the respiratory system, lung and chest wall measured at Vr.

($p < 0.0001$). The average values of coefficients a and b in Equation (1) for the total respiratory system, chest wall and lung of the seven patients are given in table 4. On ZEEP, the static inflation V-P curves of the total respiratory system, chest wall and lung exhibited a concavity towards the horizontal axis in all patients, and therefore the coefficient b in Equation (1) was always >1, indicating that elastance increased with inflating volume. Values of coefficient b in Equation (1) for the chest wall on ZEEP was higher than in the lung (table 4), thus indicating that the rate of increase in elastance with volume was higher in the chest wall than in the lung.

Application of PEEP levels of 5 and 10 cmH_2O of PEEP did not increase lung volume, and therefore end-expiratory pressures in the total respiratory system, chest wall and lung remained unchanged (table 3). As a consequence, static inflation V-P curves of the total respiratory system (fig. 3a and b), chest wall (fig. 4a and b)

Table 3. – Effects of positive end-expiratory pressure on total intrinsic PEEP and static elastance of respiratory system, lung, and chest wall and ΔEELV in mechanically-ventilated COPD patients

	PEEP cmH_2O			
	0	5	10	15
PEEPtot,rs cmH_2O	12.0±0.41	12.3±0.26	12.2±0.24	16.4±0.41*
PEEPtot,cw cmH_2O	4.5±0.52	4.6±0.40	4.4±0.37	7.5±0.93*
PEEPtot,L cmH_2O	7.5±0.63	7.7±0.32	7.8±0.23	8.8±0.58*
ΔEELV L	0.93±0.07	0.93±0.04	0.94±0.05	1.22±0.06*
Est,rs $cmH_2O \cdot L^{-1}$	18.7±2.0	18.1±2.0	20.7±2.0	33.3±2.8*
Est,cw $cmH_2O \cdot L^{-1}$	8.9±1.5	8.8±1.5	9.1±1.6	19.6±1.7*
Est,L $cmH_2O \cdot L^{-1}$	9.8±0.2	9.3±0.6	11.6±0.6	13.7±0.5*

Data are presented as mean±SEM of seven patients with chronic obstructive pulmonary disease (COPD). PEEP: positive end-expiratory pressure; PEEPtot: total intrinsic positive end-expiratory pressure; ΔEELV: difference between end-expiratory lung volume and relaxation volume; Est: static elastance; rs: total respiratory system; L: lung; cw: chest wall. *: significantly ($p < 0.001$) different from PEEP 0.

Table 4. – Coefficients *a* and *b* of the static volume pressure relationship of the total respiratory system (rs), chest wall and lung fitted to a power equation of the type $\Delta P_{st} = a \cdot V^b$ in seven COPD patients at different levels of PEEP

| | *a* cmH$_2$O·L^{-1} | | | | *b* | | | |
	PEEP 0	PEEP 5	PEEP 10	PEEP 15	PEEP 0	PEEP 5	PEEP 10	PEEP 15
Lung	10.9 (1.03)	10.2 (1.13)	10.2 (1.07)	13.6 (1.33)*	1.14 (0.08)	1.13 (0.03)	1.11 (0.09)	1.45 (0.07)*
Chest wall	2.59 (0.06)	2.51 (0.07)	2.55 (0.06)	3.51 (0.07)	2.21 (0.06)	2.29 (0.07)	2.38 (0.11)	2.64 (0.06)*
Total rs	13.1 (1.09)	13.2 (1.11)	13.3 (1.01)	18.9 (1.00)*	1.34 (0.09)	1.31 (0.04)	1.33 (0.08)	1.89 (0.03)*

Values are presented as mean (±SEM) of seven patients with chronic obstructive pulmonary disease (COPD). PEEP: postive end-expiratory pressure; P_{st}: static pressure; ΔV: changes in lung volume relative to relaxation volume; *a*: represents static elastance of the relevant respiratory component at ΔV of 1 L; *b*: dimensionless number that indicates the variation of elastance with inflating volume. *: significantly (p<0.001) different from PEEP 0.
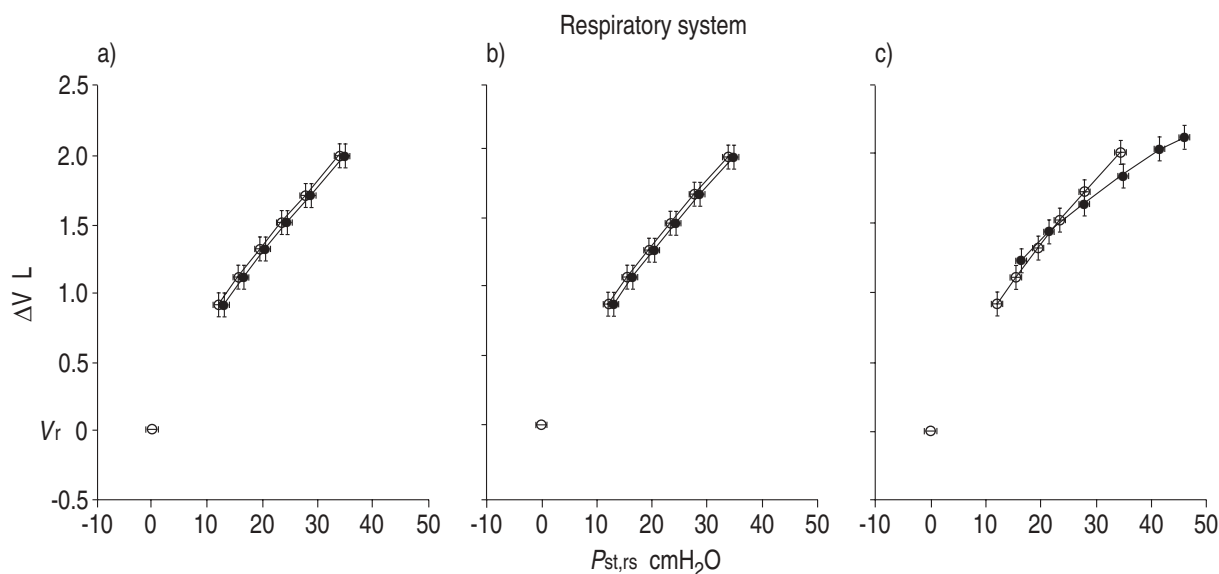

Fig. 3. – Mean static inflation volume-pressure curves of the respiratory system on zero end-expiratory pressure (ZEEP) and at different levels of positive end-expiratory pressure (PEEP). a) PEEP 0–5 cmH$_2$O; b) PEEP 0–10 cmH$_2$O; c) PEEP 0–15 cmH$_2$O. ○ : ZEEP; ● : PEEP. $P_{st,rs}$: static end-inspiratory recoil pressure of the total respiratory system; ΔV: changes in lung volume relative to the elastic equilibrium volume of the respiratory system (V_r).
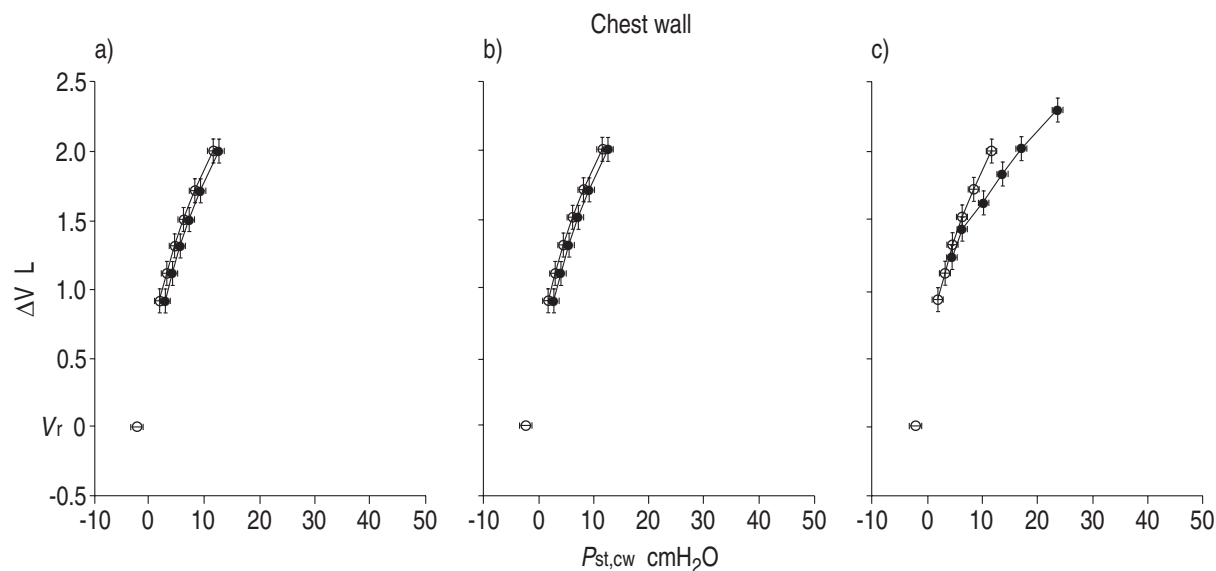

Fig. 4. – Mean static inflation volume-pressure curves of the chest wall on zero end-expiratory pressure (ZEEP) and at different levels of positive end-expiratory pressure (PEEP). a) PEEP 0–5 cmH$_2$O; b) PEEP 0–10 cmH$_2$O; c) PEEP 0–15 cmH$_2$O. $P_{st,cw}$: static end-inspiratory recoil pressure of the chest wall. For abbreviations and details see legend to figure 3.
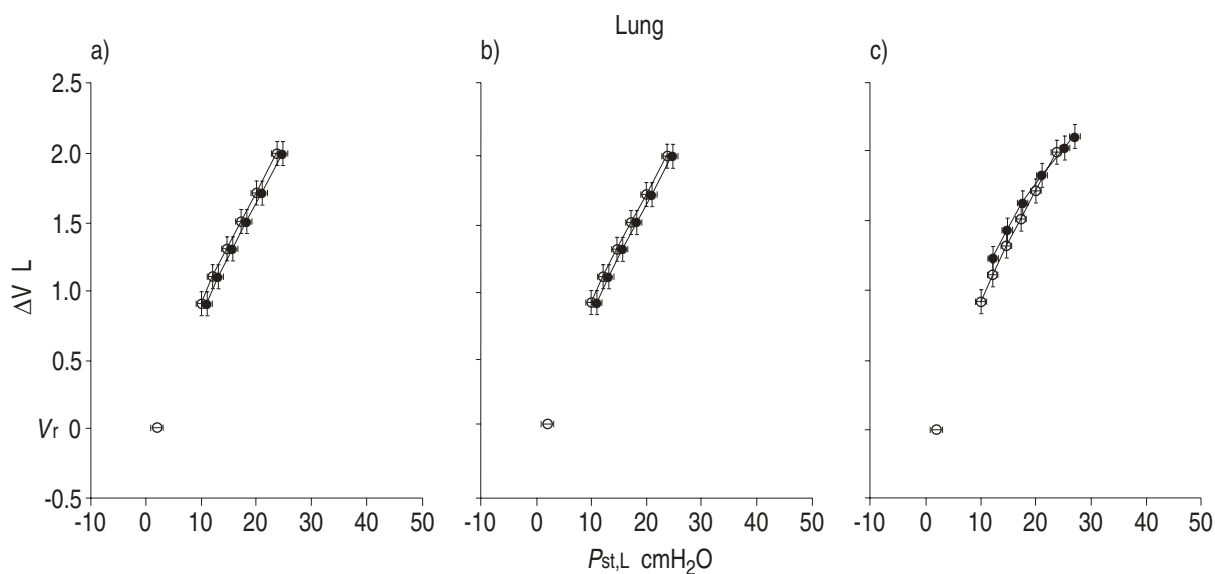
Lung

Fig. 5. – Mean static inflation volume-pressure curves of the lung on zero end-expiratory pressure (ZEEP) and at different levels of positive end-expiratory pressure (PEEP). a) PEEP 0–5 cmH$_2$O; b) PEEP 0–10 cmH$_2$O; c) PEEP 0–15 cmH$_2$O. Pst,L: static end-inspiratory recoil pressure of the lung. For abbreviations and details see legend to figure 3.

and lung (fig. 5a and b) obtained at PEEP levels of 5 and 10 cmH$_2$O of PEEP were virtually superimposed on the V-P curves obtained on ZEEP. Values of coefficients a and b in Equation (1) at PEEP levels of 5 and 10 cmH$_2$O did not differ from those obtained on ZEEP (table 4). Only at a PEEP level of 15 cmH$_2$O, changes in lung volume, pleural and lung pressures started to occur (table 3), and changes in the shape of the V-P curves of the total respiratory system (fig. 3c), chest wall (fig. 4c) and lung (fig. 5c) appeared. The increase in lung volume at 15 cmH$_2$O of applied PEEP induced a shift of the V-P curve of the lung along the curve on ZEEP (fig. 5c) and coefficients a and b increased (p<0.001) with 15 cmH$_2$O of PEEP (table 4). At 15 cmH$_2$O of applied PEEP, the V-P of the chest wall was initially displaced along the curve on ZEEP, whilst a downward displacement relative to ZEEP appeared at higher lung volume (fig. 4c), and coefficients a and b increased (p<0.001) (table 4). The V-P curve of the total respiratory system on 15 cmH$_2$O of PEEP shows an initial shift along the curve on ZEEP and a subsequent downward displacement with inflating volume (fig. 3c) as shown by the significant (p<0.001) increase of coefficients a and b in Equation (1) (table 4).

Discussion

Recently POLESE and co-workers [3] reported values of PEEPi,cw on ZEEP amounting to 16% of the value of PEEPi,rs. Based on these findings POLESE and co-workers [3] concluded that in COPD patients, PEEPi is almost entirely due to the end-expiratory elastic recoil pressure of the lung [3], and that alterations of respiratory mechanics in COPD patients are mainly due to abnormalities of the lung rather than chest wall [4]. However, these data conflict with our previous findings [5], which suggest that the chest wall plays a significant role in the mechanical impairment of COPD patients [6], since PEEPi,cw accounts for 47% of PEEPi,rs [5]. POLESE and

co-workers [3] computed PEEPi,cw as the difference in Poes between the preinterruption level and the plateau during EEO, whilst in our previous study [5] we computed PEEPi,cw as the EEO oesophageal plateau pressure referred to the correspondent value at Vr. Neither of these measurements provide the true PEEPi,cw value. The definition of POLESE and co-workers [3] gives the resistive pressure of the chest wall at end-expiration [12] (which is expected to be very small) and, therefore, underestimates PEEPi,cw. On the other hand, our previous definition [5] overestimates PEEPi,cw by an amount equal to the value of the pleural pressure at Vr. In the present study, we quantified the contribution of the chest wall to PEEPi,rs by determining the static V-P curve of the chest wall [13].

Before proceeding to further discussion of our results, some considerations regarding the method we used to measure pleural pressure are required. Whilst in upright subjects the values of Poes obtained with the method originally described by MILIC-EMILI and PETIT [14] and used in the present investigation, closely reflect both dynamic changes and absolute static values of pleural pressure, in supine subjects measurement of absolute values of Poes are likely to overestimate pleural pressure values because of uneven distribution of pleural surface pressure [15]. However, correction for the gradient in pleural surface pressure, as performed in the present investigation, should approximate absolute values of Poes to absolute values of pleural pressure [10].

In normal subjects: 1) the relaxation volume of the chest wall is about 0.5 L above the relaxation volume of the total respiratory system; 2) the Pst,cw at the relaxation volume of the total respiratory system is around -5 cmH$_2$O; 3) the static V-P curve of the chest wall has an upward concavity; and 4) at total lung capacity Pst,cw amounts to about ±10 cmH$_2$O [15, 16]. In COPD patients, because of loss of elastic recoil of the lung, the relaxation volume of the chest wall and the Pst,cw at the relaxation volume of the respiratory system are expected to be closer to the relaxation volume of the respiratory

system and less negative, respectively [16]. On the other hand, no changes in shape of the static V-P curve of the chest wall are expected [16]. We found that the relaxation volume of the chest wall was 0.36 ± 0.12 L above the relaxation volume of the total respiratory system and that the $P_{st,cw}$ at the relaxation volume of the respiratory system amounted to -2.42 ± 0.12 cmH_2O (fig. 2). However, in contrast to previous results [17], we found that the static V-P curve of the chest wall showed a concavity towards the horizontal axis. In other words, elastance progressively increased with inflation volume, as reflected by values of coefficient b in Equation (1) >1 in all patients (table 4).

These results are in contrast with those obtained by COUSSA *et al*. [17], who found that, in experimental conditions similar to ours, elastance progressively decreased with inflating volume in the total respiratory system, chest wall and lung. As a consequence, COUSSA *et al*. [17] found that values of coefficient b in Equation (1) were <1 in all patients. The patients of COUSSA *et al*. [17] exhibited a smaller degree of dynamic pulmonary hyperinflation ($\Delta EELV=0.34\pm0.06$ L), and EELV was, hence, closer to V_r than in our patients. Furthermore, our values of $P_{st,cw}$ at maximal inspiration averaged 9.66 ± 0.52 cmH_2O, whilst in the study by COUSSA *et al*. [17] they amounted to roughly 5 cmH_2O. Our unexpected results can, therefore, be explained by the fact that our patients were inflated to higher values of $P_{st,rs}$ than those in the study by COUSSA *et al*. [17] (34.0 ± 0.6 and 14.8 ± 1.0 cmH_2O respectively). We may, therefore, assume that patients included in the study by COUSSA *et al*. [17] were operating well below their total lung capacity, whilst in our patients tidal ventilation occurred close to total lung capacity. Alteration of the mechanical properties of the chest wall may also explain our findings. In fact, it has been shown that in some, but not all, COPD patients, chest wall configuration may be altered in adapting to increased lung volume [18].

In COPD patients, the static V-P curve of the lung would be expected to exhibit, at low lung volume, an inflection point reflecting small airway closure. On the other hand, at and above EELV, all small airways would be expected to be open because of the high values of transpulmonary pressure. In our patients, the static V-P curve of the lung did not show any inflection point below EELV. To confirm this unexpected finding, experimental points between V_r and EELV (not collected in the present investigation) are required to trace the entire V-P curve.

In flow limited COPD patients, PEEPi and dynamic hyperinflation are a direct result of dynamic airway compression [19]. The characteristic of this phenomenon is that increasing the pressure downstream (applied PEEP) from the site of critical closure has no influence on either the expiratory flow or the pressure upstream of the site of critical pressure (PEEPi). The waterfall analogy [19] assumes PEEPi is the same as the critical closing pressure of the airways. However, the transpulmonary pressure at which expiratory flow limitation occurs must be somewhat less than the total elastic recoil pressure available, due to resistive pressure losses across the up-stream segment proximal to the point of dynamic airway collapse. MINK *et al*. [20] demonstrated, through direct measurements of regional alveolar pressure
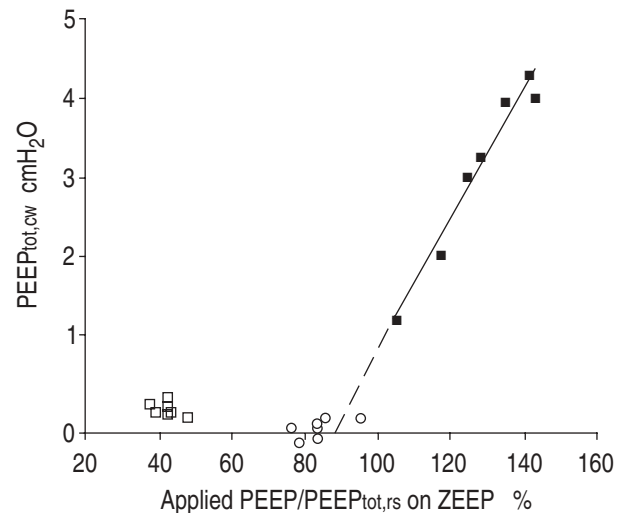

Fig. 6. – Changes in the plateau pressure in the chest wall during end-expiratory occlusion (PEEPtot,cw) referred to values on zero end-expiratory pressure (ZEEP) are plotted against the applied PEEP/PEEPtot,rs ratio at 0, 5, 10 and 15 cmH_2O externally applied PEEP. PEEPtot,rs: plateau pressure in the respiratory system during end-expiratory occlusion. Solid line indicates linear regression of experimental points at 15 cmH_2O of PEEP; dotted line extrapolates regression line to the horizontal axis. □ : PEEP 5 cmH_2O; ○ : PEEP 10 cmH_2O; ■ : PEEP 15 cmH_2O.

in animals, that significant heterogeneity may occur in the presence and in the magnitude of expiratory flow limitation amongst regional lung units. On this basis, the simple waterfall analogy [19] to describe the flow limitation phenomenon may not be accurate. A more complex system with marked heterogeneity of regional mechanical properties should be considered [5]. In terms of mechanically-ventilated COPD patients, this implies that the critical value of PEEP (P_{crit}), above which changes in EELV and intrathoracic and alveolar pressures are expected to occur, must be somewhat less than the measured PEEPi,rs on ZEEP. Hence, expiratory flow limitation will persist as long as the positive pressure applied at the airway does not exceed P_{crit} rather than PEEPi,rs. Based on this physiological rationale, the use of PEEP was proposed to counterbalance the inspiratory threshold load imposed by PEEPi during mechanical ventilation [21, 22]. However, none of these studies provide precise indications regarding the maximum PEEP/continuous positive airway pressure (CPAP) level to be applied in COPD patients without causing further increase in dynamic hyperinflation.

In order to identify the critical value of PEEP (P_{crit}) above which changes in mechanics are expected to occur, variations in end-expiratory pleural pressure with 5, 10 and 15 cmH_2O of applied PEEP were plotted against applied PEEP/PEEPtot,rs on ZEEP ratio in all patients (fig. 6) [5]. The linear regression of experimental points at 15 cmH_2O of PEEP intercepted the horizontal axis at a value of PEEP/PEEPtot,rs on ZEEP ratio amounting to 0.90, *i.e.* P_{crit} was equal to the 90% of the measured PEEPtot,rs on ZEEP. The increase of EELV with a PEEP level higher than P_{crit} induced an initial shift along the V-P curve on ZEEP of both the respiratory system (fig. 3c) and the chest wall (fig. 5c), followed by a downward displacement as inflating volume approach tidal volume. On the other hand, 15 cmH_2O of PEEP induced

a shift along the entire V-P curve of the lung on ZEEP (fig. 5c). As a consequence, 15 cmH$_2$O of PEEP significantly increased (p<0.001) coefficient *a* in Equation (1) (*i.e.* static elastance at ΔV of 1 L) in the respiratory system lung and chest wall. Application of 15 cmH$_2$O of PEEP significantly increased (p<0.001) coefficient *b* in Equation (1) either in the total respiratory system, lung and chest wall (table 4), indicating that application of PEEP levels higher than *P*crit induced a flattening of the V-P curves (*i.e.* a more rapid decrease in elastance with inflating volume). However, the possible role of changes in thoracic blood volume with high levels of PEEP should also be considered [23].

In conclusion, our data show that, in patients with chronic obstructive pulmonary disease, who are mechanically-ventilated for management of acute ventilatory failure with intrinsic positive end-expiratory pressure and dynamic hyperinflation due to expiratory flow limitation, the relative contribution of the chest wall to total respiratory system intrinsic positive end-expiratory pressure is small. On the other hand, alterations of the elastic properties of the chest wall seem to occur. In patients in whom intrinsic positive end-expiratory pressure is due to expiratory flow limitation, the critical values of intrinsic positive end-expiratory pressure below which changes in chest wall and lung mechanics did not occur amounted to 90% of the total respiratory system intrinsic positive end-expiratory pressure measured on ZEEP. Application of positive end-expiratory pressure levels higher than such critical value caused an important worsening in the elastic properties of the lung and chest wall.

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