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Association of PEEP with two different inflation volumes in ARDS patients: effects on passive lung deflation and alveolar recruitment

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Abstract *Objective*: To assess the effects of the association of positive end-expiratory pressure (PEEP) with different inflation volumes (V_T's) on passive lung deflation and alveolar recruitment in ARDS patients.
Design: Clinical study using PEEP with two different V_T's and analyzing whether passive lung deflation and alveolar recruitment (Vrec) depend on end-inspired (EILV) or end-expired (EELV) lung volume in mechanically ventilated ARDS patients.
Setting: Medical intensive care unit in a university hospital.
Patients and participants: Six mechanically ventilated consecutive supine patients with ARDS.
Interventions: Time-course of thoracic volume decay during passive expiration and Vrec were investigated in six ARDS patients ventilated on PEEP with baseline V_T (V_T,b) and $0.5V_T$ ($0.5V_T$,b), and on zero PEEP (ZEEP) with V_T,b. Time constants of the fast (τ_1) and slow (τ_2) emptying compartments, as well as resistances and elastances were also determined.
Measurements and results: (a) the bi-exponential model best fitted the volume decay in all instances. The fast compartment was responsible for 84 ± 7 ($0.5V_T$,b) and 86 ± 5 % (V_T,b) on PEEP vs 81 ± 6 % (V_T,b) on ZEEP (*P*:ns) of the exhaled V_T, with τ_1 of 0.50 ± 0.13 and 0.58 ± 0.17 s vs 0.35 ± 0.11 s, respectively; (b) only τ_1 for V_T,b on PEEP differed significantly ($P < 0.02$) from the one on ZEEP, suggesting a slower initial emptying; (c) for the same PEEP, Vrec was higher with a higher volume (V_T,b) than at a lesser one ($0.5V_T$,b), reflecting the higher V_T.
Conclusions: In mechanically ventilated ARDS patients: (a) the behavior of airway resistance seems to depend on the degree of the prevailing lung distension; (b) alveolar recruitment appears to be more important when higher tidal volumes are used during mechanical ventilation on PEEP; (c) PEEP changes the mechanical properties of the respiratory system fast-emptying compartment.

Key words Passive lung deflation · Respiratory time constants · Airway resistance · Alveolar recruitment · PEEP · ARDS

Introduction

Originally, acute respiratory distress syndrome (ARDS) was thought to be due to a generalized increase in lung stiffness, resulting in a decrease in lung volume [1]. In reality, the lungs of ARDS patients do not exhibit generalized stiffness but instead are functionally small (baby lung) [2]. Consequently, the common clinical practice of ventilating

Table 1 Clinical entry data of ARDS patients

Patient	Sex	Age (years)	Wt (kg)	Ht (cm)	Days	PaO_2 (mmHg)	PaO_2 (kPa)	F_IO_2	ID (mm)	Outcome	Cause (I/II)
1	M	16	60	176	4	56	7.5	0.4	7.5	S	I
2	F	51	46	164	5	50	6.7	0.6	7.5	D	I
3	F	29	56	162	4	59	7.9	0.6	7.5	D	II
4	F	50	46	163	6	53	7.1	0.6	8.0	D	II
5	F	60	56	165	4	59	7.9	0.6	7.0	D	I
6	M	37	77	176	2	56	7.5	0.8	8.0	D	I

Days days after intubation, F_IO_2 inspired O_2 fraction, *ID* internal diameter of endotracheal tube, *S* survived, *D* died, *Cause of ARDS* I (pulmonary), II (extrapulmonary)

ARDS patients with a relatively large inflation volume (V_T) may result in alveolar overdistention of "normally aerated" areas (volutrauma). Recent reports indicate that the respiratory system resistance (Rrs) increases and compliance decreases markedly in ARDS [3, 4], with expiratory resistance (strongly influenced by the mechanical properties of the airways and lung parenchyma) exceeding inspiratory resistance [5]. Finally, many authors have reported strategies to ventilate ARDS patients in order to improve the outcome [6, 7, 8].

Measurement of resistance during expiration is problematic because flow is continuously changing. Previous studies in ARDS patients [9] and normal subjects [10] have shown that the volume-time course during a passive expiration can be characterized by a fast and a slow emptying compartment. In these studies the fast compartment reflected the time constant due to the respiratory compliance and to the pure (ohmic) resistance component of total expiratory flow resistance (Rrs), whereas the slow compartment kinetic behavior was attributed to the viscoelastic properties of the respiratory system and time constants inequalities within the lung ("pendelluft").

In mechanically ventilated ARDS patients, positive end-expiratory pressure (PEEP) is generally assumed to cause a decrease in airway resistance due to the concomitant increase in lung volume. Indeed, PEEP is thought to augment lung volume by recruiting collapsed alveoli, thus improving pulmonary gas exchange. However, in ARDS patients the number of aerated lung units is markedly reduced and, as a result, the range of inflation volumes required to reach the flat portion of their static V-P curve – corresponding to a deleterious zone from a mechanical point of view – is narrower [11]. Under these conditions it is not surprising that the use of high PEEP and relatively large tidal volumes can induce ventilator-induced lung injury.

With the exception of Gattinoni et al. [2, 12] and Eissa et al. [13, 14], there are no systematic studies in which the recruitment of collapsed lung units by PEEP and different V_T's has been quantified.

The aim of the present study was to determine in mechanically ventilated ARDS patients the effects of the association of PEEP with two different V_T's on passive lung deflation and alveolar recruitment. Thus, we evaluated: (a) the behavior of the respiratory system resistance and elastance during mechanical ventilation on PEEP and increasing tidal volume; (b) the dependence of recruited alveolar volume (Vrec) on both PEEP and end-inspiratory lung volume (EILV); (c) the presence of a two-compartment kinetic behavior of the respiratory system during relaxed expiration; and, finally (d) how the constants describing these two compartments would be affected by different tidal volumes and PEEP.

Materials and methods

Six supine patients with ARDS, as defined by the American-European Consensus Conference on ARDS [15] were studied. They had no cardiac failure as judged by bidimensional echocardiography. The clinical entry data of the patients are shown in Table 1. The lung injury score, computed according to Murray et al. [16], was > 2.5 in all patients and their arterial oxygen tension/fractional inspiratory oxygen ratio (PaO_2/F_IO_2) was lower than 200 mmHg, indicating severe ARDS. The average duration of mechanical ventilation amounted to 4 days. The investigation was approved by the Institutional Ethics Committee, and informed consent was obtained from the next of kin.

Patients were intubated with Portex cuffed endotracheal tubes (ETT) (internal diameter from 7 to 8 mm), and mechanically ventilated with a fractional inspired O_2 concentration (F_IO_2) ranging from 0.5 to 0.8 (Table 1). After adequate sedation with flunitrazepam the patients were paralyzed with 4 mg i. v. of vecuronium bromide followed by additional aliquots of 2 mg every 10 min. They were paralyzed to assure respiratory muscle relaxation during the respiratory mechanics measurements. Respiratory muscle relaxation was assumed to be achieved when there was no breath-by-breath variation in end-expiratory thoracic volume and airway pressure (Paw), and when a plateau was observed in Paw-tracing during 5 to 6-s end-inspiratory airway occlusions.

Changes in thoracic volume were measured by respiratory inductive plethysmography (RIP) (Respigraph, NIMS, Miami, Flo., USA). In paralyzed, intubated patients, without thoraco-abdominal surgery or X-ray asymmetry, Dall'Ava et al. [17] showed that the respiratory system moves with a single degree of freedom and thoraco-abdominal partitioning of tidal volume is constant across a large range of V_T's. Therefore, a single RIP coil was used. Volume was corrected for continuing gas exchange which takes place throughout end-inspiratory airway occlusions as previously de-

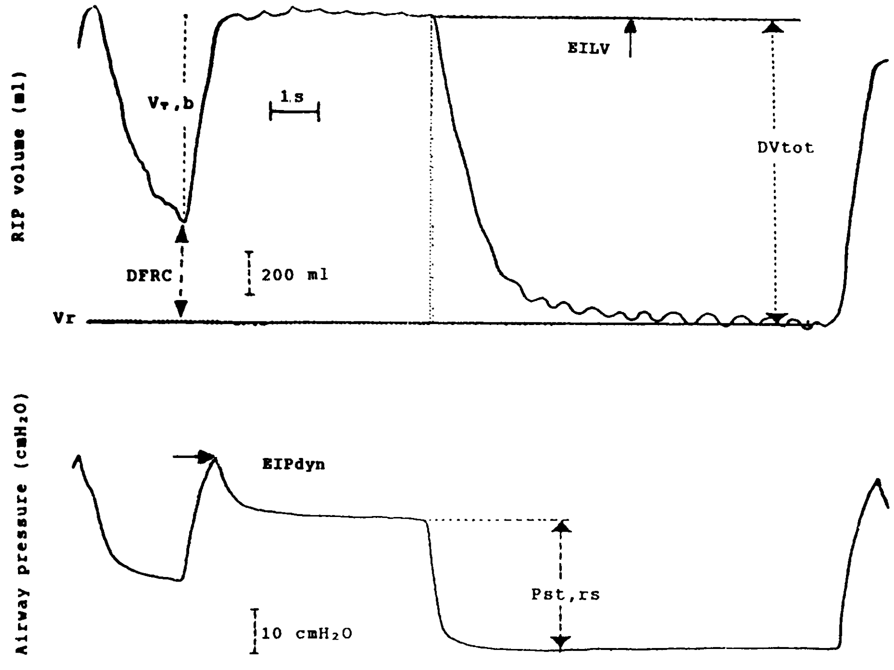

Fig. 1 (Top) Example of changes in thoracic gas volume during passive expiration measured with a respiratory inductance plethysmograph (*RIP*) as a function of time. After removal of PEEP, passive deflation from baseline V_T (V_T,b) starts from the end-inspiratory lung volume (*EILV*) and ends at relaxation volume (*Vr*). *DFRC* end-expiratory lung volume relative to Vr during baseline ventilation, *DVtot* total exhaled volume to *Vr*. (Bottom) Changes in airway pressure measured at the airway opening as a function of time. *Pst,rs* represents the static elastic recoil pressure of respiratory system; *EIPdyn* represents the end-inspiratory dynamic pressure

scribed [17]. This procedure provided reliable thoraco-pulmonary V-P curves, and allowed continuous monitoring of end-expiratory volume changes.

The coil was positioned on the skin of the abdomen at mid-distance from the iliac crest and the axilla. The direct current (DC) mode was used in order to monitor the end-expiratory level. Since in DC mode the oscillator drift is sensitive to temperature, we waited for 30 min to allow for thermal equilibrium before taking any measurements. Non-cumulative calibration was performed by incremental inflation with a hand-driven 2 l syringe, as previously described [17]. Paw was measured at the proximal end of the endotracheal tube with a differential pressure transducer (Validyne MP-15, ± 60 cmH_2O, Northridge, Calif., USA). Paw and RIP outputs were recorded on a two-pen potentiometric recorder (2 YT Sefram; Valizy, France). The recorder and the RIP had time constants of 10 and 5 ms, respectively.

Passive lung deflation

Experimental procedure

After a period of stable mechanical ventilation, end-inspiratory airway occlusions were performed manually with a two-way tap. During the ensuing period of apnea (5–6 s), relaxation of the respiratory muscles was shown by the appearance of a plateau on the Paw. The occlusion was then rapidly released, and the patients allowed to expire freely into the atmosphere (thus avoiding any equipment resistance, except for the ETT) until the relaxation volume (Vr) was achieved, i. e., until the RIP signal was steady for at least 1.5 s and indistinguishable from baseline (Fig. 1). A steady end-expiratory RIP signal was taken as evidence that the expiration was complete [18].

Respiratory frequency ranged between 15–18 breaths · min^{-1} and V_T,b was initially set at 10 ml · kg^{-1}, but was subsequently adjusted to keep arterial blood gases within normal limits.

End-inspiratory occlusions were randomly performed on PEEP (13 ± 4 cmH_2O, on average) at baseline tidal volume (V_T,b = 8.5 ml · kg^{-1}, on average) and at an inflation volume of about 0.5V_T,b (4.3 ml · kg^{-1}, on average), and on ZEEP at V_T,b.

End-inspiratory occlusions were performed at each setting in each patient. Two almost superimposable curves were used in each condition. Prior to each study, at least ten consecutive breaths displaying the same RIP signal were recorded. Then, the lungs were inflated with three cumulative V_T's, by occluding the expiratory line of the ventilator for two breaths, in order to produce standardized deep breaths.

In each patient PEEP was adjusted as "best" PEEP [19]. PEEP was initially defined clinically by measuring PaO_2 while increasing F_IO_2, with the goal of reaching the minimal pressure required to achieve a $PaO_2 > 50$ mmHg at a $F_IO_2 < 1$ with minimal hemodynamic effect and limited peak pressure. Best PEEP was defined as that giving the highest arterial PO_2.

For ZEEP measurements PEEP was removed 20 min before the study, and patients were judged to have reached a steady-state by demonstrating stability of respiratory mechanics and blood-gas records. Volume-time curves on PEEP were carried after the desired PEEP had been set on the ventilator for 20 min.

The two-way valve was also used to occlude the airway at the end of expiration in order to search for intrinsic PEEP [20]. The procedure was repeated during the steady-state period of time that preceded each measurement.

Each study comprised the same sequence of maneuvers: inflation with the randomly pre-selected tidal volume (V_T,b or 0.5V_T,b); airway occlusion at end-inflation; end-inspiratory pause of 5–6 s so that both RIP volume and airway pressure reached a steady-state; disconnection of the expiratory line of the ventilator; release of airway occlusion; recording of RIP volume as a function of time during passive deflation to Vr (Fig. 1) [18]. In all instances the inspired volume prior to the passive exhalation was the tidal volume and the subsequent total expired volume to relaxation volume was DVtot.

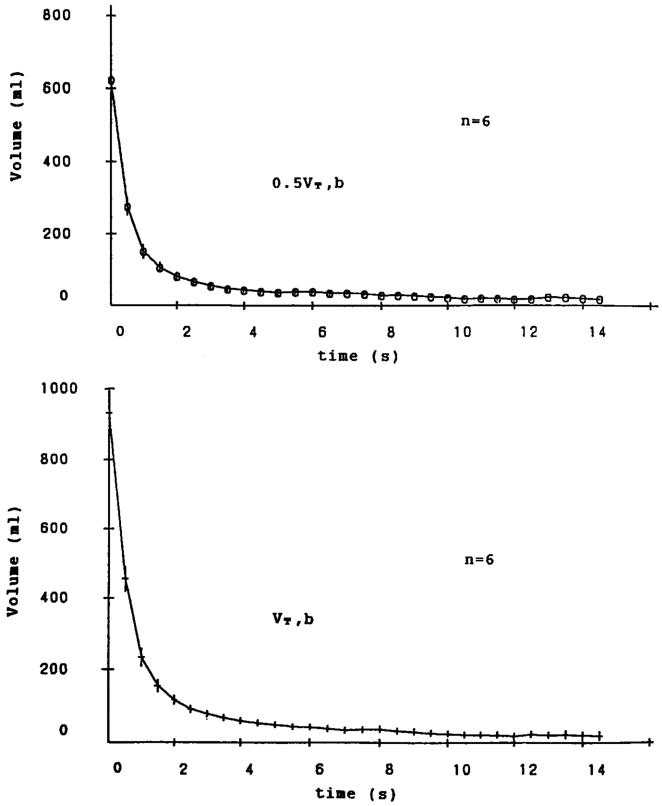

Fig. 2 Each data point corresponds to the group average changes of volume as a function of time during passive expiration after inspiration to half tidal volume (*0.5V_T*,b) (top) and to tidal volume (*V_T*,b) (bottom) of six ARDS patients on PEEP. *Bars* represent ± 1 SD

Data analysis

RIP volume-time curves were digitized at 0.1-s intervals (sampling frequency = 10 Hz) down to Vr, and in all instances the two best curves were taken together for fitting. In order to perform the mono- and bi-exponential fitting, the data were analyzed in terms of "goodness of fit" [21], and the bi-exponential function was described by

$$V(t) = A_1.\exp(-t/\tau_1) + A_2.\exp(-t/\tau_2) \quad (1)$$

where A_1, A_2 are the initial volumes of the fast- and slow-emptying compartment and τ_1, τ_2 are the corresponding time constants. The total volume exhaled during the passive expiration (DVtot) is A_1 plus A_2. The mono-exponential model was compared with the bi-exponential one by analysis of variance, based on the least-squares sum calculated from each curve fitting: the bi-exponential model was preferred to the mono-exponential one when the Fisher test indicated a significant result ($P < 0.05$) [21].

Decay slopes (τ_1 and τ_2) obtained from all experimental conditions were assessed by the determination coefficients and compared by a repeated measurements analysis of variance (ANOVA).

Parameters of the bi-exponential model were determined with an optimized computer algorithm based on a Gauss-Newton procedure using the least-squares methods (Ph. D'Atis, Programme Triomphe, Laboratoire d'Informatique Médicale, Faculté de Médecine, Dijon, France) [9, 10].

Paw at the end of inspiratory pause (5–6 s) was taken to represent the static end-inspiratory elastic recoil pressure of the respiratory system (Pst,rs). Static elastance of the respiratory system (Est,rs) was computed by dividing Pst,rs by the volume expired into the atmosphere (DVtot) (Fig. 1).

Respiratory system dynamic elastance (Edyn,rs) [9, 10] was computed by dividing peak Paw, i. e., Paw immediately preceding occlusion (dynamic end-inspiratory Paw, EIPdyn), by DVtot.

Resistance of the fast emptying compartment, reflecting the mean airway resistance (Rawmean) [22], was estimated as the product of τ_1 by Edyn,rs.

Alveolar recruitment

The effects of PEEP and different V_T's on alveolar recruitment were assessed from static V-P curves, which were derived from a series of measurements of Pst,rs and DVtot made at EILV and EELV on zero PEEP (ZEEP) and on PEEP with 0.5V_T,b and V_T,b [23, 24]. Alveolar recruitment (Vrec) was quantified in each patient as the difference in lung volume between PEEP and ZEEP conditions for the same Pst,rs (= 16 cmH_2O). We chose Pst,rs of 16 cmH_2O because this probably would enable measuring Vrec in all patients at all levels of PEEP [24]. This was, indeed, the case.

Statistical analysis

Results were expressed as mean ± SD. When patients were supported with PEEP, data from 0.5V_T,b and from V_T,b support were compared using the two-way analysis of variance. If there was a significant difference between V_T,b and 0.5V_T,b inflations, the values at each V_T were compared to those on ZEEP with V_T,b using the paired t-test of Dunnett.

Regression analysis was done with the least-squares method. Significance level was 5 %.

Results

Passive lung deflation

In all patients the bi-exponential model fitted the data better than the mono-exponential one under PEEP. In all instances the V(t) curves closely fitted the bi-exponential function (Eq. 1): $0.972 < r^2 < 0.998$, and $0.978 < r^2 < 0.998$ at 0.5V_T,b and V_T,b, respectively. The group average curves obtained under the two experimental conditions are shown in Fig. 2.

On PEEP the fast compartment (A_1) was responsible for 84 ± 7 % (0.5V_T,b) and 86 ± 5 % (V_T,b) vs 81 ± 6 % on ZEEP (*P*:ns) of the total exhaled volume, with τ_1 of 0.50 ± 0.13 s and 0.58 ± 0.17 s vs 0.35 ± 0.11 s on ZEEP, respectively. There was a significant difference ($P < 0.02$) in the mean τ_1 only between V_T,b on PEEP (0.58 s) and V_T,b on ZEEP (0.35 s) (Table 2).

On PEEP the slow compartment (A_2) contributes 16 ± 7 % (0.5V_T,b) and 14 ± 5 % (V_T,b) vs 19 ± 6 % on

Table 2 Effects of PEEP and tidal volume on parameters in Eq. 1

Tidal volume	PEEP (cmH_2O)	DVtot (ml)	A_1 (ml)	A_1 /Dvtot (%)	A_2 (ml)	A_2/DVtot (%)	τ_1 (s)	τ_2 (s)
$0.5V_T$,b	13 (4)	610 (127)	524 (119)	84 (7)	101 (45)	16 (7)	0.50 (0.13)	6.46 (3.45)
V_T,b	13 (4)	934 (134)	803 (98)	86 (5)	131 (60)	14 (5)	0.58 (0.17)	6.44 (2.79)
V_T,b	0	508 (101)	410 (96)	81 (6)	97 (37)	19 (6)	0.35 (0.11)	4.67 (2.38)

Values are means and (SD). *V_T,b* baseline tidal volume, *$0.5V_T$,b* V_T,b/2, *PEEP* positive end-expiratory pressure, *DVtot* total volume exhaled during passive expiration to relaxed volume of the respiratory system, *A_1*, A_2, τ_1 and τ_2 are constants in Eq. 1. Results with zero PEEP are from a previous study on the same patients [9]

Table 3 Effects of PEEP and inflation volumes on average parameters of respiratory mechanics in six ARDS patients

Tidal volume	PEEP (cmH_2O)	Pst,rs (cmH_2O)	Est,rs ($cmH_2O \cdot l^{-1}$)	Edyn,rs ($cmH_2O \cdot l^{-1}$)	Rawmean ($cmH_2O \cdot l^{-1} \cdot s$)
$0.5V_T$,b	13 (4)	20.9 (3.8)	35.3 (9.4)	43.0 (14.0)	20.2 (4.4)
V_T,b	13 (4)	32.3 (6.3)	34.9 (6.3)	40.5* (8.5)	23.2** (8.3)
V_T,b	0	19.2 (5.5)	37.6 (6.1)	47.0* (9.9)	15.9** (4.3)

Values are means and (SD); *V_T,b* baseline tidal volume, *$0.5V_T$,b* V_T,b/2, *PEEP* positive end-expiratory pressure, *Pst,rs* static pressure of respiratory system, *Est,rs* static elastance of respiratory system, *Edyn,rs* dynamic elastance of respiratory system, *Rawmean* mean airway resistance, estimated as the product of *τ_1* by *Edyn,rs*. Results pertaining to *V_T,b* on PEEP = 0 are from a previous study on the same patients [9]; *: $P < 0.02$; **: $P < 0.05$

Table 4 Mechanical parameters under PEEP and half baseline tidal volume in six ARDS patients

Patient #	Pst,rs (cmH_2O)	EILV (ml)	$0.5V_T$,b (ml)	EELV (ml)	Vrec (ml)	Vrec/EELV (%)
1	21.8	598	343	255	40	15.7
2	18.0	515	209	306	0	0
3	16.3	554	227	327	60	18.3
4	21.0	857	189	668	230	34.4
5	20.5	608	249	359	0	0
6	27.5	526	276	250	0	0
Mean	20.9	610	249	361		
SD	3.8	127	55	156		

Pst,rs static end-inspiratory pressure of respiratory system, *EILV* and *EELV* end-inspiratory and end-expiratory lung volumes relative to relaxation volume, respectively, *$0.5V_T$,b* V_T,b/2, *Vrec* recruited alveolar volume

ZEEP (*P*:ns) of the total exhaled volume, with τ_2 of 6.46 ± 3.45 s ($0.5V_T$,b) and 6.44 ± 2.79 s (V_T,b) with PEEP vs 4.67 ± 2.38 s (V_T,b) on ZEEP, respectively (*P*:ns) (Table 2).

While the values of Est,rs did not change significantly among the various conditions studied, Edyn,rs and Rawmean were significantly lower ($P < 0.02$) and higher ($P < 0.05$), respectively, at V_T,b on PEEP than at V_T,b on ZEEP (Table 3).

Alveolar recruitment

Fig. 3 depicts static volume-pressure (V-P) curves of the respiratory system obtained in patient #1 on ZEEP at V_T,b and on PEEP with $0.5V_T$,b and V_T,b. With PEEP there was an upward shift of the V-P curves, which was more pronounced with V_T,b than $0.5V_T$,b.

The recruited alveolar volume on PEEP was 55 ml in three (#1, 3, 4) of six patients and 102 ml in four (#1, 3, 4, 5) of six patients under $0.5V_T$,b and V_T,b, respectively (Tables 4 and 5). Under V_T,b Vrec in patients #1, 3, 4 increased in relation to $0.5V_T$,b and patient #5 presented Vrec, as can be seen in Tables 4 and 5.

The increase in Vrec with V_T,b relative to $0.5V_T$,b, was associated with a markedly higher (EILV-Vr) (934 ± 134 ml vs 610 ± 127 ml, $P < 0.001$) while the corresponding increase in (EELV-Vr) was relatively smaller (446 ± 166 vs 361 ± 156 ml; $P < 0.05$) (Tables 4 and 5).

With $0.5V_T$,b on PEEP, the end-expiratory Pst,rs was increased (PEEP of 13 ± 4 cmH_2O) relative to V_T,b on ZEEP while the end-inspiratory Pst,rs did not change significantly (20.9 ± 3.8 vs 19.2 ± 5.5 cmH_2O) (Table 3).

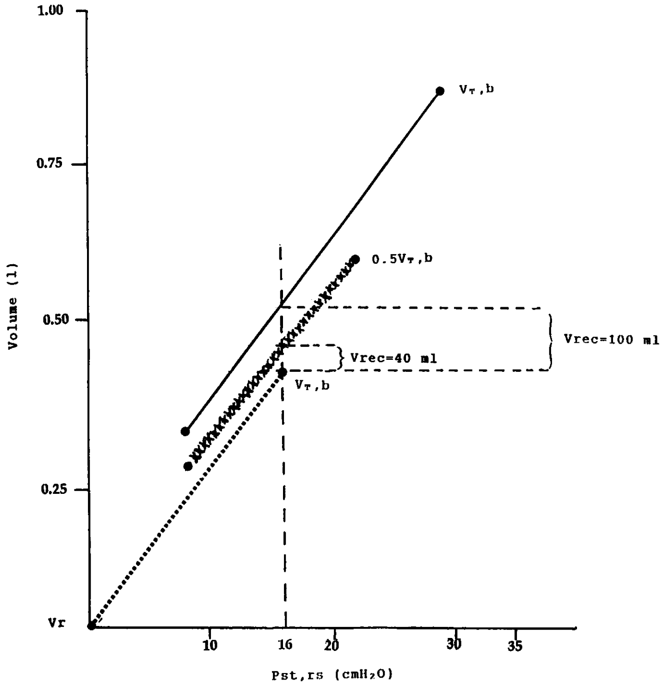

Fig. 3 This figure shows the relationship between changes in lung volume and static elastic recoil pressure of the respiratory system (*Pst,rs*), obtained in a representative patient at two levels of PEEP (8 cmH_2O and zero) and at two levels of inflation volume (V_T,b) (*solid line*) and half inflation volume (*0.5*V_T,b) (*crosses*). Data in figure are stylized. Changes in volume are expressed relative to initial end-expiratory lung volume at zero end-expiratory pressure with V_T,b (*dotted line*). The recruited alveolar volume (*Vrec*) is given by the difference in volume (or vertical distance) between the lowermost line and lines obtained with PEEP and two levels of inspired volume at *Pst,rs* of 16 cmH_2O, and amounts of 40 and 100 ml for *0.5*V_T,b and V_T,b, respectively. *Vr* relaxation volume

Discussion

Our study provides a detailed analysis of the combined effects of PEEP and different V_T's on both passive lung deflation and alveolar recruitment in ARDS patients. This study shows three noteworthy observations: (a) the application of PEEP and higher static end-inspiratory pressure (through higher tidal volume) both increase the volume of recruited lung; (b) that achieving similar end-inspiratory plateau pressures with higher tidal volumes without PEEP or lower tidal volumes with PEEP lead to different end-expiratory volumes (higher end-expiratory volume with PEEP); (c) airway resistance appears to increase as tidal volume (and end-inspiratory plateau pressure) increase.

One of the main findings of the present study is that, for a PEEP of 13 cmH_2O, alveolar recruitment was higher when higher V_T's (476 ml on the average) were used, in four of our six patients. The larger inflation volume (V_T,b) results in a larger Vrec than the smaller inflation volume (0.5V_T,b, 241 ml on the average), reflecting recruitment of lung units at a PEEP of 13 cmH_2O (Tables 4 and 5). The increase in Vrec with V_T,b was associated with a slightly higher (EELV-Vr) compared to 0.5V_T,b (446 ± 166 vs 361 ± 156 ml) ($P < 0.05$).

In line with Ranieri et al. [23], however, even with PEEP of 13 ± 4 cmH_2O and V_T,b there was alveolar recruitment only in four out of six ARDS patients (Table 5). In one of the two patients who did not exhibit Vrec on PEEP with V_T,b, the end-inspiratory Pst,rs on ZEEP was 29 cmH_2O during mechanical ventilation with V_T,b. At such end-inspiratory Pst,rs, all "recruitable" alveoli have been shown to be opened in ARDS [23], even though Lachmann and his colleagues [25] use much higher pressures.

In five subjects, however, the end-inspiratory Pst,rs on ZEEP was well below the above critical opening pressure of atelectatic lung units (range: 12.8–20.5 cmH_2O) [9], and hence Vrec would be expected to exist in all five of these patients. This was the case in four of the patients. In subject #2, however, there was no recruitment with PEEP and V_T,b, though his end-inspiratory Pst,rs amounted to 29 cmH_2O.

On the basis that lung injury occurs from both overdistension and under-recruitment, so that simply limiting tidal volume may not be enough, new mechanical ventilatory strategies include the use of PEEP (to keep open the lung) associated with low V_T's, to limit the

Table 5 Mechanical parameters under PEEP and baseline tidal volume in six ARDS patients

Patient #	Pst,rs (cmH_2O)	EILV (ml)	V_T,b (ml)	EELV (ml)	Vrec (ml)	Vrec/EELV (%)
1	29.0	870	561	309	100	32.4
2	29.0	765	420	345	0	0
3	25.8	859	491	368	100	27.2
4	29.5	1150	439	711	260	36.6
5	40.5	1000	403	597	150	25.1
6	40.0	960	612	348	0	0
Mean	32.3	934	488	446		
SD	6.3	134	84	166		

Symbols as in Table 4, except for V_T,b baseline tidal volume volutrauma [6, 7, 8]. Indeed, in line with Brunet et al. [26], EILV is more important than end-inspiratory Pst,rs in terms of lung lesions (leading to the concept of "volutrauma").

Using usual V_T's with no PEEP (ZEEP) also limits the volutrauma. However, Muscedere [27] and Dreyfuss [28] showed that without PEEP tidal ventilation in experimental animals occurs in the lower zone of the compliance curve, with a cyclic "sheer stress" able to augment the lung injury.

While with V_T,b on ZEEP and $0.5V_T$,b on PEEP the total exhaled volumes were similar (Table 2), EELV was different (0 vs 361 ± 156 ml, respectively) (Table 4). Furthermore, with $0.5V_T$,b on PEEP there was alveolar recruitment relative to V_T,b on ZEEP (Table 4). In spite of these findings, there was no significant difference among values characterizing passive lung deflation (Table 2). This suggests that the mechanical properties of the recruited units are similar to those of the previously open lung and that the dynamics of lung deflation depends mainly on EILV.

On the other hand, considering V_T,b with and without PEEP, a significant increase in τ_1 ($P < 0.02$) was found. Possibly it results from the higher flow generated by the higher EILV (Tables 2 and 5). As a result, the non-linear resistance offered by the endotracheal tube (ETT) could increase [9, 10, 29, 30].

However, even though τ_1 may be influenced somewhat by the non-linearities of ETT resistance, this should play a minor role. The same finding was reported by Behrakis et al. [31]. Indeed, according to the aerodynamic theory of Pedley [32], if respiratory frequency is < 1 Hz and flow rate is $< 1\ \mathrm{l} \cdot \mathrm{s}^{-1}$, as in this study, the pressure-flow relationship of the ETT is almost linear, flow is essentially laminar, and the pressure gradient changes so gradually that the velocity profile remains parabolic at all times. Conversely, Guttmann et al. [33] reported that the time constants of passive expiration are markedly modified by the flow-dependent resistance of the ETT and equipment resistance. However, it should be stressed that experimental conditions were different from ours and a direct comparison of the results is unwarranted. Clearly further studies are required to clarify this point.

A significant decrease in dynamic elastance measured with V_T,b and PEEP in relation to V_T,b and ZEEP was found (Table 3), and amounted to 16%. This finding supports the conclusion that the increase in τ_1 was due mainly to increased Rawmean (46%). Indeed, the effects of PEEP on airway resistance may depend on the degree of lung distension. Possibly this behavior is a consequence of longitudinal stretching of large airways by high lung volumes (V_T,b + PEEP), which results in a decrease in their caliber secondary to the mechanical interdependence of lung parenchyma and airways [34, 35].

As already reported by Auler et al. [36] in ARDS patients, no intrinsic PEEP was detected in the present group of subjects.

In conclusion, in ARDS patients: (a) the behavior of airway resistance seems to depend on the degree of the prevailing lung distension; (b) alveolar recruitment appears to be more important when higher tidal volumes are used during mechanical ventilation on PEEP; (c) PEEP changes the mechanical properties of the respiratory system fast-emptying compartment.

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