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Prone position improves mechanics and alveolar ventilation in acute respiratory distress syndrome

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Abstract *Objective:* We tested the hypothesis that ventilation in the prone position might improve homogenization of tidal ventilation by reducing time-constant inequalities, and thus improving alveolar ventilation. We have recently reported in ARDS patients that these inequalities are responsible for the presence of a "slow compartment," excluded from tidal ventilation at supportive respiratory rate. *Design:* In 11 ARDS patients treated by ventilation in the prone position because of a major oxygenation impairment ($PaO_2/FIO_2 \leq 100$ mm Hg) we studied mechanical and blood gas changes produced by a low PEEP (6±1 cm H_2O), ventilation in the prone position, and the two combined. *Results:* Ventilation in the prone position significantly reduced the expiratory time constant from 1.98±0.53 s at baseline with ZEEP to 1.53±0.34 s, and significantly decreased $PaCO_2$ from 55±11 mm Hg at baseline with ZEEP to 50±7 mm Hg. This improvement in alveolar ventilation was accompanied by a significant improvement in respiratory system mechanics, and in arterial oxygenation, the latter being markedly increased by application of a low PEEP (PaO_2/FIO_2 increasing from 64±19 mm Hg in supine position with ZEEP to 137±88 mm Hg in prone with a low PEEP). *Conclusion:* In severely hypoxemic patients, prone position was able to improve alveolar ventilation significantly by reducing the expiratory time constant.

Keywords ARDS · Prone position · Slow compartment · Time constant · Compliance

Introduction

In acute respiratory distress syndrome (ARDS) of pulmonary origin [1], mechanical ventilation with a positive end-expiratory pressure (PEEP) appears necessary but may be of a limited efficacy. On one hand, recruitment obtained by a low PEEP is restricted [2]. Moreover, use of a high PEEP may worsen working conditions for the right ventricle, and thus precipitate circulatory failure [3], which is the major determinant of outcome in ARDS [4]. Ventilation in the prone position (PP) was long proposed as an alternative way of improving oxygenation in ARDS [5]. Reversal of hydrostatic pressure gradient by positional change has been also found to improve ventilation/perfusion matching [6]. Computed tomographic studies have demonstrated re-aeration in the posterior condensed areas of the lung by PP [7]. Recently, a cooperative study has emphasized that a better outcome can be expected in ARDS patients in whom prone position improved alveolar ventilation [8].

We hypothesized that, if prone position causes ventilation to be distributed more evenly, it should increase alveolar ventilation, and, all things being equal, arterial oxygenation should benefit from this increase. In a previous clinical study in ARDS, we demonstrated the presence of a "slow compartment," excluded from tidal ventilation at supportive respiratory rate, because there was insufficient expiratory time [9, 10]. This slow compartment was heralded by the presence of intrinsic PEEP at ZEEP, when the patient was ventilated at supportive respiratory rate [9, 10]. The present study was thus performed to assess the effect of ventilation in the prone position on this "slow compartment," and its impact, if any, on alveolar ventilation, when compared with ventilation in the supine position. This work was presented at the "32nd Congress of the Société de Réanimation de Langue Française" [11].

Patients and methods

In our unit, hemodynamically stable ARDS patients remaining severely hypoxemic after 48 h of respiratory support are systematically treated by ventilation in the prone position, as previously reported [4]. In January 2002 we started a prospective study in these patients to assess the effect of prone position on respiratory mechanics and alveolar ventilation.

Inclusion criteria were: (a) presence of ARDS as defined by the North American–European Consensus Committee criteria for ARDS; (b) persistence of severe oxygenation impairment defined as $PaO_2/FIO_2 \leq 100$ mm Hg after 48 h of respiratory support; (c) hemodynamic stability with a systolic arterial pressure greater than 90 mm Hg without any hemodynamic support; and (d) presence of a substantial slow compartment (≥70 ml) measured at zero end-expiratory pressure (ZEEP) during a prolonged exhalation, as previously described [9].

We thus studied 11 patients between January 2002 and August 2003. This group included six women and five men, with a mean age of 45±13 years, and an average body weight of 68±14 kg. No patient had previously presented chronic obstructive pulmonary disease.

All patients were sedated with midazolam and sufentanyl, and paralyzed with cisatracurium. They were all ventilated in volume-controlled mode, with a low-stretch strategy including a limited plateau pressure (<30 cm H_2O). Heart rate, arterial systolic pressure by an indwelling radial artery catheter, and oxygen saturation by a pulse oxymeter were continuously monitored. Initial ventilator settings included a constant inspiratory flow, an average tidal volume (V_T) of 8±1 ml/kg of measured body weight, a respiratory rate of 15 breaths/min, an inspiratory/expiratory ratio of 1:2, and an end-inspiratory pause of 0.5 s. The positive end-expiratory pressure selected was that "neutralizing" intrinsic PEEP, as described below [2, 9].

The study was accepted by the Ethics Committee of the "Société de Réanimation de Langue Française" (SRLF, Paris, France), and waived inform consent for measurement included in a routine strategy was authorized.

The study was performed on the first day of prone positioning, which was the third day of respiratory support for each patient.

Airway pressure (P), flow, and volumes (V) were measured with the pressure transducers and pneumotachographs incorporated into the ventilator used in the study (Puritan-Bennet 7200). They were previously checked for pressure with a disposable pressure transducer (Edwards Lifesciences, Irvine, Calif.) and for flow and volume with a disposable pneumotachograph (McGaw volume monitor, AHS corporation, Irvine, Calif.) manually calibrated with a 500-ml syringe. In-built software was used to monitor these variables, and on-line records of the time course of Paw and V were recorded by connecting an Epson LX-300 printer to the respirator.

Protocol

Baseline blood gas analysis and mechanical measurements were obtained in the supine position. Prone positioning was thus implemented, as described by Chatte et al. [12], and measurements were repeated after 3 h of prone positioning.

Measurements of intrinsic PEEP and slow compartment

After a 5-min sequence of ventilation at the supportive frequency of 15 breaths/min and ZEEP, intrinsic PEEP (PEEPi) was assessed by occluding the airway during a prolonged expiratory pause of 4 s [9]. Then, after a similar 5-min sequence of ventilation at the supportive frequency of 15 breaths/min and ZEEP, measurement of the slow compartment was performed during a prolonged expiration (>6 s) obtained by reducing the respiratory frequency to 6 breaths/min as previously described [9]. By definition, because it was measured as the gas exceeding functional residual capacity and remaining in the lung after a complete exhalation of tidal volume at supportive respiratory rate, this slow compartment was totally excluded from tidal ventilation, because of insufficient expiratory time. After restoring the supportive respiratory rate, PEEPe was determined in the supine position as it was the lowest external PEEP whose application suppressed any PEEPi. This phenomenon was called PEEPi "neutralization," as previously described [2, 9].

Because the Puritan-Bennet 7200 uses pneumatic stabilization of PEEP by a low flow gas, measurement of exhaled volume during a prolonged expiration with PEEP is inaccurate; thus, measurements of the slow compartment by this method were only obtained with ZEEP.

Pressure–volume loops

After a prolonged expiration to ensure complete lung emptying, pressure–volume (PV) loops of the total respiratory system were recorded during a single inspiration of a 10 ml/kg volume at a constant inspiratory flow of 10 l/min, followed by a low-flow exhalation, which was obtained by partially occluding the expiratory port to limit expiratory flow, as previously described [2, 9]. Four loops were obtained for each patient, in the supine position with ZEEP, in the supine position with PEEPe, in the prone position with ZEEP, and in the prone position with PEEPe. On each loop, we manually drew two straight lines tangentially to the first two portions of the inspiratory limb, and both the starting compliance (C_{START}) and the linear compliance (C_{LIN}) of the respiratory system were calculated, as the slope of these two straight lines, respectively. The lower inflexion point was defined as the intersection between the two lines, and characterized by its pressure coordinate [2]. Changes in end-expiratory lung volume produced by PEEP application (ΔEELV) were read on the expiratory limb of the first supine or prone PV loop at ZEEP, as previously described [2].The chord compliance of the whole inspiratory curve (C_{CHORD}) was calculated as the slope of a straight line drawn between the first and last points of the inspiratory limb of each PV loop.

Compliance, resistance, and time constant

The compliance of the respiratory system at the supportive respiratory rate (C_{rs}) was calculated as tidal volume/(plateau pressure minus occluded end-expiratory pressure). The inspiratory resistance of the respiratory system (R_{rs}) was calculated as (peak airway pressure minus plateau pressure)/inspiratory flow. Because the resistance of the tubing was unchanged during the whole protocol, no correction was made for it. We also calculated an uncorrected value for the compliance of the respiratory system at the supportive respiratory rate ($C_{rs,nc}$) as tidal volume/(plateau pressure minus end-expiratory pressure). Because it was not corrected for PEEPi, $C_{rs,nc}$ only reflected the compliance of the "fast compartment."

Expiratory time constant (TC) was measured from the expiratory volume–time curve obtained during a prolonged expiration, as proposed by Dall'ava-Santucci et al. [13]. As for the "slow compartment," this measurement was only obtained with ZEEP.

Statistical analysis

Statistical calculations were performed using the Statgraphics plus package (Manugistics, Rockville, Md.). Comparisons of the size of the slow compartment and TC before and during the prone position were performed by a Wilcoxon signed-rank test. Comparisons of other variables were performed by means of two-way ANOVA for repeated measurements, followed by Bonferroni's multiple comparison procedure. Data are expressed as mean±1 SD. A p value <0.05 was considered as statistically significant.

Results

All patients studied were treated by ventilation in the prone position because of a persistent PaO_2/FIO_2 ratio≤100 mm Hg after 48 h of controlled ventilation with a PEEP ≥5 cm H_2O. All these patients had ARDS of pulmonary origin, as a large majority of ARDS patients treated in our medical Intensive Care Unit [4]. Main clinical data are summarized in Table 1. All patients of this small group finally recovered, after an average duration of mechanical ventilation of 25±8 days, including 5±3 days of ventilation in the prone position.

Figure 1 illustrates an example of the measurement of the slow compartment and the TC during a prolonged expiration.

Respiratory rate (15 breaths/min) and average tidal volume (541±125 ml) were maintained constant throughout the study. All respiratory changes produced by PEEP, ventilation in the prone position, and both together are presented in Table 2. At baseline (supine with ZEEP), a slow compartment of 164±85 ml was present. This slow compartment was significantly reduced to 73±74 ml by ventilation in the prone position (p=0.015).

Patterns of the inspiratory limb of the low flow pressure-volume loop were markedly changed with PEEP and prone position, both increasing C_{START} and decreasing

Table 1 Main clinical data. PaO_2/FIO_2 value after 48 h of respiratory support, C_{rs} compliance of the respiratory system, *SAPS II* simplified acute physiological score (version 2), *LISS* lung injury severity score

Patient no.	Etiology	PaO_2/FIO_2 (mmHg)	C_{rs} (ml/cm H2O)	SAPS II	LISS
1	Bacterial pneumonia	83	41	50	3
2	Viral pneumonia	75	17	42	3.3
3	Bacterial pneumonia	71	15	38	3
4	Aspiration pneumonia	55	59	53	3.3
5	Aspiration pneumonia	93	32	45	2.8
6	Bacterial pneumonia	81	22	73	3
7	Bacterial pneumonia	72	32	45	3.7
8	Aspiration pneumonia	99	31	48	2.8
9	Bacterial pneumonia	50	33	38	3.3
10	Aspiration pneumonia	100	27	26	3.7
11	Bacterial pneumonia	99	34	65	2.5
Mean±SD		80±17	31±17	48±13	3.1±0.4

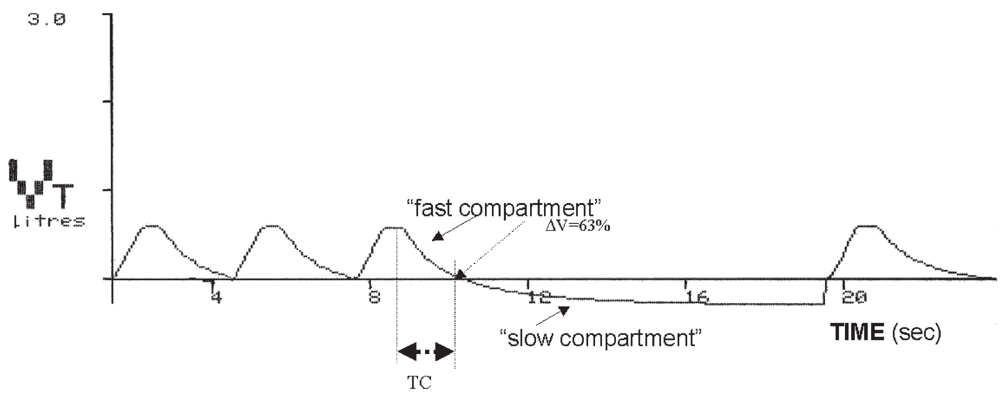

Fig. 1 Measurement of the "slow compartment" during a prolonged expiration. This prolonged expiration also permitted measurement of the time constant (*TC*), as the time between the onset of expiration and exhalation of 63% of the total expiratory volume (ΔV=63%). This example illustrates that the slow compartment, which was measured after complete exhalation of the tidal volume, was, by definition, excluded from tidal ventilation.

Table 2 Respiratory changes. *ZEEP* zero end-expiratory pressure, *PP* prone position, *Pplateau* plateau pressure, *PEEPe* external positive end-expiratory pressure, *PEEPi* intrinsic PEEP, V_{slow} volume of the "slow compartment," $\Delta EELV$ change in end-expiratory lung volume produced by PEEP application, C_{rs} compliance of the total respiratory system, $C_{rs,nc}$ compliance of the "fast compartment" (both values were obtained at supportive respiratory rate), C_{START} starting compliance, C_{LIN} linear compliance, C_{CHORD} chord compliance, *LIP* pressure coordinate of the lower inflexion point, R_{rs} inspiratory resistance of the total respiratory system including tubing, *TC* expiratory time constant.

	Supine ZEEP	Supine PEEPe	PP ZEEP	PP PEEPe
Pplateau (cmH_2O)	23±4	25±4*	20±4*	24±4
PEEPi (cmH_2O)	4.2±1.6	0.4±0.8*	1±1.3*	0±0*
PEEPe (cmH_2O)		6±1		6±1
V_{slow} (ml)	164±85		73±74*	
ΔEELV (ml)		172±109		176±89
C_{rs} (ml/cm H_2O)	31±18	31±12	31±14	30±8
$C_{rs,nc}$ (ml/cm H_2O)	25±9	30±11*	29±10*	31±7*
C_{START}, (ml/cm H_2O)	5±2	15±3*	11±3*	15±3*
C_{LIN} (ml/cm H_2O)	40±19	34±12*	36±15*	34±12*
C_{CHORD}, mL/cm H_2O	23±6	29±7*	28±8*	29±7*
LIP (cm H_2O)	12±3	12±3	8±3*	11±2
R_{rs}, cm H_2O/l s^{-1}	17±7	15±5	13±4*	13±4*
TC (s)	1.98±0.53		1.53±0.34*	
PaO_2/FIO_2 (mm Hg)	64±19	80±17	96±23*	137±88*,**
$PaCO_2$ (mm Hg)	55±11	56±11	50±7*	54±11

*$p<0.05$, vs Supine ZEEP; **$p<0.05$, *PP* PEEPe vs PP ZEEP

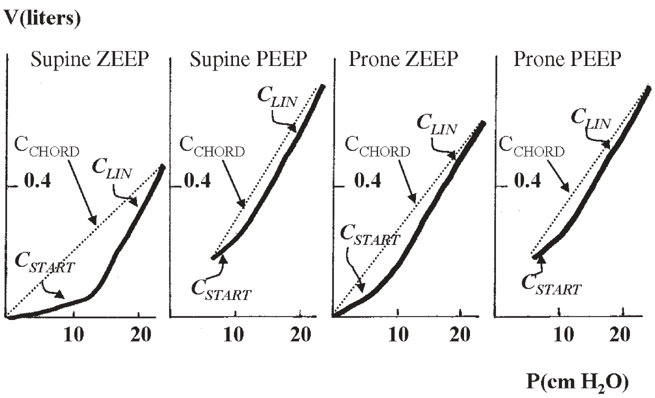

Fig. 2 Simultaneous changes in starting compliance (C_{START}) and in linear compliance (C_{LIN}) produced by PEEP application, prone position, and both combined. Chord compliance is shown by the *dotted line*. This figure was produced using the average values given in Table 2. Moreover, we hypothesized that end-expiratory lung volume was not changed by prone position, as evidenced in a clinical study by Pelosi et al. [20].

C_{LIN} (Table 2). A schematic representation of these changes is shown in Fig. 2: the four diagrammatic inspiratory curves presented were constructed using the average data for C_{START}, C_{LIN}, end-expiratory pressure, pressure coordinate of the lower inflexion point, and ΔEELV given in Table 2. An example in an illustrative patient is also shown in Fig. 3. These changes resulted in a significant and concurrent increase in $C_{rs,nc}$, calculated at supportive respiratory rate, and in C_{CHORD}, read on the low-flow PV curve (Table 2).

Intrinsic PEEP was almost "neutralized" by an external PEEP of 6±1 cm H_2O in the supine position, and was also markedly reduced by ventilation in the prone position (Table 2). An example is shown in Fig. 3. Whereas C_{rs} did not change, R_{rs} exhibited a trend to a progressive reduction by PEEP and by ventilation in the prone position. Expiratory time constant was significantly reduced from an average value of 1.98±0.53 s in the supine to 1.53±0.34 in the prone position (Table 2). Oxygenation was progressively improved during the study, but this improvement was more marked in PP. Additionally, $PaCO_2$ was slightly but significantly reduced by ventilation in the prone position (Table 2).

Individual decreases in $PaCO_2$ and in TC produced by the prone position, and expressed as percentage of baseline value in the supine position, are weakly but significantly correlated (Fig. 4).

Discussion

A major requirement for a safe ventilatory strategy in ARDS is to maintain plateau pressure below 30 cm H_2O [4, 14]. On the other hand, it is currently believed that more hypoxemic the patient the higher should be the supportive PEEP [15]. When respiratory system compliance is low, these two requirements are often not compatible. Moreover, increasing PEEP in ARDS patients with localized infiltrates is of limited efficacy in improving oxygenation [16]. Thus, there are two potential reasons for considering prone position as an alternative in very hypoxemic patients [17]; however, the exact mechanism by which prone position improves gas exchange is not perfectly elucidated. The present study provides indirect evidence for a reduction in time constant heterogeneity, thus suggesting a more even distribution of tidal volume.

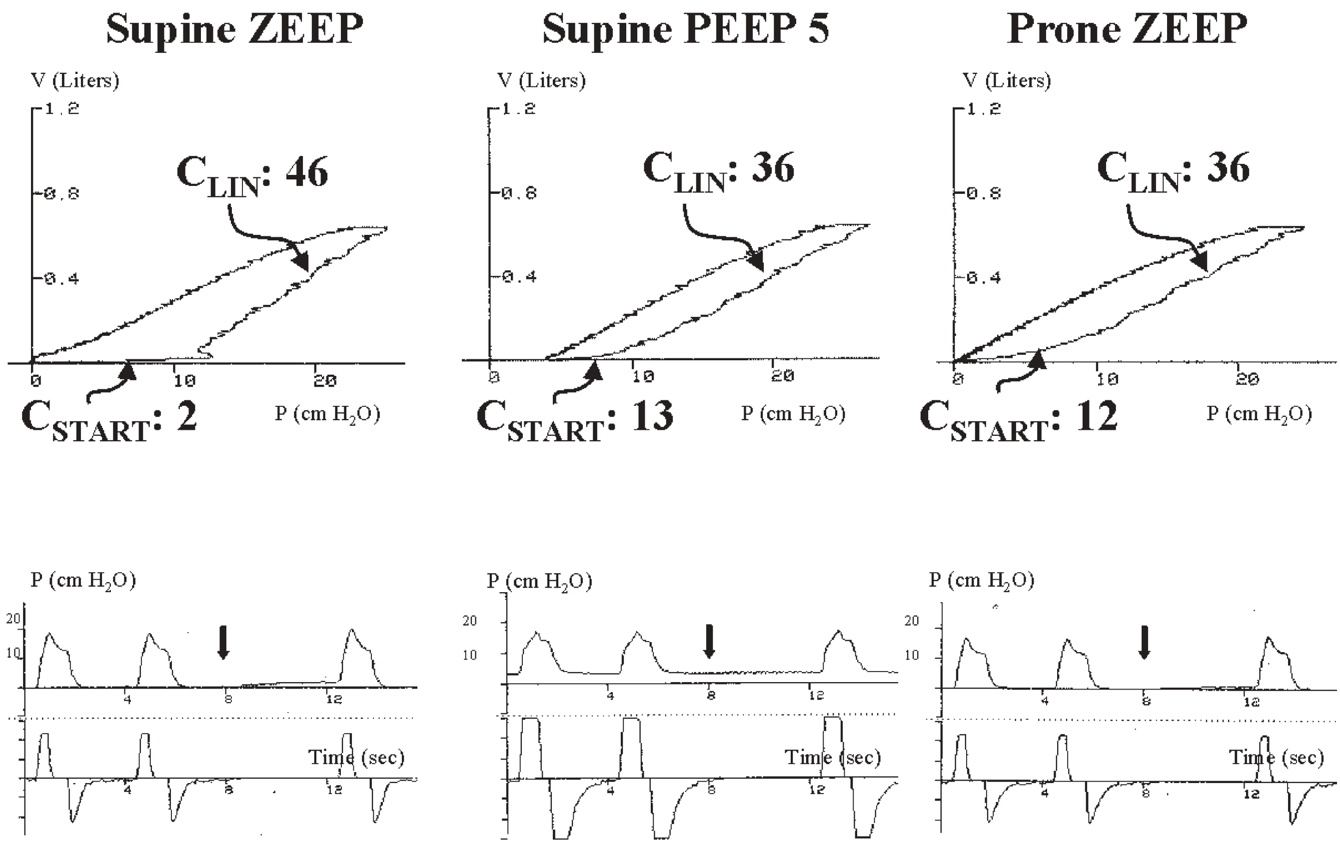

Fig. 3 Simultaneous changes in intrinsic PEEP and in PV loop pattern produced by an external PEEP and by prone positioning. On the *top panel* PV loops were recorded in the supine position with ZEEP (*left*), in the supine position with an external PEEP (*middle*), and in the prone position with ZEEP (*right*). Whereas a marked inflexion of the inspiratory limb was present on the left loop, it disappeared on the middle and right loops. C_{START} starting compliance (ml/cm H_2O), C_{LIN} linear compliance (ml/cm H_2O). On the *bottom panel*, recordings of airway pressure, in the supine position with ZEEP (*left*), in the supine position with an external PEEP (*middle*), and in the prone position with ZEEP (*right*). Intrinsic PEEP was measured after a prolonged end-expiratory occlusion maneuver, whose onset is shown by a *vertical arrow*. Whereas some PEEPi was present on the left recording, it disappeared on the middle and right recordings. Pressure volume loops presented in the top panel are those recorded directly, and no correction was made for change in end-expiratory lung volume produced by PEEP (*middle loop*).

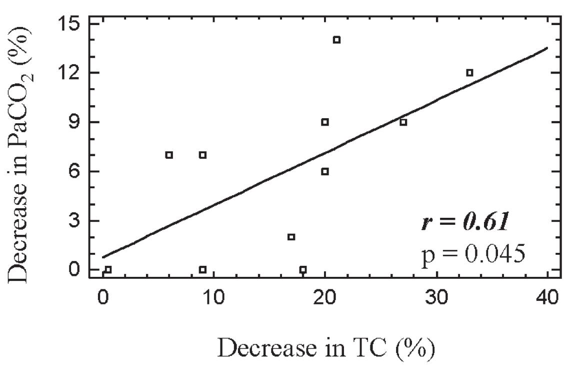

Fig. 4 A plot of individual decrease of $PaCO_2$ against individual decrease in TC with prone position, both expressed as a percentage of baseline value in the supine position

The time constant is defined as the time required to passively exhale 63% of the total expiratory volume, which, in the lack of gas trapping, represents tidal volume [18]. In the present study, we directly measured the time constant during a prolonged expiration, as proposed by Dall'ava-Santucci et al. [13]. This prolonged expiration also permitted detection of a slow compartment and measurement of its size, as we have previously reported [9, 10]. Because the time constant reflects an average value of all individual units, an increased time constant in a given setting suggests that some areas may have an abnormally increased specific time constant acting as a "slow compartment," unable to empty at supportive respiratory rate, and producing gas trapping. Conversely, a reduction in average time constant obtained by any therapeutic means suggests a better homogenization of the time constant of individual units, and relief of gas trapping. This was a positive effect of prone position, directly evidenced in the present study by a significant reduction in both time constant and the amount of gas trapped in the "slow compartment." Gas trapping was also indirectly heralded by the presence of a substantial level of intrinsic PEEP in the supine position, almost completely suppressed by the prone position. It has been shown that prone position decreases the vertical gradients of pleural and transpulmonary pressure, tending to reopen the previously dependent dorsal regions [19]. This mechanism might induce a better time constant homogenization.

Prone position in the present study also improved respiratory mechanics. Firstly, it improved the kinetics of inspiration, probably by preventing small airways closure preceding end-expiration. We have recently suggested that low PEEP applied in the supine position may also have this beneficial effect [9]. In the present study, this improvement was heralded at supportive respiratory rate by a significant decrease in inspiratory resistance with prone position. Secondly, prone position was accompanied by a significant increase in $C_{rs,nc}$, which was corroborated on the low-flow pressure–volume loop. On this loop, C_{CHORD} was significantly increased, with a marked attenuation of the inflexion on the inspiratory limb. We have also previously observed the same result with a low PEEP applied in the supine position [9]. This parallel change in $C_{rs,nc}$ and in C_{CHORD} reinforces our previous suggestion that, in ARDS patients ventilated with ZEEP, effective compliance should be calculated without correction for intrinsic PEEP when a slow compartment is present [9]. The mechanical improvement with prone position might result from relief of cardiac and abdominal compression exerted on the lower lobes in the supine position [14]. But our results are at variance with three previous studies, where respiratory system compliance and resistance were unchanged by the prone position [17, 20, 21]. In these studies, however, no distinction was made between C_{rs} and $C_{rs,nc}$, and measurements were recorded after a shorter period in the prone position: 120 min in Pelosi et al.'s study [20], 60 min in Guérin et al.'s study [21], and an average 95 min in Gainnier's study [17], whereas prone position was evaluated after 180 min in our present study.

Mechanical improvement by the prone position, which concerned both the expiratory and inspiratory phases, was accompanied by a significant improvement in alveolar ventilation, which produced, despite an unchanged minute ventilation, a small but significant decrease in $PaCO_2$. We also observed a simultaneous improvement in oxygenation, which might in part result from this increase in alveolar ventilation, because any increase in alveolar ventilation decreases $PaCO_2$ and increases PaO_2. In the present study, adding PEEP in the prone position did not have any further beneficial effect on respiratory mechanics, whereas a low PEEP significantly improved C_{rs} in the supine position in our previous work [9]. This strongly suggests that mechanical improvement observed in both studies resulted from the neutralization of the slow compartment, already obtained when PEEP was applied in the prone position in the present study, thus precluding any further mechanical improvement with PEEP.

Another interesting finding of the study was the fact that a low PEEP, another efficient means of neutralizing the slow compartment when used in supine position [9], acted against the effect of prone position on alveolar ventilation. In our opinion, this demonstrated that the two maneuvers act in a different way: whereas PP reduced the slow compartment and increased alveolar ventilation, PEEP neutralized the slow compartment without changing alveolar ventilation. This finding suggested that, at the same time that it neutralized the slow compartment, PEEP was associated with some increase in alveolar dead space, precluding any improvement in alveolar ventilation. In fact, we have shown in our previous study that relieving the slow compartment by PEEP was always associated with an increase in end-expiratory lung volume greater that the size of the slow compartment [9]; however, neither the lack of mechanical improvement nor the increase in alveolar dead space produced by PEEP argue against the use of PEEP in the prone position in these patients. Much more important, the benefit in arterial oxygenation obtained by PEEP was marked when used in the prone position, whereas the associated increase in $PaCO_2$ was minor. In this group of severely hypoxemic patients, use of low PEEP in the prone position appeared to be a valuable alternative in clearly improving PaO_2/FIO_2, thus avoiding an excessive plateau pressure generated by a higher PEEP. This additive benefit of PEEP and prone position in oxygenation in ARDS was recently underscored by Gainnier et al. [17]. In ARDS patients, PEEP improves oxygenation by reducing the extent of intrapulmonary shunt, i.e., the pulmonary areas exhibiting a ventilation/perfusion ratio of nil [22]. Two specific mechanisms may be involved in this beneficial effect of PEEP on oxygenation: a reduction of lung blood flow, and some recruitment in shunt area. Our results suggested that this beneficial effect of PEEP might be more efficient in the prone position, and this could be related to the fact that this postural change homogenizes blood flow in the lung [6].

Conclusion

In conclusion, our present study has shown that prone positioning in ARDS patients significantly shortens the expiratory time constant, reduces gas trapping produced by supportive respiratory rate, and significantly improves alveolar ventilation. Moreover, when associated with a low PEEP, it results in a major improvement in arterial oxygenation.

References

1. Gattinoni L, Pelosi P, Suter P, Pedoto A, Vercesi P, Lissoni A (1998) Acute respiratory distress syndrome caused by pulmonary and extrapulmonary disease. Different syndromes? Am J Respir Crit Care Med 156:3–11
2. Vieillard-Baron A, Prin S, Chergui K, Page B, Beauchet A, Jardin F (2003) Early patterns of static pressure-volume loops in ARDS and their relations with PEEP-induced recruitment. Intensive Care Med 29:1929–1935
3. Schmitt JM, Vieillard-Baron A, Augarde R, Prin S, Page B, Jardin F (2001) PEEP titration in ARDS patients: impact on right ventricular outflow impedance evaluated by pulmonary artery Doppler flow velocity measurements. Crit Care Med 29:1154–1158
4. Page B, Vieillard-Baron A, Beauchet A, Aegerter P, Prin S, Jardin F (2003) Low stretch ventilation strategy in acute respiratory distress syndrome: 8 years of clinical experience in a single center. Crit Care Med 31:765–769
5. Douglas W, Rehder K, Beynen R, Sessler A, Marsh D (1977) Improved oxygenation in patients with acute respiratory failure: the prone position. Am Rev Respir Dis 115:559–566
6. Nyren S, Mure M, Jacobsson H, Larsson S, Lindhal S (1999) Pulmonary perfusion is more uniform in the prone than in the supine position: scintigraphy in healthy humans. J Appl Physiol 86:1135–1141
7. Langer M, Mascheroni D, Marcolin R, Gattinoni L (1988) The prone position in ARDS patients: a clinical study. Chest 94:103–107
8. Gattinoni L, Vaffinelli F, Carieso E, Taccone P, Conte V, Chiumello D, Valenza F, Caironi P, Pesenti A (2003) Decrease in $PaCO_2$ with prone position is predictive of improved outcome in acute respiratory distress syndrome. Crit Care Med 31:1–7
9. Vieillard-Baron A, Prin S, Schmitt JM, Augarde R, Page B, Beauchet A, Jardin F (2002) Pressure/Volume curves in acute respiratory distress syndrome: clinical demonstration of the influence of expiratory flow limitation on the initial slope. Am J Respir Crit Care Med 165:1107–1112
10. Vieillard-Baron A (2002) Erratum: pressure-volume curve in acute respiratory distress syndrome. Am J Respir Crit Care Med 166:1517
11. Rabiller A, Chergui K, Jardin F, Vieillard-Baron A (2003) Impact du décubitus ventral sur le compartiment pulmonaire à vidange lente dans le SDRA. Réanimation, 12:126 s (Abstract)
12. Chatte G, Sab J, Dubois J, Sirodot M, Gaussorgues P, Robert D (1997) Prone position in mechanically ventilated patients with severe acute respiratory failure. Am J Respir Crit Care Med 155:473–478
13. Dall'ava-Santucci J, Armangadis A, Brunet F, Dhainaut JF, Nouira S, Morisseau D, Lockhart A (1990) Mechanical effect of PEEP in patients with adult respiratory distress syndrome. J Appl Physiol 68:843–848
14. Rouby JJ, Constantin JM, Cassio R, Zhang M, Lu Q (2004) Mechanical ventilation in patients with acute respiratory distress syndrome. Anesthesiology 101:228–234
15. The Acute Respiratory Distress Syndrome Network (2000) Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 342:1301–1308
16. Puybasset L, Gusman P, Muller JC, Cluzel P, Coriat P, Rouby JJ (2000) Regional distribution of gas and tissue in acute respiratory distress syndrome. III. Consequence for the effects of positive end-expiratory pressure, CT Scan ARDS Study Group. Adult Respiratory Distress Syndrome. Intensive Care Med 26:1215–1227
17. Gainnier M, Michelet P, Thirion X, Arnal M, Sainty JM, Papazian L (2003) Prone position and positive end-expiratory pressure in acute respiratory distress syndrome. Crit Care Med 31:2719–2726
18. Nunn JF (1971) Resistance to gas flow. In: Nunn JF (ed) Applied respiratory physiology with special reference to anaesthesia. Butterworths, London, pp 74–111
19. Gattinoni L, Pelosi P, Vitale G, Pesenti A, D'Andrea L, Mascheroni D (1991) Body position changes redistribute lung computed-tomographic density in patients with acute respiratory failure. Anesthesiology 74:15–23
20. Pelosi P, Tubiolo D, Mascheroni D, Vicardi P, Crotti S, Valenza F, Gattinoni L (1998) Effects of the prone position on respiratory mechanics and gas exchange during acute lung injury. Am J Respir Crit Care Med 157:387–393
21. Guérin C, Badet M, Rosselli S, Heyer L, Sab JM, Langevin B, Philit F, Fournier G, Robert D (1999) Effects of prone position on alveolar recruitment and oxygenation in acute lung injury. Intensive Care Med 25:1222–1230
22. Dantzker D, Brook C, Dehart P, Lynch J, Weg J (1979) Ventilation–perfusion distribution in the adult respiratory distress syndrome. Am Rev Respir Dis 120:1039–1052