Effects of the Prone Position on Respiratory Mechanics and Gas Exchange during Acute Lung Injury

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We studied 16 patients with acute lung injury receiving volume-controlled ventilation to assess the relationships between gas exchange and respiratory mechanics before, during, and after 2 h in the prone position. We measured the end-expiratory lung volume (EELV, helium dilution), the total respiratory system (Cst,rs), the lung (Cst,L) and the thoracoabdominal cage (Cst,w) compliances (end-inspiratory occlusion technique and esophageal balloon), the hemodynamics, and gas exchange. In the prone position, Pa_{O_2} increased from 103.2 ± 23.8 to 129.3 ± 32.9 mm Hg ($p < 0.05$) without significant changes of Cst,rs and EELV. However, Cst,w decreased from 204.8 ± 97.4 to 135.9 ± 52.5 ml/cm H_2O ($p < 0.01$) and the decrease was correlated with the oxygenation increase ($r = 0.62$, $p < 0.05$). Furthermore, the greater the baseline supine Cst,w, the greater its decrease in the prone position ($r = 0.82$, $p < 0.01$). Consequently, the oxygenation changes in the prone position were predictable from baseline supine Cst,w ($r = 0.80$, $p < 0.01$). Returning to the supine position, Cst,rs increased compared with baseline (42.3 ± 14.4 versus 38.4 ± 13.7 ml/cm H_2O; $p < 0.01$), mainly because of the lung component (57.5 ± 25.1 versus 52.4 ± 23.3 ml/cm H_2O; $p < 0.01$). Thus, (*1*) baseline Cst,w and its changes may play a role in determining the oxygenation response in the prone position; (*2*) the prone position improves Cst,rs and Cst,L when the supine position is resumed. Pelosi P, Tubiolo D, Mascheroni D, Vicardi P, Crotti S, Valenza F, Gattinoni L. Effects of the prone position on respiratory mechanics and gas exchange during acute lung injury.

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Patients with acute lung injury (ALI) may be characterized by various degrees of hypoxemia, alterations in respiratory mechanics, and reduction in end-expiratory lung volume (EELV). The prone position has been proposed as a relatively simple maneuver to improve oxygenation (1), and an increased EELV was originally suggested as the main mechanism for oxygenation improvement (2). More recently, experimental studies in animal model of ALI found that the prone position causes a venous admixture reduction and a more even ventilation distribution, without affecting EELV (3, 4).

In the adult respiratory distress syndrome (ARDS), the most severe form of ALI, similar improvement in oxygenation, decrease in venous admixture (5), and more homogeneous regional lung inflation (6) have been reported. However, no data are available on the EELV change, which is still considered a possible mechanism to explain the oxygenation improvement in the prone position (7, 8). Furthermore, oxygenation improvement is not a constant finding during prone positioning, and no evidence is available so far to explain why the majority of the patients improve, whereas others remain unchanged or deteriorate. In a small sample of patients with ALI studied with computed tomography, we previously observed that changes in oxygenation were somewhat related to the lung and thoracic cage shape (9).

In this study we investigated the effects of the prone position on EELV, lung and chest wall mechanics, and the relationships between the changes in oxygenation and in respiratory mechanics.

METHODS

Study Population

We studied 16 consecutive patients with ALI. Eleven of the 16 met the ARDS criteria of the American European Consensus Conference on ARDS (10). None of them had asthma or chronic lung diseases or cardiogenic pulmonary edema. The main clinical characteristics, the time from onset, the ventilatory settings, and the gas exchange at the moment of the study, as well as the outcome, are summarized in Table 1. Thirteen patients were nasotracheally intubated with a cuffed endotracheal tube (7.5 to 8 mm inner diameter) and three had tracheostomies (8 to 10 mm inner diameter). In five of the 16 patients, prone positioning had been already used before performing the study, whereas the remaining 11 patients were studied at the first time of prone positioning.

Ventilatory Setting

All patients were studied while sedated with fentanyl (1.5 to 5.5 μg/kg/h) and diazepam (0.03 to 0.18 mg/kg/h), paralyzed with pancuronium bromide (0.05 to 0.1 mg/kg/h), and ventilated in the volume control

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TABLE 1

PATIENTS' CHARACTERISTICS, VENTILATORY SETTING, GAS EXCHANGE, AND RESPIRATORY MECHANICS AT THE TIME OF THE STUDY

Patient No.	Sex (*M/F*)	Age (*yr*)	Weight (*kg*)	Onset (*days*)	$\dot{V}_E$ (*L/min*)	PEEP (*cm H_2O*)	$F_{I_{O_2}}$	Pa_{O_2} (*mm Hg*)	Pa_{CO_2} (*mm Hg*)	EELV (*L*)	Cst,rs (*ml/cm H_2O*)	Cst,L (*ml/cm H_2O*)	Cst,w (*ml/cm H_2O*)	Outcome of Respiratory Disease (*S/D*)	
1	F	56	60	8.0	7.0	12	0.90	95	73	0.98	46.4	58.2	228.5	S	*Legionella* pneumonia
2*	M	67	55	4.0	11.5	5	0.50	109	48	1.36	43.0	71.5	107.8	S	*Mycoplasma pneumoniae*
3*	F	79	50	3.0	7.5	12	0.60	166	40	1.10	23.3	27.6	149.7	S	Caustic agent inhalation
4	M	23	60	4.0	7.8	18	0.55	70	57	1.28	33.7	45.4	131.5	S	Hemorragic alveolitis
5	M	65	85	1.0	13.7	18	0.90	96	46	1.21	42.1	93.1	76.8	S	Sepsis
6	M	30	55	8.0	10.5	10	0.55	104	47	0.61	22.4	25.7	178.8	D	CMV pneumonia in immunosuppression
7	F	25	65	1.0	7.2	10	0.55	78	45	0.59	21.1	23.6	196.0	S	Pneumonia of unknown ethiology
8*	M	19	90	18.0	9.9	14	0.50	117	40	1.74	43.2	63.0	137.6	S	Multiple trauma, lung contusion
9*	F	25	50	3.0	7.0	14	0.40	120	44	1.09	28.1	31.7	249.6	D	*Legionella* pneumonia in immunosuppression
10	M	51	80	1.0	10.8	12	0.90	99	52	1.36	39.4	43.2	443.1	D	Pneumonia of unknown ethiology
11*	M	53	75	1.0	8.6	10	0.50	125	32	2.17	76.7	99.0	341.4	S	Pneumonia of unknown ethiology
12	M	44	67	4.0	10.9	8	1.00	111	66	0.62	27.2	31.5	198.5	D	Viral pneumonia in immunosuppression
13	F	62	69	1.0	9.3	15	1.00	64	38	0.87	36.7	45.1	197.2	D	*Aspergillus* pneumonia in immunosuppression
14	M	29	70	2.0	10.6	12	0.60	95	47	1.13	41.8	68.4	107.6	D	Viral pneumonia in immunosuppression
15	M	34	70	1.0	11.0	15	0.55	104	35	1.39	51.4	68.6	204.1	S	*Pneumocystis* pneumonia
16	M	62	90	8.0	9.0	12	0.80	98	59	1.26	37.9	42.9	328.0	D	Pneumonia of unknown ethiology
Mean	11 M/5 F	45	68	4.3	9.5	12.3	0.68	103	48	1.17	38.4	52.4	204.8	9 S/7 D	
SD		19	13	4.5	1.9	3.5	0.20	24	11	0.41	13.7	23.3	97.4		

Definition of abbreviations: PEEP = positive end-expiratory pressure; $F_{I_{O_2}}$ = fraction of inspired oxygen; $\dot{V}_E$ = minute ventilation; EELV = end-expiratory lung volume; Cst,rs = total respiratory system static compliance; Cst,L = lung static compliance; Cst,w = thoracoabdominal cage static compliance.

* Patients with acute lung injury.

mode with constant inspiratory flow. Mechanical ventilation was provided with a Servo Ventilator 900 C (Siemens-Elema, Solna, Sweden). The ventilatory setting, positive end-expiratory pressure (PEEP), and inspired oxygen fraction ($F_{I_{O_2}}$) were set according to the clinical needs and kept constant throughout the study. Tidal volume was 0.682 ± 0.144 L, respiratory rate was 13.5 ± 2.5 breaths/min, T_I/T_{tot} was 0.39 ± 0.08, inspiratory flow was 0.386 ± 0.077 L/s, PEEP was 12.3 ± 3.5 cm H_2O, $F_{I_{O_2}}$ was 0.68 ± 0.20, and peak inspiratory pressure was 37.8 ± 6.3 cm H_2O.

Protocol and Measurements

Change of position was manually performed by four or five attendants (usually three nurses and two doctors). In the prone position the head was turned laterally and the arms were parallel to the body. A roll under the upper part of the chest wall and a pillow under the pelvis were positioned in an effort to minimize restriction of abdominal movements.

Measurements were obtained in the supine position (baseline) after 30 and 120 min in the prone position and 30 min after returning to the supine position. In 13 patients additional measurements were obtained at 120 min after returning to the supine position.

Gas exchange and hemodynamics. All of the patients already had an arterial and pulmonary artery thermodilution catheter inserted at the time of the study. Arterial and mixed venous samples were analyzed for gas tensions and pH immediately after sampling (IL BGM, 1312; Instrumentation Laboratory, Spa, Italy). The right to left intrapulmonary shunt ($\dot{Q}_S/\dot{Q}_T$) was computed by the shunt equation, assuming a respiratory quotient equal to 1. Mean arterial, pulmonary artery, pulmonary wedge, and central venous pressures were measured with pressure transducers (Transpac IV L974; Abbott Ireland, Sligo, Republic of Ireland). Zero level was set at the midaxillary line in both positions. Cardiac output (CO) was measured in triplicate by the thermodilution method, and the cardiac index (CI) was computed normalizing the CO for the body surface area.

Physiologic dead space. Expired gases were collected over a 2-min period in a Douglas bag at the same time as blood gas samples were collected. Expired gas was analyzed for mixed expired CO_2 concentration (Model 760 Capnograph; Teledyne Electronic Devices, Bellmafiok, Mirandola, Italy). The physiologic dead space fraction (V_D/V_T) was computed according to the standard formulas.

End-expiratory lung volume. EELV was measured using a simplified closed-circuit helium dilution method (11) at PEEP during an end-expiratory pause. An anesthesia bag filled with 1.5 L of a known gas mixture (13% helium in oxygen) was connected to the airway opening previously clamped at end-expiration to maintain the PEEP level, and 10 deep manual breaths were performed. The helium concentration in the anesthesia bag was then measured with a helium analyzer (PK Morgan Ltd, Chatham, Kent, UK), and EELV was computed according to the following formula:

$$EELV = Vi[He]_i/[He]_{fin} - Vi$$

where Vi is the initial gas volume in the anesthesia bag and $[He]_i$ and $[He]_{fin}$ are the initial and final helium concentrations in the bag. The limitations of this method have been fully discussed elsewhere (12).

Intra-abdominal pressure. Average intra-abdominal pressure was measured through a transurethral bladder catheter (13). Using a sterile technique, an average of 100 ml of normal saline were infused through the urinary catheter to fill the catheter tubing. The catheter was then clamped distally to the sampling port. A 20-gauge needle was inserted through the catheter sampling membrane, and the bladder catheter pressures were measured using a water manometer zeroed at the pubis level.

Intra-abdominal pressure was measured only at the baseline, at the end of prone position period, and 120 min after returning to the supine position. The intra-abdominal pressure data were not collected in the first four patients.

Respiratory mechanics. Airway pressure (Paw) and gas flow were measured by a self-calibrating flow transducer (Varflex; Bicore Monitoring System, Irvine, CA) connected at the endotracheal or tracheostomy tube opening. Esophageal pressure (Pes) was measured by an esophageal balloon (Bicore Monitoring System) automatically inflated with 0.5 to 1 ml of air and positioned at the lower third of the esophagus as shown by chest roentgenograph. All the signals were acquired on a CP100 Pulmonary Monitor (Bicore Monitoring System), converted to digital form and processed separately for subsequent analysis with a dedicated computerized program.

To measure the compliance of the respiratory system and to partition it into its pulmonary and chest wall components the occlusion method was used. The end-inspiratory hold button of the Servo 900 C was pressed for brief (7 to 8 s) airway occlusion (14). Occlusion was maintained until both Paw and Pes decreased from the maximal value (Paw_{max} and Pes_{max}, respectively) to an apparent plateau (Paw_2 and Pes_2, respectively). Similarly the end-expiratory airway pressure ($P_E aw$) and the end-expiratory esophageal pressure ($P_E es$) were recorded after a brief end-expiratory hold maneuver. The static respiratory system (Cst,rs) and thoracoabdominal (Cst,w) compliances were obtained dividing the tidal volume, respectively, by the difference be-

TABLE 2

ARTERIAL BLOOD GAS VALUES AND PHYSIOLOGIC DEAD SPACE DURING THE STUDY*

	Baseline 0 min	Prone 30 min	Prone 120 min	Supine 30 min	Supine 120 min
Pa_{O_2}, mm Hg	103.19 ± 23.79	119.06 ± 31.81	129.25 ± 32.86†	123.13 ± 50.02	117.92 ± 54.99
Pa_{CO_2}, mm Hg	48.04 ± 11.13	50.23 ± 11.76	49.61 ± 11.74	49.96 ± 12.57	48.21 ± 12.64
pHa	7.346 ± 0.086	7.337 ± 0.067	7.334 ± 0.068	7.336 ± 0.07	7.348 ± 0.065
$\dot{Q}_S/\dot{Q}_T$	0.28 ± 0.12	0.27 ± 0.11	0.25 ± 0.11	0.27 ± 0.10	0.28 ± 0.11
V_D/V_T	0.55 ± 0.08	0.58 ± 0.07	0.55 ± 0.08	0.55 ± 0.09	0.55 ± 0.09

Definition of abbreviations: $\dot{Q}_S/\dot{Q}_T$ = right to left intrapulmonary shunt; V_D/V_T = physiologic dead space.
* Values are expressed as mean ± SD. Data at 120 min after repositioning supine refer to 13 patients.
† $p < 0.05$ compared with baseline.

tween $Paw_2 - PEaw$ and $Pes_2 - PEes$. The static lung compliance (Cst,L) was obtained with the following formula:

$$Cst,L = V_T/[(Paw_2 - Pes_2) - (PEaw - PEes)].$$

One could question the comparison of esophageal balloon measurements in the supine and the prone positions. In fact, it is possible that the transmission of the alveolar pressure to the pleural space is different in the two conditions because of the different relative position of the heart, which moves ventrally on turning prone. However, no alternative methods are available in humans, and this method was considered adequate also in the prone position, and it was adopted to perform lung-volume curves in both awake (15) and paralyzed subjects (11, 16). Moreover, if the change of position would result in artefacts when measuring the esophageal pressure, this would lead to systematic changes in the same direction (false increase or false decrease), but this was not the case in our study (*see* RESULTS).

Total resistance of the respiratory system (Rtot,rs) and of the chest wall ($\dot{R}$tot,w) were computed as $(Paw_{max} - Paw_2)/\dot{V}i$ and $(Pes_{max} - Pes_2)/\dot{V}i$, respectively, where $\dot{V}i$ is the flow immediately before the occlusion. Total lung resistance (Rtot,L) was obtained as the difference between Rtot,rs and Rtot,w. Rtot,rs and Rtot,L include the endotracheal or tracheostomy tube resistance.

All respiratory mechanics data (except the EELV) were obtained as an average of three measurements.

Statistics

All data are expressed as mean ± 1 standard deviation. Comparisons between the different periods were performed using Friedman's nonparametric analysis of variance. Individual comparison with baseline were performed with a nonparametric paired *t* test; Bonferroni's correction was applied for multiple comparisons. The least-squares method was used to perform linear regression analysis; $p \leq 0.05$ was considered statistically significant.

RESULTS

Gas Exchange and Hemodynamics

In this series of patients the prone position resulted in a significant increase in oxygenation within 120 min (Table 2), even if there was considerable individual variation in oxygenation response in the prone position. Indeed in 12 patients, Pa_{O_2} increased (range, 9 to 73 mm Hg), whereas in four patients it decreased (range, −7 to −16 mm Hg) compared with baseline. When the patients were repositioned supine the oxygenation was not significantly different from that in the prone position or that at baseline. Shunt fraction, Pa_{CO_2}, and dead space did not significantly change when the patients were turned prone and when they were repositioned supine. These responses were similar both in the patients with ALI and in those with ARDS. We could not find any relationship between the oxygenation response and the time elapsed from disease onset.

As shown in Table 3, mean pulmonary artery pressure, wedge pressure, and central venous pressure slightly, but significantly, increased during the prone position and returned to baseline values after returning to the supine position. However, since we kept the midaxillary line as a zero reference level, these minimal changes could be due to a shift of the real zero pressure level because of ventral movement of the heart. Other hemodynamic variables remained unchanged during the prone position.

Respiratory Mechanics

Overall results are shown in Table 4. No significant EELV differences were observed between supine and prone positions

TABLE 3

HEMODYNAMIC VALUES DURING THE STUDY*

	Baseline 0 min	Prone 30 min	Prone 120 min	Supine 30 min	Supine 120 min
HR, beats/min	111 ± 24	113 ± 21	115 ± 23	113 ± 19	116 ± 14
$\overline{Pa}$, mm Hg	79 ± 15	82 ± 15	84 ± 18	82 ± 15	83 ± 16
Ppa, mm Hg	28 ± 7	32 ± 7†	32 ± 6†	28 ± 5	29 ± 5
Pw, mm Hg	14 ± 4	16 ± 4†	17 ± 4†	14 ± 3	13 ± 4
Pcv, mm Hg	11 ± 5	12 ± 5†	13 ± 4†	11 ± 4	11 ± 4
CI, L/min/m^2	4.4 ± 1.6	4.4 ± 1.4	4.5 ± 1.6	4.7 ± 1.4	4.7 ± 1.2
$\dot{V}_{O_2}$, ml/min/m^2	126.9 ± 35.4	139.6 ± 46.2	139.9 ± 48.4	148.6 ± 50.4	150.7 ± 49.3
TSVR, dyne∗s/cm^5	746 ± 258	759 ± 239	763 ± 273	723 ± 236	710 ± 206
PVR, dyne∗s/cm^5	151 ± 50	163 ± 41	160 ± 50	133 ± 42	157 ± 45

Definition of abbreviations: HR = heart rate; $\overline{Pa}$ = mean arterial pressure; Ppa = pulmonary artery pressure; Pw = wedge pressure; Pcv = central venous pressure; CI = cardiac index; $\dot{V}_{O_2}$ = oxygen consumption; TSVR = total systemic vascular resistance; PVR = pulmonary vascular resistance.
* Values are expressed as mean ± SD. Data at 120 min after repositioning supine refer to 13 patients.
† $p < 0.05$ compared with baseline.

TABLE 4

RESPIRATORY MECHANICS VALUES DURING THE STUDY*

	Baseline 0 min	Prone 30 min	Prone 120 min	Supine 30 min	Supine 120 min
EELV, L	1.17 ± 0.41	1.25 ± 0.49	1.29 ± 0.57	1.20 ± 0.58	1.29 ± 0.66
IAP, cm H_2O	11.4 ± 7.2	—	14.8 ± 6.6	—	10.4 ± 7.2
Cst,rs, ml/cm H_2O	38.4 ± 13.7	36.8 ± 11.8	35.9 ± 10.7	42.3 ± 14.4‡§	43.0 ± 15.2†
Cst,L, ml/cm H_2O	52.4 ± 23.3	55.3 ± 26.2	53.9 ± 23.6	57.5 ± 25.1‡§	58.5 ± 27.3†
Cst,w, ml/cm H_2O	204.8 ± 97.4	146.8 ± 55.5	135.9 ± 52.5‡	219.1 ± 100.9	232.0 ± 84.0
Rtot,rs, cm H_2O/L/s	17.5 ± 6.4	17.6 ± 4.8	17.6 ± 5.7	17.9 ± 5.2	16.6 ± 4.5
Rtot,L, cm H_2O/L/s	15.2 ± 6.5	15.1 ± 5.3	15.0 ± 5.5	15.8 ± 5.7	14.5 ± 4.5
Rtot,w, cm H_2O/L/s	2.3 ± 1.8	2.5 ± 1.6	2.6 ± 1.3	2.1 ± 1.4	2.1 ± 1.2

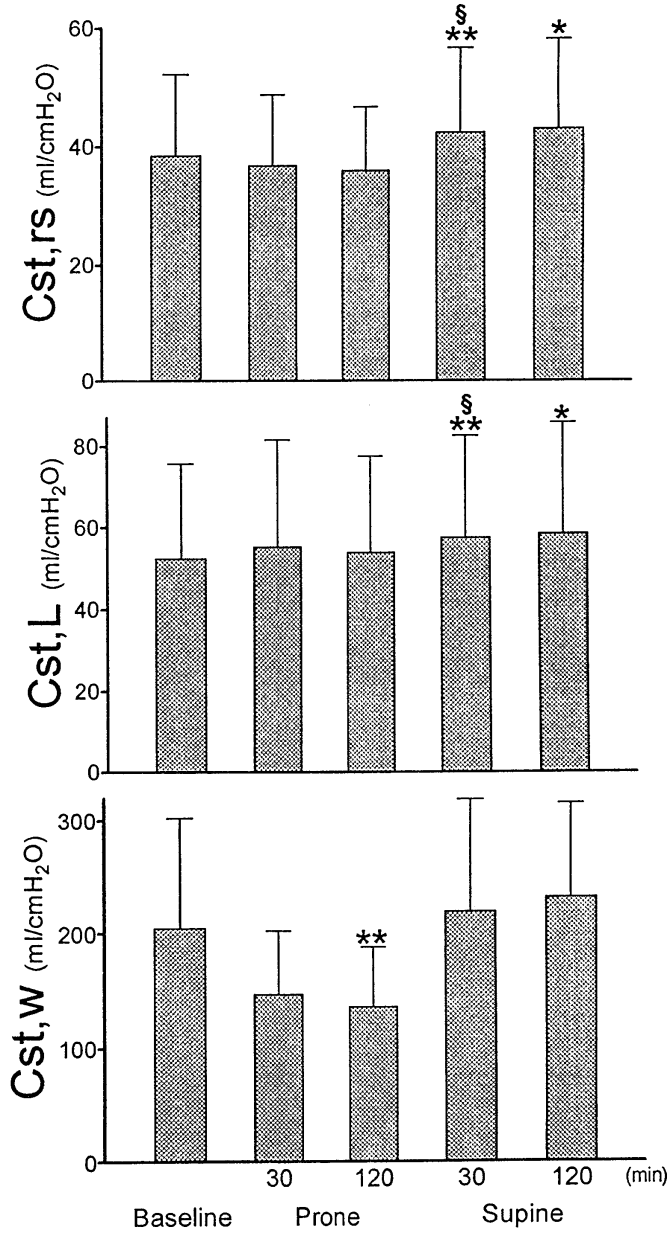
Definition of abbreviations: EELV = end-expiratory lung volume; IAP = intra-abdominal pressure; Cst,rs = total respiratory system static compliance; Cst,L = lung static compliance; Cst,w = thoracoabdominal cage static compliance; Rtot,rs = total resistance of the respiratory system (including the endotracheal tube); Rtot,L = total lung resistance (including the endotracheal tube); Rtot,w = total thoracic cage resistance.

* Values are expressed as mean ± SD. Data at 120 min after repositioning supine refer to 13 patients. Data regarding IAP refer to 12 patients.

† $p < 0.05$ compared with baseline.

‡ $p < 0.01$ compared with baseline.

§ $p < 0.01$ compared with prone position.



despite a trend toward increases while prone. Similarly, the intra-abdominal pressure was not significantly affected by the positional changes. The prone position did not significantly affect Cst,rs and Cst,L (Figure 1), but it resulted in a significant reduction in Cst,w. Thirty minutes after returning to the supine position, Cst,rs increased compared with either baseline or prone position values ($p < 0.01$). This improvement was mainly due to the lung component ($p < 0.01$), but the Cst,w returned to baseline levels. The improvement in total respiratory system and lung compliance was consistent in the majority of our patient population. Indeed, in 14 of the 16 patients, plateau pressure was reduced after returning supine compared with that at baseline, with a range of 1.3 to 4.2 cm H_2O (average, 2.32 ± 0.92 cm H_2O) ($p < 0.01$). This effect also persisted 120 min after returning supine. Airway resistances were not significantly affected by postural changes.

Oxygenation-Respiratory Mechanics Relationships

The changes in oxygenation induced by the prone position were not related to changes in EELV or total respiratory system or lung compliance. However, the oxygenation changes in the prone position were predictable from the baseline supine Cst,w. As shown in Figure 2, higher Cst,w were associated with greater Pa_{O_2} improvements in the prone position ($\Delta Pa_{O_2} = -32.4 + 0.24 * Cst,r$; $r = 0.80$, $p < 0.01$). Moreover, Cst,w changes in the prone position were correlated with the baseline Cst,w values ($\Delta Cst,w = 88.5 - 0.72 * Cst,w$; $r = 0.82$, $p < 0.01$) (Figure 3).

Furthermore, we found a fair correlation between the early changes of oxygenation (30 min after prone positioning) and the changes in the compliance of the thoracoabdominal cage. ($\Delta Pa_{O_2} = 3.9 - 0.2 * \Delta Cst,w$; $r = 0.62$, $p < 0.05$). The greater the decrease of thoracoabdominal compliance, the greater the improvement in oxygenation (Figure 4). At 120 min the Pa_{O_2} further increased, and the Cst,w further decreased. However,

Figure 1. Total respiratory system, lung and thoracoabdominal compliance during the study. Data are expressed as mean ± SD. Data at 120 min after repositioning supine refer to 13 patients. *$p < 0.05$, compared with baseline; **$p < 0.01$ compared with baseline; §$p < 0.01$ compared with prone position.

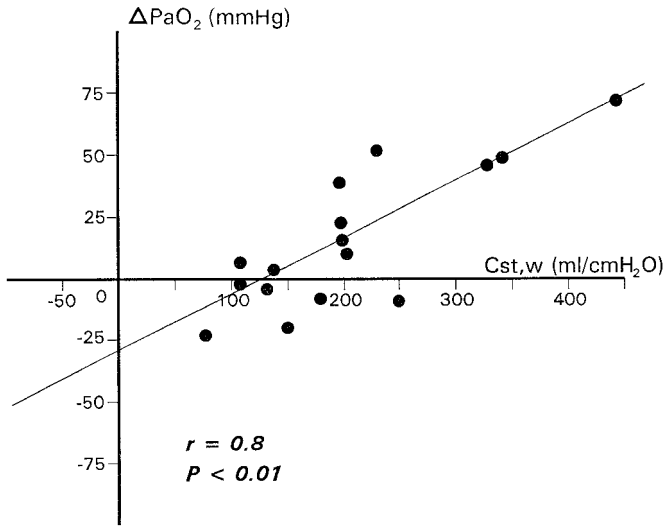


Figure 2. Relationship between baseline thoracoabdominal cage compliance (Cst,w) and oxygenation changes (ΔPa_{O_2}) (prone 30 min minus baseline). $\Delta Pa_{O_2} = -32.4 + 0.24 * Cst,w$; r = 0.80, p < 0.01.

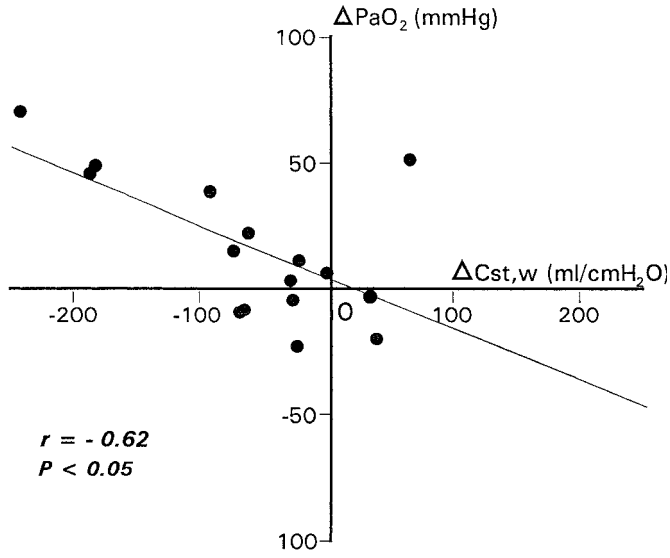


Figure 4. Relationship between changes (prone 30 min minus baseline) in the thoracoabdominal cage compliance (ΔCst,w) and oxygenation (ΔPa_{O_2}). $\Delta Pa_{O_2} = 3.9 - 0.2 * \Delta Cst,w$; r = 0.62, p < 0.05.

the correlation between the thoracoabdominal compliance changes and oxygenation changes was only close to statistical significance (r = 0.45; p = 0.07).

DISCUSSION

As previously shown by other studies (5, 17, 18), in this series of patients we observed a great variability of individual responses in oxygenation. On average, however, the Pa_{O_2} after 120 min in the prone position was significantly higher than that at baseline. This improvement was not due to EELV changes. At the same time, the compliance of the thoracoabdominal cage was significantly lower than that at baseline. When returning to the supine position, the total respiratory system and lung compliance values were significantly higher than baseline values.

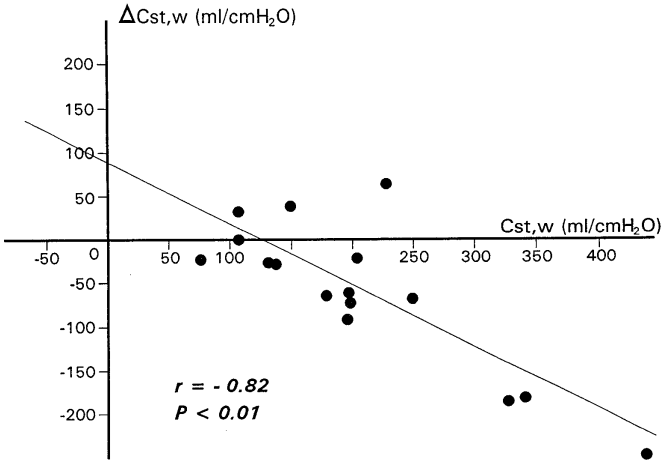


Figure 3. Relationship between baseline thoracoabdominal cage compliance (Cst,w) and its modification in the prone position (prone 30 min minus baseline) (ΔCst,w). ΔCst,w = 88.5 −0.72 * Cst,w; r = 0.82, p < 0.01.

Supine to Prone Shifting

Oxygenation. An increase in EELV was originally proposed by Douglas and colleagues (2) to explain the improvement in oxygenation observed in their pioneering study on the prone position in ALI, and it has since been considered a possible explanation for the improvement in gas exchange associated with the prone position (7, 8, 17). This hypothesis seems unlikely in adult patients with ALI since no significantly EELV changes were observed during prone positioning, and the EELV variations were not related to the changes in oxygenation. The lack of correlation between improvement in oxygenation and changes in EELV is in keeping with previous findings in oleic-acid-injured dogs (3), in normal (16) and in obese (11) anesthetized subjects, and in pediatric patients with ALI (19). Moreover, in a previous study using computed tomography, we did not find any difference in the average slice densities between the prone and the supine positions, suggesting an unmodified total gas volume (6). However, because of the relatively small patient population, we cannot safely exclude a possible marginal increase in EELV during prone positioning; in fact, a trend towards increased EELV was present in this study and in a previous one on animals (3). Nonetheless, this study clearly shows that an increase in global EELV is not necessary to obtain improved gas exchange in the prone position.

Therefore, the rise in oxygenation during prone positioning may only be explained by regional changes of inflation/ventilation or perfusion with an unmodified global EELV. Indeed, data obtained in experimental animal settings attributed the improvement in oxygenation primarily to a regional variation of ventilation, which was found more evenly distributed between the dorsal and the ventral lung regions in the prone position (20). Moreover, in patients with ALI we found, with the CT scan, a more homogeneous regional inflation in the prone position than in the supine position (6), which was actually associated with better oxygenation (9). In summary, the available human and experimental data suggest that the main determinant of the improvement in oxygenation in the prone position is the redistribution of the inflation gradient from

dorsal to ventral regions (6), resulting in more even regional inflation/ventilation along the vertical axis, in the absence of a gravitary perfusion distribution (4). However, the regional assessment of perfusion in patients is technically difficult, and this hypothesis remains to be proved.

Respiratory mechanics. Shifting from the supine to the prone position resulted in a significant reduction in the compliance of the thoracoabdominal cage. This decrease could be explained by a decrease of the compliance of either the rib cage or diaphragmatic component of the chest wall or both. We can reasonably assume that the diaphragmatic wall compliance as a whole (notwithstanding differences in regional distribution) remained substantially unchanged in the prone position because the intra-abdominal pressure was not significantly different in the prone and supine positions. The decrease of thoraco-abdominal compliance should therefore be explained by a greater rigidity of the rib cage component of the chest wall in the prone position when compared with the supine position.

Indeed, the compliance of the rib cage component of the chest wall is known to be nonhomogeneous, the ventral part (sternal) presenting a "larger freedom to move," than the dorsal part (vertebral) (21). The dishomogeneity is further enhanced in the supine position where movement remains unimpeded in only the ventral part (the dorsal part of the chest lies on the bed). This is one of the possible mechanisms causing the preferential distribution of ventilation to ventral lung areas in supine, paralyzed subjects with ALI (22). In the prone position, the stiffer component of the rib cage (dorsal part) is free to move, whereas movement of the more compliant (ventral part) becomes impeded by lying on the bed. This results in a decrease in net rib cage compliance. However, because of this rearrangement, at least during volume-controlled ventilation, the prone position should partly redistribute the tidal ventilation towards the dependent ventral regions, resulting in an overall more even regional distribution than that in the supine position.

Returning Supine after the Prone Position

Oxygenation. When returning to the supine position oxygenation slightly declined, but no significant differences were observed when compared with baseline or the prone position. However, because of the small population, we cannot exclude a type II error. Once again, these average values were derived from variable individual responses. Different oxygenation responses when returning to the supine position have been previously described, including both a reversal of oxygenation improvement (5) and a maintenance of improved oxygenation (17, 18). We were unable to find any relationship between respiratory mechanics and oxygenation when the supine position was resumed.

Respiratory mechanics. A main finding of this study was the significant increase of the compliance of the total respiratory system above baseline values when returning to the supine position. This improvement was mainly due to an increase of the lung compliance. It is somewhat surprising to find that the changes in lung compliance were not associated with changes in EELV, which did not significantly change. It is worth considering, however, that the way we measured the compliance included a possible intratidal recruitment (i.e., recruitment during the inspiratory phase of tidal ventilation) (22). In fact the substantial redistribution of regional lung collapse observed during the prone position (6) could well have resulted in an increased portion of the lung becoming recruitable during tidal insufflation when returning to the supine position (22), thus explaining the increase in lung compliance associated with an unmodified lung volume. An alternative explanation could be a change of specific compliance.

Relationships between Changes in Oxygenation and Changes in the Mechanical Properties of the Respiratory System

We submit an integrated interpretation of the findings obtained in this and in other studies of ALI.

Paralyzed patients with ALI in the supine position at end-expiration exhibit an inflation gradient (i.e., relative difference of regional inflation) much greater than that in normal subjects; this is due to the increase in lung weight. The progressive decrease of regional inflation along the vertical axis results in regional collapse of the most dorsal regions (6, 23). At PEEP levels usually applied when these lungs are insufflated, the tidal volume preferentially distributes to the ventral lung regions, causing higher regional Cst,rs than in the dorsal regions (22). When shifting from the supine to the prone position, the pattern is almost completely reverted. At end-expiration, the regional inflation decreases from dorsal to ventral, and the most dependent ventral regions collapse.

It must be noted, however, that the inflation gradient is decreased compared with that in the supine position, i.e., the differences of regional inflation are less pronounced, resulting in an overall more homogenous regional inflation. The decrease of the inflation gradient in the prone position could be due to the changed position of the heart, which no longer compresses the dorsal lung regions (24, 25). The more even regional inflation per se could result in better oxygenation. In fact, we previously found by CT scan at end-expiration a correlation between the increased homogeneity of lung inflation induced by the prone position and the increase of oxygenation (9).

In the present study we found, in addition, that the decrease of the thoracoabdominal compliance in the prone position when compared with the supine position was associated with improvement of oxygenation. We hypothesize a different distribution of tidal volume compared with that in the supine position as a possible mechanism. Indeed, in the prone position, because of the greater stiffness of the dorsal part of the thoracic cage, the insufflated gases should distribute more towards the ventral and diaphragmatic regions (now dependent) where minimal inflation or collapse are present at end-expiration. The greater the stiffness of the dorsal part of the thoracic cage, the greater should be insufflation of the less aerated ventral regions, and the greater the improvement in oxygenation.

Although a thorough understanding of the mechanisms underlying the changes in oxygenation also requires knowledge of regional perfusion, this study showed that the mechanical properties of the thoracoabdominal cage and its variations play an important role in dictating the oxygenation response in the prone position.

Long-term Effects of Prone Position

In recent years a very large number of studies have reported an improvement in oxygenation in patients with ALI when placed in the prone position (7–9). Indeed, this manuever is now widely accepted as a useful tool to improve oxygenation in patients with severe ALI.

However, besides the improvement in oxygenation associated with prone positioning, some of these studies reported other interesting observations such as the persistent improvement above baseline values when returning to the supine position (17, 18), a dramatic redistribution of CT-lung densities in the prone position (6), and a decrease of densities when returning supine after 4 h in the prone position, compared with baseline (26). More recently, Broccard and colleagues (27)

showed that the prone position may decrease the damaging effect of large tidal volume ventilation in dogs with preinjured lungs. In the present study, we have shown that the prone position leads, independent of gas exchange, to an improvement in the mechanical properties of the respiratory system when returning to the supine position, thus adding another piece of evidence to the hypothesis that the prone position, besides improving gas exchange, induces modifications in underlying lung conditions that persist after returning to the supine position.

We believe that these findings taken together, represent a solid base to justify a prospective trial evaluating whether the prone position may affect the clinical course of acute lung injury.

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