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Effects of ventilation in ventral decubitus position on respiratory mechanics in adult respiratory distress syndrome

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Abstract *Objective:* To assess the potential benefits of a period of ventilation in ventral decubitus (VD) on oxygenation and respiratory mechanics in the adult respiratory distress syndrome (ARDS).
Design: In a stable condition during baseline ventilation in dorsal decubitus (DD), after 15 min of ventilation in VD and after 10 min of restored DD, the following parameters were studied: arterial blood gas tension, haemodynamics and static respiratory compliance (Crs), evaluated with the rapid airway occlusion technique.
Setting: The study was completed in the intensive care units of university hospitals as part of the management of the patients studied.
Patients: Twelve patients (7 males, 5 females, mean age 51.8 ± 16.6 years) suffering from ARDS of different aetiologies.
Interventions: Before and during each evaluation, the patients were kept under stable haemodynamic and metabolic conditions. The ventilatory setting was kept constant. All the patients were sedated, paralysed and mechanically ventilated.
Results: A statistically significant increase in the ratio between the arterial partial pressure of oxygen and fractional inspired oxygen ($p < 0.01$) was observed between the baseline conditions (mean 123.9 ± 22.6) and VD (mean 153.0 ± 16.9), while no statistical significance was noted between baseline conditions and after 10 min of restored DD (mean 141.1 ± 19.7). A significant increase in Crs ($p < 0.001$) was observed between baseline conditions (mean 42 ± 10.1) and VD (mean 48.8 ± 9.6) and between baseline conditions and restored DD (mean 44.7 ± 10.6). Two patients were considered nonresponders. All the patients were haemodynamically stable. No side effects were noted.
Conclusions: We observed an increase in oxygenation and Crs when the patients were turned from the supine to the prone position with the upper thorax and pelvis supported.

Key words Acute respiratory failure · Gas exchange · Mechanics · Body position · Compliance of respiratory system · Mechanical ventilation

Introduction

Since the mid-seventies, oxygenation has been repeatedly shown to be improved in most patients with the adult respiratory distress syndrome (ARDS) when turned from the supine to the prone position [1–5]. Despite the fact that the mechanism of the increase in the partial pressure of oxygen in arterial blood (PaO_2) is still debated, a combination of modification of ventilation distribution and rearrangement of V/Q ratios is presently the most widely accepted hypothesis. With regard to ventilation, Bryan and Bryan et al. [1, 6] hypo-

Table 1 Clinical characteristics of patients and individual partial pressure of oxygen in arterial blood *PaO_2*/fractional inspired oxygen *FIO_2* ratios (*DD* dorsal decubitus, *VD* ventral decubitus, $p < 0.01$, *LIS* lung injury score) ratio in the different times studied

Patient	General characteristics					PaO_2/FIO_2		
	Sex	Age (years)	Diagnosis	LIS	Outcome	DD basal	VD 15 min	DD after 10 min
1	M	48	Acute leukemia	2.8	Died	112	138	120
2	F	64	Acute leukemia	2.6	Survived	121	146	132
3	F	41	Hodgkin's	3.2	Died	103	145	135
4	M	22	Trauma	2.6	Survived	158	190	170
5	M	48	Pancreatitis	3.0	Died	90	182	181
6	F	64	Pneumonia	2.5	Died	164	160	162
7	M	30	Pneumonia	2.6	Survived	120	143	124
8	F	44	Pneumonia	2.5	Survived	142	140	140
9	M	48	Sepsis	2.6	Died	121	146	132
10	F	65	Sepsis	2.5	Survived	140	155	145
11	M	72	Sepsis	2.8	Died	112	138	121
12	M	76	Sepsis	3.0	Died	104	153	132
Mean		51.8		2.7		123.9	153*	141.1
SD		16.6		0.2		22.6	16.9	19.7

$p < 0.01$

thesized that ventral decubitus (VD) could enhance expansion and ventilation of the dorsal areas of the lungs, once the patient was placed in a non-dependent position. In fact, Gattinoni et al. [7, 8] and then Pelosi et al. [9, 10] documented on computed tomography (CT) the disappearance of lung dorsal densities in ARDS patients placed prone. However, these data were not correlated with respiratory mechanics, and the authors noticed that the CT pattern was similar in both responders and non-responders. Indeed, recent animal experiments document increases in functional residual capacity and lung compliance during VD [12–16]; however, respiratory mechanics have rarely been assessed in patients with ARDS during VD, and total pressure/volume (P/V) curves have never been reported. In 14 infants with IRDS in the prone position, Wagaman et al. [4] measured total respiratory and lung compliances and found them significantly increased. However, due to the peculiarities of mechanical ventilation in neonates (persistence of spontaneous breathing, tracheal tube without cuffs), tidal volume (V_T) was allowed to increase, making it difficult to interpret variations in compliance. Douglas et al. [3] measured total respiratory compliance in five adults with acute respiratory failure during VD and dorsal decubitus (DD). Despite PaO_2 improving markedly, compliance was not modified. The authors measured the "effective" compliance, proposed by Suter a few years before [12], which is a rather rough measurement and could have missed some subtle variations of P/V curves. Fridrich et al. [18], in 18 patients with multiple trauma and ARDS, assessed the long-term effects of prone positioning. No details are given on how static compliance was measured in these patients, but compliance and PaO_2 rose simultaneously over time.

The aim of this clinical study was to document the changes occurring in the short term in total respiratory compliance in patients with ARDS in both supine and prone positions. Our hypothesis was that compliance increases in the prone position, and the resolution of the dorsal lung densities, by increasing regional ventilation, should play a role in improvement in gas exchange.

Patients and methods

Twelve patients (7 males and 5 females, mean age 51.8 ± 16.6 years), suffering from ARDS of different aetiologies, were enrolled in our study. The lung injury score was computed as described by Murray et al. [19], taking into account the number of quadrants involved on chest X-ray, the PaO_2/FIO_2 (fractional inspired oxygen) ratio, the positive end-expiratory pressure (PEEP) level and the quasi-static compliance, each scored from 0 to 4. In four patients CT and heart catheterization were performed as part of normal care. Patients are described in Table 1.

All the patients included in our protocol were studied in the intensive care unit of the University of Naples "Federico II", Italy and the medical intensive care unit of the Hopital Henri Mondor, Paris XII University, Creteil, France. Informed consent was obtained from the patients' next of kin before the study.

During the study, all patients were sedated (propofol 2 mg/kg per h), paralysed (pancuronium 0.1 mg/kg per h). Mechanical ventilation was carried out with a Servo Ventilator 900 C (Siemens Elema, Sweden) (V_T 8–10 ml/kg; respiratory rate 12–18 breaths/min; PEEP 10 ± 3 cm H_2O; inspiratory-expiratory (I:E) ratio 1:2).

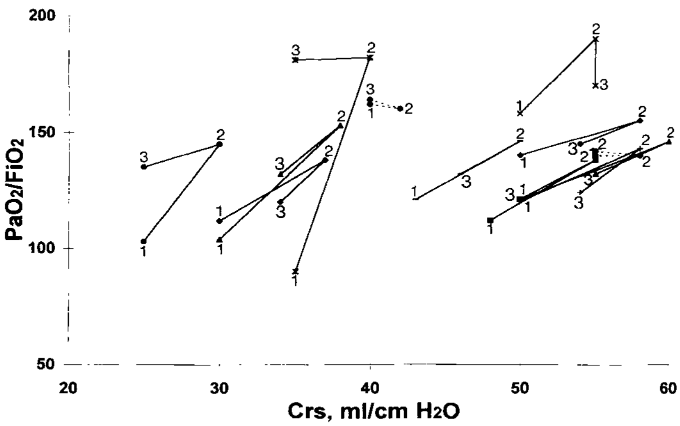

Fig. 1 Individual data for Crs and PaO_2/FIO_2. Dorsal decubitus is indicated with *1*, ventral decubitus with *2* and the restored dorsal decubitus with *3*. It is interesting to observe the behaviour of the non-responding patients *dotted line*

Under stable conditions during ventilation in DD the following data were collected: arterial blood gas tensions, haemodynamics, static respiratory compliance (Crs). Soon after data collection the patients were turned in VD and data collection was repeated after 15 min. Ten minutes after the patients were shifted to DD, a new set of data was collected. During the study, FIO_2 and all ventilatory parameters were kept constant. We considered as responders the patients who showed a minimum 10 mmHg PaO_2 increase over baseline conditions at data collection in VD. The patients were then divided into two groups: responders and non-responders.

During the study, in both positions, the following parameters were monitored in all patients: electrocardiography, blood pressure, central venous pressure, arterial oxygen saturation, PaO_2 and the partial pressure of carbondioxide in arterial blood ($PaCO_2$). Arterial blood samples were promptly analysed with an IL 1312 for oxygen saturation, PaO_2 and $PaCO_2$.

Static P/V curve analysis

P/V curves were traced using the rapid airway occlusion technique [20–23]. Measurements were made with a Servo Ventilator 900 C provided with a built-in sensor for flow, airway pressure and airway occlusion devices. Inspiratory and expiratory flow sensors were calibrated before data collection. To control for the absence of leaks in the circuit, before each P/V curve measurement, the absence of a decrease in pressure during a 5-s holding period at 30 cmH_2O was checked. The inflation static P/V curve was obtained by intermittently changing the inspired volume while keeping constant the inspiratory flow. To eliminate the need for altering the ventilatory frequency setting an external device (DEC) was used [24]. This device maintains a stable ventilator setting, ensuring a constant volume. DEC allowed a single inspiration or expiration to be shortened, or prolonged, by interrupting the flow, and the institution of a prolonged pause until a plateau in airway pressure was reached. By changing the frequency of flow cuts, incremental V_Ts were obtained. The smallest volume used was 50 ml and no volume higher than 1600 ml or pressure higher than 50 cmH_2O was used. I:E ratio and minute volume were kept constant. At each new V_T, an end-inspiratory pause of at least 3 s was made and the corresponding elastic recoil pressure of the respiratory system was recorded. Between each flow interruption, baseline ventilation was resumed. Intrinsic PEEP (PEEPi) was determined in patients by pressing the expiratory pause hold knob for 3 s at end-expiration. P/V curves were then constructed by plotting volume against the corresponding elastic recoil pressure of the respiratory system; 20 respiratory cycles were studied to construct each curve. All curves were constructed from zero end-expiratory pressure (ZEEP). In four patients who were unstable at ZEEP, the study was shortened. Compliance was measured on the linear part of the P/V curve. Two straight lines were drawn manually through the data points above and below the linear part of the P/V curve. These lines crossed the linear curve at two specific points, denoted the lower and upper inflection points (LIP and UIP, respectively).

Ventral decubitus

In VD the upper thorax and pelvis were supported by folded towels, 10 ± 2 cm thick. The head was turned laterally and supported by a pillow, and the arms were abducted and supported at 90°. Special care was taken to avoid pressure on the eyes. Turning of patients was quickly mastered by a staff of four nurses and two physicians.

Statistical analysis

All data are expressed as mean ± SD. The SPSS 5.0 program was used for statistical analysis. Medians, skew and coefficients of variation were used to characterize the PaO_2/FIO_2 and Crs distribution in DD, VD and restored DD in the 12 patients. Linear correlation in PaO_2/FIO_2 and Crs data collected in DD, VD and restored DD was performed by calculating Pearson's R. Comparison between DD and VD, DD and restored DD and VD and restored DD was performed using a two-tailed Student's t-test for paired data. The accepted level of significance, was $p < 0.01$.

Results

All patients were stable during the study, and haemodynamic data evaluation, carried out in four patients, showed good stability. A good distribution and a significant linear correlation ($R > 0.91$; $p < 0.001$) was found for PaO_2/FIO_2 and Crs data. Table 1 lists the PaO_2/FIO_2 ratio calculated in all patients during the different times of the study. A statistically significant increase ($p < 0.01$) of the PaO_2/FIO_2 ratio was observed between DD (mean 123.9 ± 22.6) and VD (mean 153.0 ± 16.9), while no statistical significance was noted between DD ventilation in baseline conditions and after 10 min from restored DD (mean 141.1 ± 19.7). In patients 6 and 8 oxygenation did not increase, and they were considered non-responders. In Fig. 1 individual data for Crs and PaO_2/FIO_2 are plotted.

Table 2 gives the Crs, PEEPi, LIP and UIP values at the different times. A significant increase in Crs

Table 2 Individual values of static respiratory compliance *Crs*, intrinsic positive end-expiratory pressure *PEEPi*, lower inflection points *LIP*, and upper inflection points *UIP* in the different study times *DD* dorsal decubitus, *VD* ventral decubitus)

Patients	Crst (ml/cmH_2O)			PEEPi[a]			LIP[a] (cmH_2O)			UIP[a] (cmH_2O)		
	DD	VD 15 min	DD after 10 min	DD	VD 15 min	DD after 10 min	DD	VD 15 min	DD after 10 min	DD	VD 15 min	DD after 10 min
1	30	37	34	7.8	7.8	7.8	10	10	10	/	/	/
2	50	60	55	10.5	10.5	10.5	/	/	/	/	/	/
3	25	30	25	1.5	1.5	1.5	/	/	/	20	/	20
4	50	55	55	5.2	5.2	5.2	8	8	8	/	/	/
5	35	40	35	2.1	2.1	2.1	/	/	/	21	/	21
6	40	42	40	7	7	7	/	/	/	/	/	/
7	50	58	54	/	/	/	7	7	7	/	/	/
8	55	58	55	5.8	5.8	5.8	8.5	8.5	8.5	/	/	/
9	43	50	46	2	2	2	5	5	5	/	/	/
10	50	58	54	/	/	/	/	/	/	16	/	16
11	48	55	50	2	2	2	/	/	/	18	/	18
12	30	38	34	5.8	5.8	5.8	10	10	10	/	/	/
Mean	42	48.8*	44.7*	4.7	4.7	4.7	8.0	8.0	8.0	18.7		18.7
SD	10.1	9.6	10.6	3.1	3.1	3.1	1.9	1.9	1.9	2.2		2.2

[a] No LIP, UIP or PEEPi could be identified, indicated by $^{*}p < 0.001$

($p < 0.001$) was observed between DD (mean 42 ± 10.1) and VD (mean 48.8 ± 9.6) and between baseline conditions and 10 min after restored DD (mean 44.7 ± 10.6). P/V curves traced in DD and VD are represented in Figs. 2 and 3, respectively.

We did not observe any negative side effects related to the positioning. Posture changes proved relatively easy to perform.

Discussion

The main findings of this study were a significant increase in respiratory compliance and in oxygenation in 10 of 12 patients when prone.

PaO_2/FIO_2 was increased by an average of 35 mmHg in the 10 responders. This beneficial effect persisted, at least partially for 10 min, after DD was resumed. Gas exchange has been reported to be significantly improved in most of the clinical studies on the prone position [11, 25], as in this study.

Crs increased significantly by a mean value of 7 ml/cmH_2O. It was only marginally modified in the two non-responders. A clear limitation of our study is that we cannot separate the lung from the chest-wall components of Crs [26]. When investigating the first patients in this series, we attempted to measure the oesophageal pressures in both positions, dorsal and ventral. Unfortunately, this proved to be impracticable, due to major artefacts of the tracings occurring in the prone position, the difficulties in securing the balloon, the uncertainties as to its possible migration during the manoeuver, and finally the imprecision of defining a new point zero after each position change. Indeed, to obtain reliable numbers, Mutoh et al. [13] inserted plastic sheets within the pleural space in order to measure pleural pressure in anesthetized pigs. A second limitation of our study is that we did not measure the absolute values of lung volumes, but only their relative changes, expressed as parts of the V_T. Specifically, we did not measure the end-expiratory lung volume (FRC). Accordingly, the P/V curves we traced in both conditions should not be placed on the same P/V plot, since the volumes corresponding to FRC were probably not the same. In consequence, we cannot be certain that the changes in Crs we measured in VD did correspond to a modification of the mechanical characteristics of the respiratory system: the global P/V curve could have remained unaltered, and the tidal ventilation simply placed on another segment. However, even if this was the case, such modification could have beneficial effects on gas exchange. It is likely that FRC increased when patients were turned. Pappert et al. [11] have shown that recruitment of atelectatic, but otherwise healthy, lung zones may be the major mechanism responsible for the improvement in oxygenation.

With these limitations in mind, we can now speculate on our results. Despite having no information on chest-wall compliance modifications in our patients, the most probable explanation for the increase in Crs is an increase of its lung component. A critical feature in ARDS is a reduction in lung compliance [25–27], which is actually part of the definition of the syndrome. Despite it being seen initially, during the 1970s and early 1980s, as indicative of an early fibrotic process, the Milan group has convincingly demonstrated using CT that the "fibrous" lung in ARDS was in fact a "small" (aerated) lung, which they called the "baby lung" [9, 27].

In a series of brilliant papers, Gattinoni et al. [7, 8, 9, 28] showed that the reduction in lung compliance in ARDS was a function of the reduction of the remaining "aerated" parenchyma and that effective compliance was in fact normal. They also showed that the dense lung areas were atelectatic, compressed by a heavy and oedematous lung. Accordingly, the increase in compliance we measured in our prone patients could indicate the reopening of previously closed dorsal areas, once placed in a non-dependent position. However, Lamm et al. [16] have shown that ventral areas are not adversely affected by ventilation in VD. Moreover, in a recent study, Fridrich et al. [18] have shown that, in patients ventilated in VD for 20 h, PaO_2 and Crs increased in the prone position after an initial fall in Crs. As we paid careful attention to the position of our patients in VD in order not to increase abdominal pressure, we possibly have avoided the initial Crs decrease these authors noticed.

Alveolar recruitment due to the prone position has actually been visualized by Gattinoni et al. [28], using CT imaging, as the disappearance of dependent densities, when a patient is placed in a non-dependent situation. But, if alveolar recruitment plays a role in improving gas exchange of patients placed prone, it should be measured as a significant increase in FRC (measured as the aerated and communicating lung at end-expiration). Such data are lacking in humans. Wagaman et al. [4] documented an increase of FRC in neonates with respiratory failure when turned prone, which did not reach significance. Albert et al. [14], in oleic acid-induced pulmonary oedema in dogs, showed an 11% increase in FRC when animals were turned prone, by a mean of 37 ml in five out of six. Rothen et al. [29] recently showed a diverging evolution of compliance and CT densities when anesthesia-induced atelectasis was reversed by a re-expansion manoeuver. However, atelectasis commonly seen during paralysis and anaesthesia is of much less magnitude than that we documented in ARDS. It is also of interest to consider the four patients who exhibited in DD an upper inflection (UIP) of their P/V curve. When they were turned prone, UIP moved upward or disappeared (Figs. 2, 3). This upward shift of UIP may be interpreted as an augmentation of the inspiratory capacity and, accordingly, as indirect evidence of alveolar recruitment.

Gattinoni et al. [7, 9] explained the clearing of densities as merely the effect of gravity. However, Albert et al. [14, 16] showed recently that the distribution of ventilation in the prone position was not determined by the same gravitational gradient as the one documented in dorsal decubitus. In several experiments, they showed that prone positioning was able to induce a more homogeneous distribution of ventilation, due to a reduction of differences of pleural pressures from sternum to vertebra [14, 16]. Finally, they also noted that an increase in regional FRC, when present, was probably not of sufficient magnitude to explain the improvement in gas exchange documented in most clinical studies. Modifications of perfusion have also to be taken into account, as clearly shown by Pappert et al. [11], who reported a shift of blood flow away from shunt zones, thus increasing areas with normal ventilation/perfusion ratio.

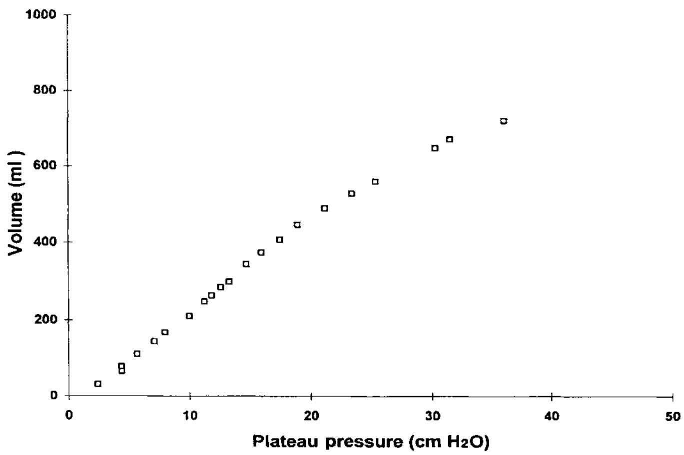

Fig. 2 Respiratory system pressure/volume curve of a representative patient (No. 3) carried out in dorsal decubitus

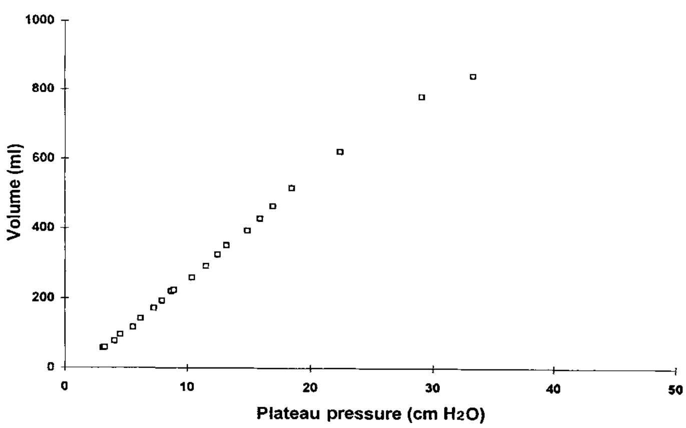

Fig. 3 Respiratory system pressure/volume curve of a representative patient (No. 3) carried out after 15 min of ventilation in ventral decubitus

Although we do not have precise criteria from which we can predict which patients would benefit most from ventilation in ventral decubitus, we suggest that a trial of the prone position should be considered for patients with hypoxaemia, decreased respiratory compliance and tendency to develop atelectasis. The VD is simple and safe, and its beneficial effects frequently allow reductions in FIO_2 and PEEP, improving oxygenation and Crs in many patients [30, 31, 32].

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