Intensive Care Med (2013) 39:1121–1127
DOI 10.1007/s00134-013-2827-x

PHYSIOLOGICAL AND TECHNICAL NOTES

J. Dellamonica
N. Lerolle
C. Sargentini
S. Hubert
G. Beduneau
F. Di Marco
A. Mercat
J. L. Diehl
J. C. M. Richard
G. Bernardin
L. Brochard

Effect of different seated positions on lung volume and oxygenation in acute respiratory distress syndrome

Received: 14 June 2012
Accepted: 7 January 2013
Published online: 24 January 2013

Electronic supplementary material
The online version of this article (doi:10.1007/s00134-013-2827-x) contains supplementary material, which is available to authorized users.

J. Dellamonica · L. Brochard
Réanimation Médicale, AP-HP, Centre Hospitalier Albert Chenevier-Henri Mondor, Créteil, France

J. Dellamonica (✉) · S. Hubert · G. Bernardin
Réanimation Médicale, CHU de Nice Hôpital L'Archet, Université de Nice Sophia Antipolis, Nice, France
e-mail: dellamonica.j@chu-nice.fr
Tel.: +33-4-92035510
Fax: +33-4-92035607

N. Lerolle · J. L. Diehl
Réanimation Médicale, AP-HP, Hôpital Européen Georges Pompidou and Faculté de Médecine, Université Paris Descartes, Sorbonne Paris Cité, Paris, France

N. Lerolle · C. Sargentini · A. Mercat
Réanimation Médicale, CHU Angers and Université D'Angers PRES UNAM, Angers, France

G. Beduneau · J. C. M. Richard
Réanimation Médicale, CHU Charles Nicolle, UPRES EA 3830, Rouen, France

F. D. Marco
Pneumologia, Ospedale San Paolo, Università degli Studi di Milano, Milan, Italy

J. C. M. Richard · L. Brochard
Soins Intensifs, Hôpitaux Universitaires de Genève, Genève, Switzerland

J. C. M. Richard · L. Brochard
University of Geneva, Geneva, Switzerland

J. Dellamonica · L. Brochard
INSERM U-955, Equipe 13, Paris EST University, Créteil, France

Abstract *Rationale:* Lung volume available for ventilation is markedly decreased during acute respiratory distress syndrome. Body positioning may contribute to increase lung volume and partial verticalization is simple to perform. This study evaluated whether verticalization had parallel effects on oxygenation and end expiratory lung volume (EELV). *Methods:* Prospective multicenter study in 40 mechanically ventilated patients with ALI/ARDS in five university hospital MICUs. We evaluated four 45-min successive trunk position epochs (supine slightly elevated at 15°; semi recumbent with trunk elevated at 45°; seated with trunk elevated at 60° and legs down at 45°; back to supine). Arterial blood gases, EELV measured using the nitrogen washin/washout, and static compliance were measured. Responders were defined by a PaO_2/FiO_2 increase >20 % between supine and seated position. Results are median [25th–75th percentiles]. *Results:* With median PEEP = 10 cmH_2O, verticalization increased lung volume but only responders (13 patients, 32 %) had a significant increase in EELV/PBW (predicted body weight) compared to baseline. This increase persisted at least partially when patients were positioned back to supine. Responders had a lower EELV/PBW supine [14 mL/kg (13–15) vs. 18 mL/kg (15–27) ($p = 0.005$)] and a lower compliance [30 mL/cmH_2O (22–38) vs. 42 (30–46) ($p = 0.01$)] than non-responders. Strain decreased with verticalization for responders. EELV/PBW increase and PaO_2/FiO_2 increase were not correlated. *Discussion:* Verticalization is easily achieved and improves oxygenation in approximately 32 % of the patients together with an increase in EELV. Nonetheless, effect of verticalization on EELV/PBW is not predictable by PaO_2/FiO_2 increase, its monitoring may be helpful for strain optimization.

Keywords Nitrogen washout/washin · End expiratory lung volume · Functional residual capacity · Acute respiratory distress syndrome · Mechanical ventilation · Positioning · Recruitment · Gas exchange

Introduction

During acute respiratory distress syndrome (ARDS), functional residual capacity (FRC) is dramatically decreased [1, 2]. Improving oxygenation and limiting maximal alveolar pressure are current goals of mechanical ventilation (MV), which include positive end expiratory pressure (PEEP) titration [3], prone positioning [4] or, less frequently, recumbent positioning [5]. Computed tomographic lung studies have observed the presence of sterno-vertebral and cephalocaudal gradients in the distribution of densities [6–8], which provide a rationale for the positioning of ARDS patients. In contrast with prone position, very few adverse events have been described with semirecumbent position [9, 10], a position frequently recommended in the ICU [11]. Preliminary encouraging results of verticalization have been shown on oxygenation [5], but very few data are available. In this study [5], patients responding to vertical positioning (defined as a 40 % PaO_2/FiO_2 increase) depicted an increase in lung volume above FRC which well correlated with a better oxygenation. However, PaO_2/FiO_2 is known as a poor indicator of recruitment during ARDS [12]. Optimizing lung volume may help to decrease the strain induced by tidal inflation and participate to protective ventilation [13]. Thanks to dedicated intensive care beds, recumbent or semi-seated position can be easily obtained for ventilated patients. Recently, the multibreath washout/washin of nitrogen [14–16] has been implemented in ICU ventilators, allowing bedside end expiratory lung volume (EELV) measurements with acceptable accuracy and reproducibility [15, 17]. We then hypothesize that lung volume monitoring at the bedside could help to define which patient may benefit of verticalization.

The aims of our study were, firstly, to evaluate the concomitant effects of verticalization on lung volume and oxygenation following a change from supine to semirecumbent, seated, and back to supine position. Secondly, to evaluate the contribution of lung volume monitoring to spot patients who may decrease their strain while verticalized.

Patients and methods

This was a multicenter study performed in five French medical intensive care units: Henri Mondor University Hospital in Créteil, Hôpital Européen Georges Pompidou in Paris, Angers University Hospital, l'Archet 1 University Hospital in Nice and Charles Nicolle University Hospital in Rouen. According to the French legislation, the institutional review board of Henri Mondor hospital approved the protocol for all centers and waived the need for informed consent considering the optimization of oxygenation using body positioning as a standard of care; information was given to the subjects or their next of kin.

Patients

Patients were enrolled if they met the standard criteria for ARDS or previously acute lung injury [18, 19]: ratio of the partial pressure of arterial oxygen to the fraction of inspired oxygen (PaO_2/FiO_2) of less than 300 mmHg, presence of bilateral pulmonary infiltrates on the chest radiograph, and no clinical evidence of left atrial hypertension. The exclusion criteria were an age under 18, pregnancy, chronic obstructive pulmonary disease according to the patient's medical history, history of pulmonary surgery, hemodynamic instability defined as increase of vasopressor (epinephrine, norepinephrine) in the last 6 h.

Patients with PaO_2/FiO_2 <100 with PEEP $\leq$5 cmH_2O at inclusion (supine 1) were considered as having severe ARDS [18].

Ventilatory strategies

All patients received volume assist control ventilation using an ICU ventilator (Engström, General Electrics, Madison, Michigan, USA). This ventilator provides bedside EELV measurements using the nitrogen washout/washin technique. Oxygenation goal (SaO_2 $\geq$90 %) was obtained by adjusting FiO_2 and PEEP which were maintained during the study, and tidal volume was set at 6 mL/kg of predicted body weight (PBW). Patients were sedated; neuromuscular blocking agents were occasionally administered only if judged necessary by the clinician in charge.

Positioning

All patients leaned on the "TotalCare" beds [Hill-Rom (Batesville, IN, USA)]. During the first epoch, patients were supine positioned at 15°–20° for routine care, this was referred as "supine 1″. For the second epoch, trunk was elevated at 45°, and this was referred to as "semirecumbent position". For the third epoch, trunk was elevated at 60° with legs down at 45°; this was referred to as "seated position". Lastly, the patient was put back in the initial supine position referred to as "supine 2".

Each position was maintained during 45–60 min; head of beds were equipped with an angle indicator to confirm the correct positioning.

Measurements

Lung volume: At the end of each 45-min period arterial blood gases were sampled, then three consecutive measures of EELV were performed using the nitrogen washout/washin technique. (See additional method ESM).

Strain: Lung strain was computed as the ratio between tidal volume and EELV [20].

Compliance: Static compliance (C_{stat}) of the respiratory system was computed as tidal volume divided by the inspiratory plateau pressure, measured during an end-inspiratory pause, minus total PEEP. Total PEEP ($PEEP_{tot}$) was measured using a 5-s expiratory pause.

Responders: PaO_2/FiO_2 increase >20 % between supine and seated position defined *responders*.

Statistical analysis

All values are given as median and (25th–75th interquartile range). Nonparametric tests were used because of the small size of the population. Friedman's nonparametric test was used to compare the values of EELV/PBW, PaO_2/FiO_2 ratio and compliance in the different epochs. Differences at the level of $p < 0.05$ were considered as significant and a Wilcoxon matched pairs signed-rank test was performed to compare the different epochs to supine 1. To correct for multiple comparisons (Bonferroni correction), we considered a p value equal to or smaller than 0.01 to indicate significance. The Mann–Witney U-test was used to compare responders and non-responders, as well as *mild* ARDS versus moderate and severe [18]. A p value <0.05 was considered as significant.

Results

Forty patients were studied, including five with mild ARDS, 30 moderate and five severe [18]. All postures were well tolerated, allowing all patients to complete the study, but four patients not receiving vasopressor infusion received saline infusion when seated to maintain blood pressure. FiO_2 was maintained stable along the study for all patients. Table 1 reports the main characteristics of the patients. Respiratory mechanics, lung volumes and blood gases during the four epochs are shown in Table E1.

Oxygenation

PaO_2/FiO_2 was significantly higher in seated than in supine position ($p < 0.003$), especially for moderate and

Table 1 Main demographic and physiological characteristics of the patients studied

	All patients	Responders $n = 13$	Non responders $n = 27$	P
Age (years)	62 (44; 74)	50 (41; 71)	62 (53; 74)	0.28
Males/females (n)	34/6	9/4	25/2	0.05
Days of ARDS at inclusion	2 (1, 4)	2 (1, 3)	3 (1, 4)	0.23
Use of vasoactive agents (n)	26 (65 %)	9 (69 %)	17 (63 %)	0.69
PBW (kg)	66 (58; 71)	66 (57; 71)	66(60; 73)	0.66
SAPS II	51 (36; 64)	50 (35; 69)	53 (37; 64)	0.98
Theoretical FRC supine (mL)	2,266 (1,860; 2,595)	2,266 (1,870; 2,540)	2,266 (1,882; 2,704)	0.90
Theoretical FRC seated (mL)	3,016 (2,747; 3,387)	3,016 (2,879; 3,325)	3,016 (2,696; 3,510)	0.81
FiO2 (%)	60 (50; 80)	60 (52; 70)	60 (57; 80)	0.5
PEEP (cmH_2O)	10 (8, 11)	9 (6, 10)	10 (8, 12)	0.09
Ventilatory parameters in supine 1				
EELV/PBW (mL/kg)	16 (13, 22)	14 (13, 15)	18 (15, 27)	0.005
Strain	0.38 (0.27; 0.45)	0.42 (0.40; 0.47)	0.34 (0.22;0.40)	0.006
Compliance (mL/cmH_2O)	36 (27; 45)	30 (22; 38)	42 (30; 46)	0.01
PaO_2 (mmHg)	84 (78; 104)	83 (77; 90)	91 (80; 109)	0.07
PaO_2/FiO_2 (mmHg)	131 (116; 180)	130 (110; 151)	132 (117; 185)	0.41
$PaCO_2$ (mmHg)	39 (35; 47)	37 (34; 39)	44 (37; 48)	0.16
SaO2 (%)	96.5 (96.0; 97.0)	97.0 (95.0; 97.0)	96.0 (96.0; 97.0)	0.94
Ventilatory parameters in seated				
EELV/PBW (mL/kg)	19 (15, 25)	16 (14, 20)	23 (16, 27)	0.08
Strain	0.31 (0.24; 0.40)	0.38 (0.30; 0.43)	0.27 (0.22;0.37)	0.08
Compliance (mL/cmH_2O)	31 (24; 38)	29 (22, 32)	32 (24; 41)	0.15
PaO_2 (mmHg)	102 (87; 110)	108 (105; 127)	90 (83; 107)	0.006
PaO_2/FiO_2 (mmHg)	160 (122; 210)	210 (175; 222)	136 (111; 178)	0.007
$PaCO_2$ (mmHg)	40 (35; 48)	36 (34; 42)	43 (35; 49)	0.18
SaO2 (%)	98.0 (96.7; 98.0)	98.0 (98.0; 99.0)	97.0 (96.0; 98.0)	0.004

Theoretical FRC seated and supine were calculated using the formulas proposed by Ibanez and Raurich [32]
Strain was calculated as Vt/EELV [20]
P responders vs non responders
EELV end expiratory lung volume, *PBW* predicted body weight

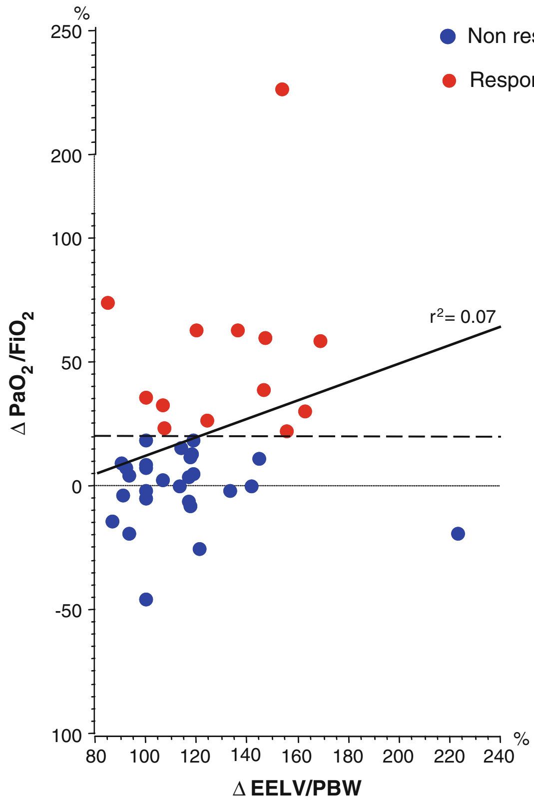

Fig. 1 Representation of PaO_2/FiO_2 increase between supine and seated position against lung volume increase. *Dotted line* represents $\Delta PaO_2/FiO_2 = 20$ %, the cutoff of for responders. Straight line represents regression. $r^2 = 0.07$, $p =$ ns

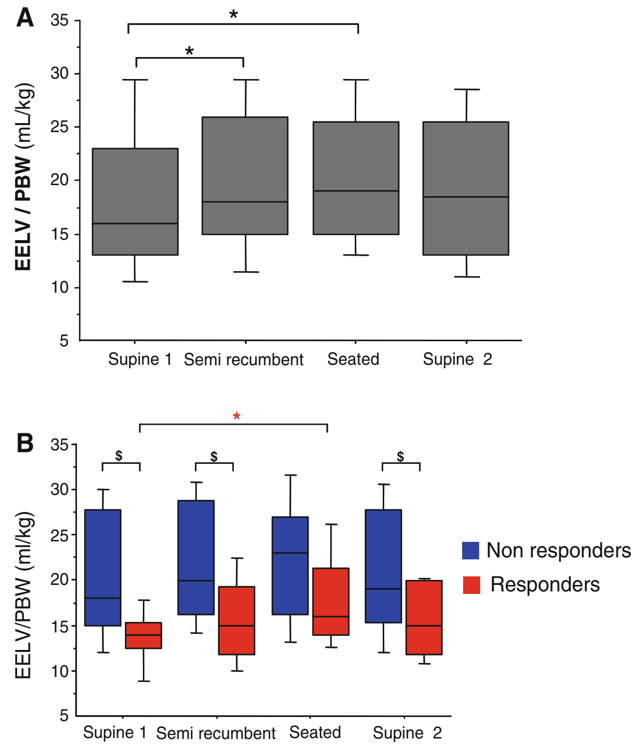

Fig. 2 EELV/PBW measured using the nitrogen washin/washout technique at the four epochs studied. Panel A represents the whole population. Panel B: *blue boxes* represents non-responders and *red boxes* responders. $^{\$}p < 0.05$ responders versus non-responders. Friedman's non-parametric test showed $p < 0.05$ for all patients and responders allowing Wilcoxon paired test. $^{*}p < 0.005$ versus supine 1 (Bonferroni correction)

severe ARDS (Fig. E1). PaO_2/FiO_2 increased by more than 20 % in 13 responders [39 % (30–63)]. In responders, PaO_2 increased from 83 mmHg (77; 90) to 108 (105; 127) ($p = 0.001$) while it did not change in non-responders. Figure 1 represents the individual changes of PaO_2/FiO_2 between supine and seated positions against the lung volume changes. No correlation was found.

Lung volume and compliance

Values of EELV/PBW measured in the four successive positions for the whole population and for responders are presented in Fig. 2. When patients were verticalized, EELV expressed in mL/kg of PBW increased from 16 (13–22) to 19 mL/kg (15–25) ($p < 0.05$). Only responders had a significant EELV/PBW increase compared to baseline. Responders had significantly lower EELV/PBW values than non-responders during all epochs except seated.

Strain was significantly higher supine 0.38 (0.27; 0.45) versus 0.31 [0.24; 0.40] ($p = 0.0006$) and decreased significantly only for responders 0.42 (0.40; 0.47) versus 0.38 (0.30; 0.43) ($p = 0.007$).

Compliance decreased with verticalization in nonresponders [42 mL/cmH_2O (30–46) vs. 32 mL/cmH_2O (24–41) supine and seated, respectively ($p < 0.002$)], while it was lower at baseline but remained stable in responders: 30 mL/cmH_2O (22–38) versus 29 mL/cmH_2O (22–32) (Fig. 3).

Discussion

In this series of ARDS patients ventilated supine, verticalization (seated position) resulted in a rapid and significant concomitant increase in lung volume and oxygenation. Interestingly, patients responding to verticalization exhibited lower EELV/PBW at baseline and higher increase in EELV/PBW compare to non-responders.

Seated position

We used the seated position provided by dedicated intensive care beds. One previous study used a comparable seated position using conventional beds [5]. Here,

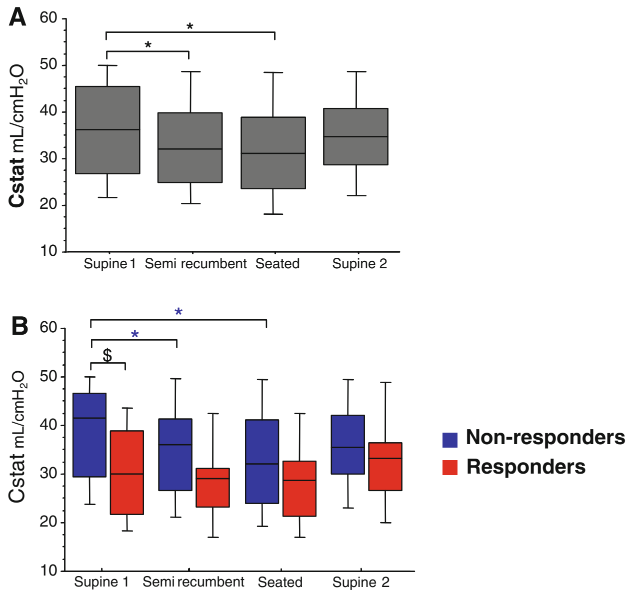

Fig. 3 Static compliance calculated at the four epochs studied. Panel A represents the whole population. Panel B: *blue boxes* represents non-responders and *red boxes* responders. $ $p < 0.05$ responders vs non-responders. Friedman's nonparametric test showed $p < 0.05$ for all patients and non-responders allowing Wilcoxon paired test: * $p < 0.001$ versus supine 1 (Bonferroni correction). * $p < 0.002$ vs supine 1 (Bonferroni correction)

the position was simply achieved by repositioning the bed electronically and was then controlled with the angle measurer included at the bed's head [21–23]. A Position was thus easily obtained and maintained. Benedik et al. [24] described in spontaneously breathing obese patients that the change in EELV was only observed in a seated position but not in semirecumbent. In the present study, both semirecumbent and seated position resulted in higher EELV. This discrepancy might be due to the *Fowler* position (45° vs. 30°) they studied [24] which can generate an extra abdominal pressure potentially participating to respiratory system compliance decrease. The semirecumbent position (45°) can generate an extra abdominal pressure close to 9 mmHg, which may contribute to a decrease in respiratory system compliance [25]. The seated position with legs down we used has not yet been precisely tested in terms of abdominal pressure.

Oxygenation and lung volume

Effect of verticalization on PaO_2/FiO_2 ratio for responders was quick and started from the semi recumbent position epoch. Completion of this study on short periods, allowed to point out only fast responders. Among the mechanisms that can explain oxygenation increase, recruitment of previously nonaerated alveoli is supported by the stability of static compliance while the EELV/PBW increased. The compliance decrease of nonresponders has already been described in surgical population [26]. Richard et al. showed in a medical ARDS population of 16 patients comparable to ours, a bimodal distribution of oxygenation and EELV increase. In their study, responders had a PaO_2/FiO_2 increase above 40 % associated with a PEEP-volume (measured with prolonged exhalation to elastic equilibrium) increase associated with chord-compliance decrease. Past studies have yielded controversial results on the effect of position on oxygenation after surgical procedures [26]. Recent meta-analysis on prone position [27] suggested a mortality reduction mostly for the most hypoxemic patients (PaO_2/FiO_2 below 140 mmHg) at the cost of increased complications (pressure ulcer, endotracheal tube dislodgment or obstruction). Already recommended in the bundles for prevention of ventilator-associated pneumonia [11], the semirecumbent position can be routinely achieved during ventilation and could be proposed as an alternative to prone position. Gas exchange are not sufficiently precise to assess recruitment [12] or lung volume increase due to positioning (Fig. 1). Lung volume is a component of ventilatory-induced strain (Vt/EELV) [20, 28, 29], if its implication in ventilatory-induced lung injury is relevant in line with recent biological [20], human [28] and animal findings [29], we believe its bedside measurements might be helpful especially to discriminate which patient may benefit of positioning. The strain decrease found (specially for responders) could be an interesting tool, sharper than oxygenation, to indicate positioning but further studies are needed to test this hypothesis.

This study has limitations. Firstly, the sequence of positions has not been randomized. This prevented us to distinguish precisely the specific effect of the seated position (with legs down and higher trunk verticalization angle) from a time dependent effect of the verticalization [5]. EELV/PBW of responders, however, already increased in the semirecumbent epoch suggesting an immediate effect while it remained stable for non-responders. Although, a delayed effect on oxygenation and lung volume can not be eliminated [30]. Secondly, some variability of the nitrogen technique may exist with PEEP, although it has been shown to be acceptable [15]. Last, we conventionally chose PaO_2/FiO_2 increase to define responders albeit oxygenation variations are multifactorial especially during ARDS and mechanical ventilation [31]. Nonetheless FiO_2 was stable all along the study. Physiological data, including abdominal pressure, esophageal pressure, cardiac output for shunt estimation in future studies would certainly improve our understanding of PaO_2/FiO_2 improvement during verticalization.

Patient positioning, especially the seated position, is a relatively simple way to improve oxygenation, notably for moderate and severe ARDS. The tools used in our study (specific beds and nitrogen washin/washout) are now routinely available outside of the research field, offering the prospect of a simple and rational use in ARDS.

Acknowledgments General Electric provided the “Engström” ventilators for the study and a research grant, but had no access to the data, the analysis and the interpretation. Hill-Rom provided the “TotalCare“beds for the study, but had no access to the data, the analysis and the interpretation.

References

1. Chiumello D, Carlesso E, Cadringher P, Caironi P, Valenza F, Polli F, Tallarini F, Cozzi P, Cressoni M, Colombo A, Marini JJ, Gattinoni L (2008) Lung stress and strain during mechanical ventilation for acute respiratory distress syndrome. Am J Respir Crit Care Med 178:346–355
2. Dellamonica J, Lerolle N, Sargentini C, Beduneau G, Di Marco F, Mercat A, Richard JC, Diehl JL, Mancebo J, Rouby JJ, Lu Q, Bernardin G, Brochard L (2011) PEEP-induced changes in lung volume in acute respiratory distress syndrome. Two methods to estimate alveolar recruitment. Intensive Care Med 37:1595–1604
3. Brochard L, Roudot-Thoraval F, Roupie E, Delclaux C, Chastre J, Fernandez-Mondejar E, Clementi E, Mancebo J, Factor P, Matamis D, Ranieri M, Blanch L, Rodi G, Mentec H, Dreyfuss D, Ferrer M, Brun-Buisson C, Tobin M, Lemaire F (1998) Tidal volume reduction for prevention of ventilator-induced lung injury in acute respiratory distress syndrome. The multicenter trail group on tidal volume reduction in ARDS. Am J Respir Crit Care Med 158:1831–1838
4. Mancebo J, Fernandez R, Blanch L, Rialp G, Gordo F, Ferrer M, Rodriguez F, Garro P, Ricart P, Vallverdu I, Gich I, Castano J, Saura P, Dominguez G, Bonet A, Albert RK (2006) A multicenter trial of prolonged prone ventilation in severe acute respiratory distress syndrome. Am J Respir Crit Care Med 173:1233–1239
5. Richard JC, Maggiore SM, Mancebo J, Lemaire F, Jonson B, Brochard L (2006) Effects of vertical positioning on gas exchange and lung volumes in acute respiratory distress syndrome. Intensive Care Med 32:1623–1626
6. Malbouisson LM, Busch CJ, Puybasset L, Lu Q, Cluzel P, Rouby JJ (2000) Role of the heart in the loss of aeration characterizing lower lobes in acute respiratory distress syndrome. CT scan ARDS study group. Am J Respir Crit Care Med 161:2005–2012
7. Malbouisson LM, Muller JC, Constantin JM, Lu Q, Puybasset L, Rouby JJ (2001) Computed tomography assessment of positive end-expiratory pressure-induced alveolar recruitment in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 163:1444–1450
8. Rouby JJ, Constantin JM, De Roberto A, Girardi C, Zhang M, Lu Q (2004) Mechanical ventilation in patients with acute respiratory distress syndrome. Anesthesiology 101:228–234
9. Girou E, Buu-Hoi A, Stephan F, Novara A, Gutmann L, Safar M, Fagon JY (2004) Airway colonisation in long-term mechanically ventilated patients. Effect of semi-recumbent position and continuous subglottic suctioning. Intensive Care Med 30:225–233
10. Orozco-Levi M, Torres A, Ferrer M, Piera C, el-Ebiary M, de la Bellacasa JP, Rodriguez-Roisin R (1995) Semirecumbent position protects from pulmonary aspiration but not completely from gastroesophageal reflux in mechanically ventilated patients. Am J Respir Crit Care Med 152:1387–1390
11. Bouadma L, Deslandes E, Lolom I, Le Corre B, Mourvillier B, Regnier B, Porcher R, Wolff M, Lucet JC (2010) Long-term impact of a multifaceted prevention program on ventilator-associated pneumonia in a medical intensive care unit. Clin Infect Dis 51:1115–1122
12. Cressoni M, Caironi P, Polli F, Carlesso E, Chiumello D, Cadringher P, Quintel M, Ranieri VM, Bugedo G, Gattinoni L (2008) Anatomical and functional intrapulmonary shunt in acute respiratory distress syndrome. Crit Care Med 36:669–675
13. Caironi P, Cressoni M, Chiumello D, Ranieri M, Quintel M, Russo SG, Cornejo R, Bugedo G, Carlesso E, Russo R, Caspani L, Gattinoni L (2010) Lung opening and closing during ventilation of acute respiratory distress syndrome. Am J Respir Crit Care Med 181:578–586
14. Bikker IG, van Bommel J, Reis Miranda D, Bakker J, Gommers D (2008) End-expiratory lung volume during mechanical ventilation: a comparison with reference values and the effect of positive end-expiratory pressure in intensive care unit patients with different lung conditions. Crit Care 12:R145
15. Dellamonica J, Lerolle N, Sargentini C, Beduneau G, Di Marco F, Mercat A, Richard JC, Diehl JL, Mancebo J, Rouby JJ, Lu Q, Bernardin G, Brochard L (2011) Accuracy and precision of end-expiratory lung-volume measurements by automated nitrogen washout/washin technique in patients with acute respiratory distress syndrome. Crit Care 15:R294
16. Olegard C, Sondergaard S, Houltz E, Lundin S, Stenqvist O (2005) Estimation of functional residual capacity at the bedside using standard monitoring equipment: a modified nitrogen washout/washin technique requiring a small change of the inspired oxygen fraction. Anesth Analg 101:206–212 table of contents
17. Chiumello D, Cressoni M, Chierichetti M, Tallarini F, Botticelli M, Berto V, Mietto C, Gattinoni L (2008) Nitrogen washout/washin, helium dilution and computed tomography in the assessment of end expiratory lung volume. Crit Care 12:R150
18. (2012) Acute respiratory distress syndrome. The Berlin definition. The ARDS definition task force. JAMA 307. doi:10.1001/jama.2012.5669
19. Artigas A, Bernard GR, Carlet J, Dreyfuss D, Gattinoni L, Hudson L, Lamy M, Marini JJ, Matthay MA, Pinsky MR, Spragg R, Suter PM (1998) The american-european consensus conference on ARDS, part 2. Ventilatory, pharmacologic, supportive therapy, study design strategies and issues related to recovery and remodeling. Intensive Care Med 24:378–398

20. Gonzalez-Lopez A, Garcia-Prieto E, Batalla-Solis E, Amado-Rodriguez L, Avello N, Blanch L, Albaiceta GM (2012) Lung strain and biological response in mechanically ventilated patients. Intensive Care Med 38:240–247
21. McMullin JP, Cook DJ, Meade MO, Weaver BR, Letelier LM, Kahmamoui K, Higgins DA, Guyatt GH (2002) Clinical estimation of trunk position among mechanically ventilated patients. Intensive Care Med 28:304–309
22. van Nieuwenhoven CA, Vandenbroucke-Grauls C, van Tiel FH, Joore HC, van Schijndel RJ, van der Tweel I, Ramsay G, Bonten MJ (2006) Feasibility and effects of the semi-recumbent position to prevent ventilator-associated pneumonia: a randomized study. Crit Care Med 34:396–402
23. Deye N, Lellouche F, Maggiore SM, Taille S, Demoule A, L'Her E, Galia F, Harf A, Mancebo J, Brochard L (2013) The semi-seated position slightly reduces the effort to breathe during difficult weaning. Intensive Care Med 39:85–92
24. Benedik PS, Baun MM, Keus L, Jimenez C, Morice R, Bidani A, Meininger JC (2009) Effects of body position on resting lung volume in overweight and mildly to moderately obese subjects. Respir Care 54:334–339
25. De Keulenaer BL, De Waele JJ, Powell B, Malbrain ML (2009) What is normal intra-abdominal pressure and how is it affected by positioning, body mass and positive end-expiratory pressure? Intensive Care Med 35:969–976
26. Bittner E, Chendrasekhar A, Pillai S, Timberlake GA (1996) Changes in oxygenation and compliance as related to body position in acute lung injury. Am Surg 62:1038–1041
27. Sud S, Friedrich JO, Taccone P, Polli F, Adhikari NK, Latini R, Pesenti A, Guerin C, Mancebo J, Curley MA, Fernandez R, Chan MC, Beuret P, Voggenreiter G, Sud M, Tognoni G, Gattinoni L (2010) Prone ventilation reduces mortality in patients with acute respiratory failure and severe hypoxemia: systematic review and meta-analysis. Intensive Care Med 36:585–599
28. Bellani G, Guerra L, Musch G, Zanella A, Patroniti N, Mauri T, Messa C, Pesenti A (2011) Lung regional metabolic activity and gas volume changes induced by tidal ventilation in patients with acute lung injury. Am J Respir Crit Care Med 183:1193–1199
29. Protti A, Cressoni M, Santini A, Langer T, Mietto C, Febres D, Chierichetti M, Coppola S, Conte G, Gatti S, Leopardi O, Masson S, Lombardi L, Lazzerini M, Rampoldi E, Cadringher P, Gattinoni L (2011) Lung stress and strain during mechanical ventilation: any safe threshold? Am J Respir Crit Care Med 183:1354–1362
30. Papazian L, Paladini MH, Bregeon F, Huiart L, Thirion X, Saux P, Jammes Y, Auffray JP (2001) Is a short trial of prone positioning sufficient to predict the improvement in oxygenation in patients with acute respiratory distress syndrome? Intensive Care Med 27:1044–1049
31. Mekontso Dessap A, Boissier F, Leon R, Carreira S, Campo FR, Lemaire F, Brochard L (2010) Prevalence and prognosis of shunting across patent foramen ovale during acute respiratory distress syndrome. Crit Care Med 38:1786–1792
32. Ibanez J, Raurich JM (1982) Normal values of functional residual capacity in the sitting and supine positions. Intensive Care Med 8:173–177