Intensive Care Med (2023) 49:991–995
https://doi.org/10.1007/s00134-023-07071-2

WHAT'S NEW IN INTENSIVE CARE

Driving pressure: applying the concept at the bedside

Oriol Roca[1,2*], Ewan C. Goligher[3,4,5] and Marcelo B. P. Amato[6]

Driving pressure (ΔP) is defined as the distending pressure above the applied positive end-expiratory pressure (PEEP) required to generate tidal volume (Vt). It is generated by the elastic forces developed during tidal inflation. Driving pressure is therefore affected by the magnitude of tidal inflation and the elastances of the lung and chest wall, and it can be expressed as the ratio between Vt and the compliance of the respiratory system (Crs) ($\Delta P = \text{Vt}/\text{Crs}$) [1]. The elastance (and its inverse, compliance) of the lung reflects the functional size of the lung. Because the specific elastance of the baby lung is unaffected by acute respiratory distress syndrome (ARDS) (i.e., unaffected lung regions maintain their normal mechanical properties), increases in overall elastance of the lung reflects lung volume loss: elastance increases as the number of lung units (acini) available to participate in tidal ventilation decreases. The relationship between elastance and lung volume was demonstrated in a classic computed tomography (CT) scan study by Gattinoni et al. [2]. In intubated patients, ΔP can be easily calculated in quasi-static conditions as plateau pressure (Pplat) minus total PEEP [3]. However, even though this measurement is completely reliable in completely passive patients, it may lead to errors due to the effect of respiratory muscles in patients on assisted ventilation.

Why is driving pressure clinically relevant?

The importance of ΔP was first described in a post hoc analysis of various randomized trials that assessed the use of low Vt ventilation or higher PEEP in patients with ARDS [1]. The results of this analysis showed that during controlled ventilation, higher levels of ΔP were independently associated with mortality, regardless of the level of PEEP, Vt, or Pplat. Additionally, ΔP was shown to mediate the association between Vt and mortality or between PEEP and mortality. Similarly, higher ΔP has also been associated with ARDS development in patients with no clinical evidence of lung injury at the time of intubation [4].

A recent secondary analysis of five randomized trials showed that the mortality benefit of lowering Vt in patients with ARDS was only observed in those patients with high elastance of the respiratory system, suggesting that lung stress, rather than lung inflation per se, was a determinant of ventilator-induced lung injury (VILI) [5]. When ΔP was low (< 15 cmH_2O), there was no difference in mortality between high Vt (12 mL/kg) and low Vt (6 mL/kg). Thus, setting Vt according to ΔP may allow for a further reduction of Vt when it generates excessive lung stress. Similarly, allowing higher Vt in patients with low elastance can facilitate spontaneous breathing and minimize the need for sedation [5]. However, as yet, there are no clinical trials focusing on clinical outcomes to definitively assess the effect of titrating Vt to a target ΔP.

The frequency of tidal inflation may also contribute to VILI. However, recent data have shown that the impact of decreasing ΔP on reducing mortality was four times stronger compared with the effect of decreasing respiratory rate (RR) [6]. In other words, reducing ΔP by 1 cmH_2O is likely to be associated with benefit unless RR needs to be increased by 4 or more breaths/min because of respiratory acidosis. In this case, in isocapnic conditions, the overall effect would be null. Thus, the deleterious effects of hypercapnia, such as the increased risk of right ventricular failure, should be balanced with improving minute ventilation by increasing RR.

*Correspondence: oroca@tauli.cat
[1] Servei de Medicina Intensiva, Parc Taulí Hospital Universitari, Institut de Recerca Part Taulí–I3PT, Parc del Taulí 1, 08028 Sabadell, Spain
Full author information is available at the end of the article

Springer

How do I measure driving pressure at the bedside?

During controlled mechanical ventilation, in the absence of asynchronies, ΔP can be easily calculated in quasi-static conditions by doing a short inspiratory pause of 0.2–0.3 s to measure Pplat. In ARDS patients, a safe ΔP is likely < 15 cmH_2O [1].

In mechanically ventilated spontaneously breathing patients, the same measurement can be performed by administering short-acting sedatives (subtle signals of reverse triggering have to be scrutinized and avoided). If inspiratory effort persists, a bolus of short-acting myorelaxant could be added. Then, Pplat and total PEEP could be measured, and Crs can be calculated. Once this measurement is performed, as we know Vt breath by breath, one can rapidly know how much ΔP the patient does at every inspiration ($\Delta P = Vt/Crs$) (Fig. 1a and b).

Alternately, if we want to avoid sedatives, we can reasonably estimate ΔP by some simple and practical maneuvers recently described. The first one requires an end-inspiratory occlusion during spontaneous breathing (mainly validated for pressure support ventilation), in those patients who achieve complete relaxation of the respiratory muscles. In these patients, a stable airway pressure measurement will be obtained. Driving pressure obtained using an end-inspiratory hold during PSV was correlated with mortality in one study [7] and can be calculated by simply subtracting Pplat minus PEEP (Fig. 1c), although the Pplat can be challenging to measure in patients with vigorous respiratory muscle effort and active expiratory efforts [8] (Fig. 1d). This maneuver requires visual inspection of airway tracings. Unstable Pplat tracings should be discarded [9], but they are not that common.

A third method can be used to estimate the "dynamic ΔP", which includes the resistive forces generated during inspiration, leading to a slight overestimation of ΔP, being thus called dynamic ΔP. In this case, we perform an expiratory pause and let the patient breathe. The swing in airway pressure generated by the patient's inspiratory effort when the airway is occluded (ΔPocc) can be used to estimate the component of dynamic ΔP generated by the inspiratory muscles (Pmusc) during non-occlude breaths: $P\text{musc} = -0.75 \times \Delta P\text{occ}$. Pocc is multiplied by 0.75 to estimate Pmusc to account for differences in the forces generated during quasi-static versus quasi-isotonic muscle contractions (a function of the force–velocity relationship of the diaphragm). This correction factor was empirically derived and validated in the original study describing the use of Pocc [10]. The ventilator component of ΔP is approximated by the set pressure support level above PEEP (or by peak pressure above PEEP) (Fig. 1e):

$$\Delta P_{\text{dyn}} = \text{PSVset} - (0.75 * \Delta P\text{occ})$$

Considering the resistive component that is intrinsically added to this calculation, dynamic ΔP values

(See figure on next page.)

Fig. 1 The four methods to estimate driving pressures (ΔP) during spontaneous breaths: Representative tracings of proximal and esophageal pressures obtained from a single patient at different moments in time. The patient was ventilated under pressure support ventilation and subsequently submitted to muscle paralysis with succinylcholine (**A**). The patient was monitored with EIT and, during paralysis, we ensured that minute ventilation was the same as during pressure support ventilation. We also ensured that EELZ (representing the EELV) did not change significantly, in order to operate at the same global lung volume, with similar mechanics of the respiratory system. After performing a short inspiratory and expiratory pause (0.5 s) we measured quasi-static compliance and driving pressure (22.5 mL/cmH_2O and 13.3 cmH_2O, respectively). In panel **B**, the patient was ventilated under pressure support ventilation set at 5 cmH_2O, when we measured VT = 300 mL. ΔP was then calculated as Vt/Crs = 300/22.5 = 13.3 cmH_2O. Note that we ensured that VT at panel **A** was the same as the VT in panel **B**. In panel **C**, the patient was also ventilated under pressure support ventilation set at 5 cmH_2O, and then we performed an inspiratory pause. Note that airway pressures increase substantially during the pause, disclosing the hidden effort the patient was performing during the inspiratory phase preceding the pause (now transformed in elastic recoil pressures). Note that negative swings in esophageal pressure were regular across the cycles, with little interference of the maneuver. ΔP is then calculated as Pplat – PEEP = 13 cmH_2O (showing negligible underestimation). In panel **D**, we can observe the effect of expiratory muscles activity during the inspiratory pause generating a persistent increase in the airway pressure during the inspiratory pause. The expiratory muscles were activated every breath (we could recognize this by comparing esophageal pressures during paralysis). Moreover, there was a clear reaction to the maneuver with a stronger contraction of the expiratory muscles. In panel **E**, the patient was still ventilated under pressure support ventilation set at 5 cmH_2O, and then we performed an expiratory pause. Note that airway pressures drop substantially during the pause, with similar magnitude (called Pocc, = – 15.7 cmH_2O) as the esophageal pressure drop, disclosing the intended effort to be performed in the next breath. Note that the negative swing in esophageal pressure is slightly higher during the occluded breath, when compared to previous ones. This is accounted for by the K factor (0.75) used in this calculation: $\Delta P = \text{PS} - (0.75 \times \text{Poccl}) = 5 - (0.75 \times -15.7) = 16.8$ cmH_2O. This method represents the dynamic ΔP, overestimating the previous one by 3.8 cmH_2O. A great part of this overestimation is caused by the resistive forces that are not subtracted from airway/muscle pressures when using this method. In panel **F**, we can observe Vt and electrical impedance tomography plethysmograph before and after paralysis (black dotted line). As we can observe, before paralysis, the amount of ΔP and Vt generated is the sum of the relaxation of the expiratory muscles, the ventilator and the inspiratory effort. After paralysis, the ΔP and Vt generated depend only on the ventilator as the muscle activity is completely abolished. In panel **G**, we used the same tracings and expiratory pause as in panel **E**. But we used it to calculate dynamic transpulmonary ΔP (ΔP_L). In this case, the coefficient 0.66 intrinsically subtract the chest wall component involved in all previous calculations. Still, it overestimates methods **B** and **C** because it was not meant to subtract resistive forces as in method **D**. We can assume that it represents the peak of dynamic lung stress during spontaneous breaths. Studies validating the safe levels for this variable are under way

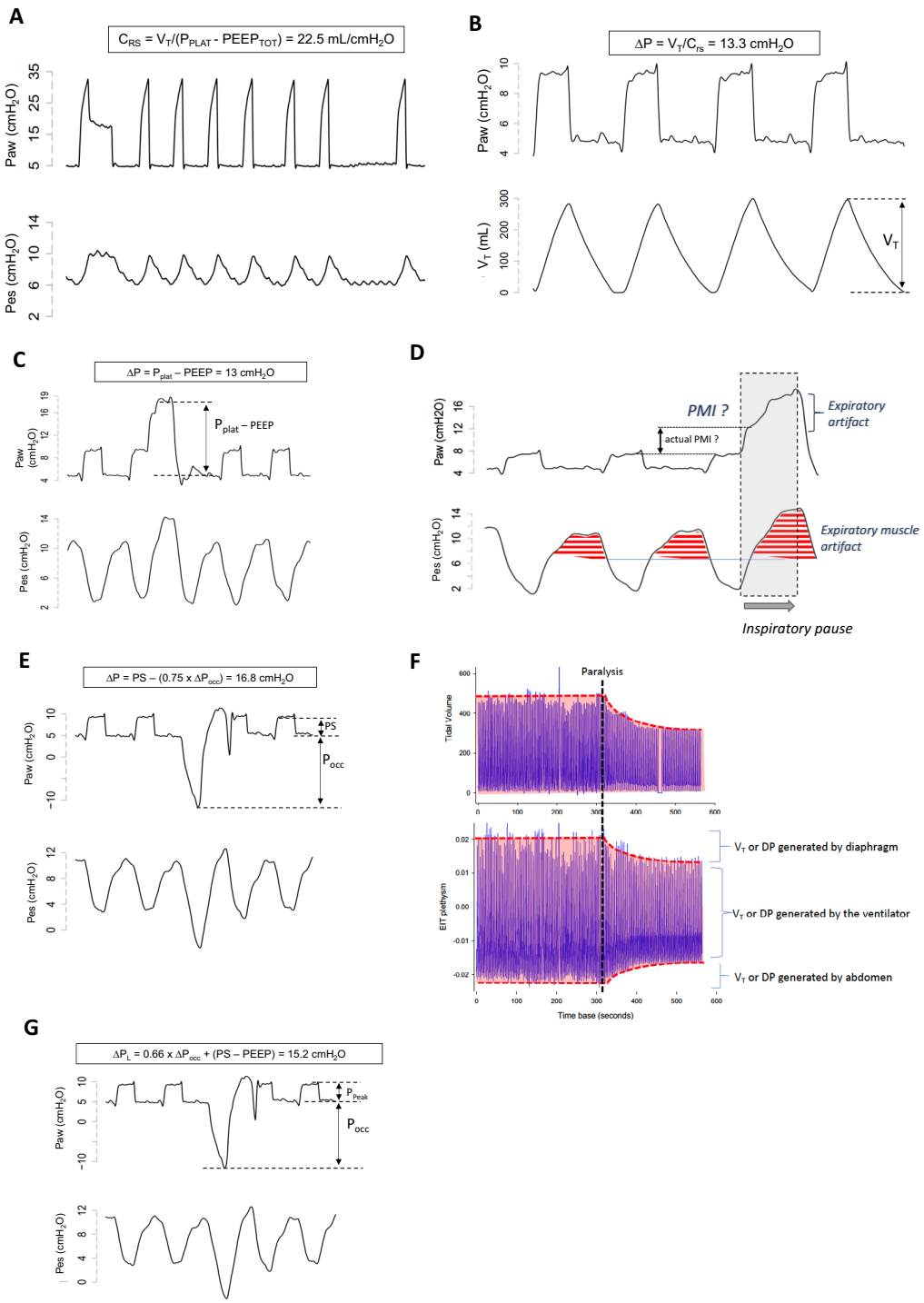

Fig. 1 (See legend on previous page.)

calculated by this method should call attention whenever exceeding by 3–5 cmH$_2$O the estimates provided by the second method (inspiratory pause). In this case, expiratory muscle activity can be suspected and the first method can be used to obtain more reliable measurement of ΔP. Moreover, as the relaxation of the expiratory muscles causes an increase in Vt (corresponding to the volume driven by restoration of transpulmonary pressure

at end exhalation), this expiratory activity generates a true increase in ΔP (Fig. 1f).

Finally, the Pocc measurement has also been validated in multiple studies [10, 11] to estimate the dynamic transpulmonary driving pressure (ΔP_{Ldyn}) as a surrogate of lung stress, i.e., the component of ΔP spent to distend the lung only, and also including the resistive forces to move gasses through airways and endotracheal (ET) tube (Fig. 1g):

$$\Delta P_{\mathrm{Ldyn}} = (P\mathrm{peak} - \mathrm{PEEP}) - (0.66 * \Delta P\mathrm{occ})$$

Pocc-based methods may overestimate static lung-distending pressure because of the resistive forces required to move gasses through airways and ET tube. However, it has been previously suggested that the dynamic pressure (rather than the static) may be more relevant during spontaneous breathing under assisted ventilation because of the regional variation in lung-distending pressure under dynamic conditions, as evident from the pendelluft phenomenon [12]. The precise upper limit of acceptable values remains to be determined. However, recent trials have targeted values of ΔP_{Ldyn} is between 15 and 20 $\mathrm{cmH_2O}$ [11, 13], but more studies are required to confirm this threshold. When using any of these methods in daily clinical practice, if total PEEP cannot be measured, set PEEP is used to calculate ΔP.

How to control driving pressure in spontaneously breathing patients?

Spontaneously breathing patients with an appropriate respiratory drive respond to changes in pressure support, which means that an increase in pressure support will be associated with a substantial decrease in inspiratory effort, leading to better control of ΔP. However, controlling ΔP in patients with an inappropriate respiratory drive is more challenging as they do not respond to changes in pressure support, keeping the same inspiratory effort regardless the increase in pressure support and, therefore, generating higher ΔP. Some of these patients may respond to an increase in PEEP level by inhibiting respiratory drive due to the Hering-Breuer reflex [13, 14]. Promoting slight alkalosis and increasing $\mathrm{FiO_2}$ to achieve normal $\mathrm{PaO_2}$ levels may be useful. Alternatively, a simulation analysis performed in a cohort of patients with ARDS showed that extracorporeal carbon dioxide removal may also help [13] in those patients with higher alveolar dead space fraction or lower Crs and patients treated with higher $\mathrm{CO_2}$ extraction [15]. However, this hypothesis should be tested in future trials. Finally, if none of these measures works, one may have to give sedatives to the patient. In this scenario, short-acting sedatives may be the preferred ones. Finally, if ΔP cannot be limited using these strategies, partial neuromuscular blockade may also facilitate lung-protective ventilation in sedated patients, decreasing ΔP_L and work of breathing [13, 16].

Limitations

In terms of assessing the risk of VILI, from a physiological perspective, we should measure ΔP_L. However, we measure ΔP more often because it is easier at the bedside. Moreover, the results of a recent large observational study that included patients with ARDS showed that ΔP_L did not improve 60-day mortality prediction compared with ΔP [17]. This result suggests that chest wall driving pressure may also be associated with disease severity and outcome. From a practical point of view, assuming that the compliance of the chest wall does not change substantially during intensive care unit admission, differences in ΔP may reflect changes in $\Delta \mathrm{P_L}$.

In conclusion, ΔP may be the most robust single variable associated with mortality in patients with ARDS as it considers both the severity of the disease and the ventilator settings. In the era of personalized medicine, one single Vt size does not fit all. Driving pressure may help to titrate Vt according to the size of the lungs and potentially improve outcomes. However, this approach needs to be tested in specifically designed randomized trials.

Author details

[1] Servei de Medicina Intensiva, Parc Taulí Hospital Universitari, Institut de Recerca Part Taulí–I3PT, Parc del Taulí 1, 08028 Sabadell, Spain. [2] Departament de Medicina, Universitat Autònoma de Barcelona, Bellaterra, Spain. [3] Interdepartmental Division of Critical Care Medicine, University of Toronto, Toronto, ON, Canada. [4] Department of Medicine, University Health Network Toronto, Toronto, ON, Canada. [5] Toronto General Hospital Research Institute Toronto, Toronto, ON, Canada. [6] Laboratório de Pneumologia LIM-09, Disciplina de Pneumologia, Heart Institute (Incor), Hospital das Clínicas da Faculdade de Medicina da Universidade de São Paulo, São Paulo, Brazil.

Data availability

No data has been used to write this article.

Declarations

Conflicts of interest

OR reports receiving a research grant from Hamilton Medical AG and Fihser&Paykel Healthcare Ltd, speaker fees from Hamilton Medical AG, Fisher&Paykel Healthcare Ltd, Aerogen Ltd and Ambu, and non-financial research support from Timpel; all outside the submitted work. EG reports research funding from the Canadian Institute of Health Research and the National Sanitarium Association for research related to the submitted work. He also reports receiving personal fees from Getinge, Vyaire, BioAge, LungPacer, and Zoll for work unrelated to the submitted work. MBPA reports that, in the last five years, his laboratory has received research grants to investigate mechanical ventilation from Covidien/Medtronics, Orange Med/Nihon Koden, and MagnaMed S.A. He also received research grants from Timpel S.A, to investigate Electrical Impedance Tomography. MBPA is a minority shareholder in Timpel.

Received: 4 February 2023 Accepted: 9 April 2023
Published: 16 May 2023

References

1. Amato MB, Meade MO, Slutsky AS, Brochard L, Costa EL, Schoenfeld DA, Stewart TE, Briel M, Talmor D, Mercat A, Richard JC, Carvalho CR, Brower RG (2015) Driving pressure and survival in the acute respiratory distress syndrome. N Engl J Med 372:747–755
2. Gattinoni L, Pesenti A, Avalli L, Rossi F, Bombino M (1987) Pressure-volume curve of total respiratory system in acute respiratory failure. Computed tomographic scan study. Am Rev Respir Dis 136:730–736
3. Chen L, Jonkman A, Pereira SM, Lu C, Brochard L (2021) Driving pressure monitoring during acute respiratory failure in 2020. Curr Opin Crit Care 27:303–310
4. Roca O, Peñuelas O, Muriel A, García-de-Acilu M, Laborda C, Sacanell J, Riera J, Raymondos K, Du B, Thille AW, Ríos F, González M, Del-Sorbo L, Del Carmen MM, Soares MA, Pinheiro BV, Nin N, Maggiore SM, Bersten A, Amin P, Çakar N, Suh GY, Abroug F, Jibaja M, Matamis D, Zeggwagh AA, Sutherasan Y, Anzueto A, Esteban A, Frutos-Vivar F (2021) Driving pressure is a risk factor for ARDS in mechanically ventilated subjects without ARDS. Respir Care 66:1505–1513
5. Goligher EC, Costa ELV, Yarnell CJ, Brochard LJ, Stewart TE, Tomlinson G, Brower RG, Slutsky AS, Amato MPB (2021) Effect of lowering tidal volume on mortality in ARDS varies with respiratory system elastance. Am J Respir Crit Care Med 203:1378–1385
6. Costa ELV, Slutsky A, Brochard LJ, Brower R, Serpa-Neto A, Cavalcanti AB, Mercat A, Meade M, Morais CCA, Goligher E, Carvalho CRR, Amato MBP (2021) Ventilatory variables and mechanical power in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med. https://doi.org/10.1164/rccm.202009-3467OC
7. Bellani G, Grassi A, Sosio S, Gatti S, Kavanagh BP, Pesenti A, Foti G (2019) Driving pressure is associated with outcome during assisted ventilation in acute respiratory distress syndrome. Anesthesiology 131:594–604
8. Bellani G, Grassi A, Sosio S, Foti G (2019) Plateau and driving pressure in the presence of spontaneous breathing. Intensive Care Med 45:97–98
9. Bianchi I, Grassi A, Pham T, Telias I, Teggia Droghi M, Vieira F, Jonkman A, Brochard L, Bellani G (2022) Reliability of plateau pressure during patient-triggered assisted ventilation. Analysis of a multicentre database. J Crit Care 68:96–103
10. Bertoni M, Telias I, Urner M, Long M, Del Sorbo L, Fan E, Sinderby C, Beck J, Liu L, Qiu H, Wong J, Slutsky AS, Ferguson ND, Brochard LJ, Goligher EC (2019) A novel non-invasive method to detect excessively high respiratory effort and dynamic transpulmonary driving pressure during mechanical ventilation. Crit Care 23:346
11. de Vries HJ, Tuinman PR, Jonkman AH, Liu L, Qiu H, Girbes ARJ, Zhang Y, de Man AME, de Grooth HJ, Heunks L (2023) Performance of noninvasive airway occlusion maneuvers to assess lung stress and diaphragm effort in mechanically ventilated critically ill patients. Anesthesiology 138:274–288
12. Yoshida T, Amato MBP, Kavanagh BP (2018) Understanding spontaneous vs. ventilator breaths: impact and monitoring. Intensive Care Med 44:2235–2238
13. Dianti J, Fard S, Wong J, Chan TCY, Del Sorbo L, Fan E, Amato MBP, Granton J, Burry L, Reid WD, Zhang B, Ratano D, Keshavjee S, Slutsky AS, Brochard LJ, Ferguson ND, Goligher EC (2022) Strategies for lung- and diaphragm-protective ventilation in acute hypoxemic respiratory failure: a physiological trial. Crit Care 26:259
14. Haberthür C, Guttmann J (2005) Short-term effects of positive end-expiratory pressure on breathing pattern: an interventional study in adult intensive care patients. Crit Care 9:R407-415
15. Goligher EC, Combes A, Brodie D, Ferguson ND, Pesenti AM, Ranieri VM, Slutsky AS (2019) Determinants of the effect of extracorporeal carbon dioxide removal in the SUPERNOVA trial: implications for trial design. Intensive Care Med 45:1219–1230
16. Doorduin J, Nollet JL, Roesthuis LH, van Hees HW, Brochard LJ, Sinderby CA, van der Hoeven JG, Heunks LM (2017) Partial neuromuscular blockade during partial ventilatory support in sedated patients with high tidal volumes. Am J Respir Crit Care Med 195:1033–1042
17. Chen L, Grieco DL, Beloncle F, Chen GQ, Tiribelli N, Madotto F, Fredes S, Lu C, Antonelli M, Mercat A, Slutsky AS, Zhou JX, Brochard L (2022) Partition of respiratory mechanics in patients with acute respiratory distress syndrome and association with outcome: a multicentre clinical study. Intensive Care Med 48:888–898