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EDITORIAL

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About the relevance of dynamic intrinsic PEEP (PEEPi, dyn) measurement

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Dynamic pulmonary hyperinflation (DPH) is defined by an increase in the end-expiratory lung volume (EELV) above the respiratory system relaxation volume (Vr) due to dynamic forces at end expiration [1]. DPH occurs whenever the time available to exhale the tidal volume (VT) is shorter than the time required to decompress the lungs to Vr. The patient's respiratory mechanics, breathing pattern and respiratory muscle activation are involved in the generation and magnitude of DPH [2]. In mechanically ventilated patients, the ventilator settings as well as the added resistance due, for example, to narrow bore endotracheal tube and ventilator circuits, tubings and valves can play a role in determining DPH [3, 4]. In the presence of DHP, the alveolar pressure can remain positive throughout expiration because of the persistent inward elastic recoil of the total respiratory system (Pel,rs). The end-expiratory Pel,rs due to incomplete expiration has been termed auto PEEP, occult PEEP [5], inadvertent PEEP, endogenous PEEP, internal PEEP and intrinsic PEEP (PEEPi). PEEPi has important pathophysiologic and clinical implications which depend on its magnitude and on the patient's condition, for example, the breathing pattern and the mode of ventilatory assistance [4].

The major clinical implication of PEEPi concerns the energetics of breathing due to the fact that PEEPi, i.e. the end-expiratory Pel,rs, acts as an inspiratory threshold load which must be fully counterbalanced by the patient's contracting inspiratory muscles to start and maintain inspiration. The extra burden imposed upon inspiratory muscles by PEEPi can be quite substantial [4, 6]. Coussa et al. [7] partitioned the work of breathing in chronic obstructive pulmonary disease (COPD) patients with acute respiratory failure during mechanical ventilation. They estimated that 47% of the total inspiratory effort was used to overcome PEEPi. Similar results were obtained by Zakynthinos et al. [8] and by Appendini et al. [6]. PEEPi and DPH can make the inspiratory muscle contraction extremely costly [6–8] and very inefficient [9, 10], such that excessive PEEPi has been recognized as one of the major determinants of ventilatory failure during acute exacerbations of COPD and weaning failure in mechanically ventilated patients with airway obstruction. In these patients, the application of PEEP or of continuous positive airway pressure (CPAP) is aimed to counterbalance PEEPi. Under these circumstances, application of external PEEP/CPAP lower than PEEPi during spontaneous/assisted breathing can substantially unload the inspiratory muscles by offsetting most of PEEPi, without creating further hyperinflation and worsening its consequences such as hemodynamic impairment, enhanced risk of barotrauma and reduced pressure generating capacity of the inspiratory muscles [2], as predicted by the waterfall theory [3]. It follows that PEEPi assessment can be crucial in the setting of these ventilatory modalities, to maximize beneficial effects and to avoid adverse effects.

The measurement of PEEPi is more easily performed under static conditions (PEEPi, stat) during controlled mechanical ventilation by means of the end-expiratory airway occlusion (EEO) [5] when the respiratory muscles are relaxed, than during assisted ventilation, weaning and spontaneous breathing when the respiratory muscles are increasingly recruited. During the EEO the pressure at the airway opening increases from the pre-occlusion level until a plateau is reached, usually be-

tween 1 and 5 s after the occlusion. PEEPi,stat is computed from the difference between the end-expiratory plateau pressure during airway occlusion and atmosphere [4]. PEEPi,stat reflects the end-expiratory Pel,rs under static conditions and is considered to represent the mean value after equilibration of lung units with unequal time constant [11].

PEEPi is also measured under dynamic conditions (PEEPi,dyn) by simultaneous recording of flow (V') and pressure at the airway opening (Pao) during mechanical ventilation [12] and esophageal pressure (Pes) during spontaneous breathing [11, 13, 14]. The rationale supporting this measurement is the following: if the alveolar pressure is positive at the end of expiration, the initial part of the pressure driving inspiration, generated either by the ventilator or by the patient's contracting inspiratory muscles, must be spent to counterbalance the end-expiratory Pel,rs, i.e. PEEPi [11]. Measurement of PEEPi from esophageal pressure, which has been used in both acutely ill [11, 15, 16] and stable [13, 14] COPD patients, is valid provided that this measurement is corrected for expiratory muscle activity [17, 18], if present [19]. PEEPi,dyn estimated from either Pao or Pes was found to be significantly lower than PEEPi,stat measured during the end-expiratory occlusion in mechanically ventilated patients with COPD [11, 20].

Petrof et al. [11] interpreted these results hypothesizing that, due to severe time constant inhomogeneity in the lungs of patients with airway and lung parenchyma diseases, the measurement of PEEPi from changes in Pao and Pes preceding flow, i.e. under dynamic conditions, does not allow equilibration among lung units with different regional time constants. Under those circumstances the units with longer time constants are still emptying while fast time constant units start filling such that the change in pressure (either Pao or Pes) preceding inspiratory flow reflects the minimum amount of pressure required to counterbalance PEEPi in the fast time constant units, i.e. the lowest PEEPi, which has been termed PEEPi,dyn because it is measured during dynamic breathing. Both PEEPi,stat [21] and PEEPi,dyn [17] have been used to set proper levels of PEEP/CPAP in patients with acute on chronic respiratory failure due to exacerbation of COPD. However, some controversy still remains about the best level of PEEP (or CPAP) to set. Gay et al. [22] showed that, in mechanically ventilated COPD patients, changes in flow-volume relationship and end-expiratory volume occur at PEEP values somewhat lower than actual PEEPi,stat. That level of PEEP was termed "Pcrit", and it was found to be unrelated to PEEPi,stat. One of the main concerns about this topic is that the relationship between Pcrit (i.e. that particular level of PEEP beyond which the EELV increases) and PEEPi has been investigated mainly in patients under controlled ventilation, whereas the clinical indication for application of PEEP/CPAP is during spontaneous/assisted ventilation, in which PEEPi,dyn and not PEEPi can be measured with some accuracy. Thus, the expression of Pcrit as a fraction of PEEPi may be useless in terms of accurate titration of PEEP/CPAP. In this respect, it is intriguing to observe that if both Pcrit and PEEPi,dyn are expressed as a fraction of PEEPi [3], the two values are very similar. Further studies are probably required to assess the precise relationship occurring between Pcrit, PEEPi,stat and PEEPi,dyn, if any.

The study by Fujino et al. [23], published in this issue of Intensive Care Medicine, challenges the above-mentioned commonly accepted ideas about PEEPi,dyn and PEEPi,stat. Using a well designed protocol in sedated and paralyzed mechanically ventilated rabbits, the authors found that PEEPi,dyn, induced by inverse ratio ventilation and high minute ventilation, was higher than PEEPi,stat under all conditions tested. Moreover, they found that differences between PEEPi,dyn and PEEPi,stat were significantly correlated with the size of the endotracheal tube, the minute ventilation and the tidal volume. They speculated that there is a time delay for the expiratory flow to return to zero at the alveoli after the pressure at the airway opening equals PEEPi level, because of the inertia of gas. They concluded that PEEPi,dyn, being dependent on ventilatory conditions (and being always higher than PEEPi,stat), cannot represent the lowest regional PEEPi. However, Fig. 1 of this paper seems to show clearly enough that a significant time lag exists between pressure and flow tracings, independent of the presence of DPH and PEEPi. Indeed, even if the time scale is not suited for this purpose, it is evident that the sharp start of expiratory flow, occurring at the opening of the expiratory valve of the ventilator after the inspiratory pause, follows the start of the airway pressure decay due to the same event (see the first expiration close to the Y axis). Using the time scale provided by the authors, the interval between the start of the pressure decay and the start of expiratory flow can be estimated to amount to about 70 ms. In other words, Fig. 1 seems to show the presence of an anomalous time lag of ≈ 70 ms between the pressure and the flow signals disclosed by their misalignment at the opening of the expiratory valve of the ventilator, the former signal preceding the latter.

It is noteworthy that this "hypothetical" technical bias can explain in full the results the authors obtained in the study published in this issue [23]. First, they showed that airway pressure reached the level of target PEEPi,stat 28 ms before the PEEPi,dyn measurement. However, in order to correct for the ≈ 70 ms time lag between signals, the "true" PEEPi,dyn should be measured on the airway pressure tracing ≈ 70 ms before the point of zero flow, the PEEPi,dyn measurement being close to or lower than PEEPi,stat, in this case according to current theory. Second, the significant linear relation-

ship found between changes of tidal volume and the difference between PEEPi,dyn and PEEPi,stat can be explained by the increase of the rate of pressure change induced by changes in the flow rate necessary to obtain higher tidal volumes, given the fixed time lag existing between pressure and flow signals. Third, the finding that "the larger the endotracheal tube, the higher the PEEPi,dyn at the same target PEEPi,stat", can also be explained by the significant increase in minute ventilation and, hence, in inspiratory flow and rate of pressure change required to reach target PEEPi,stat, again given the fixed time lag existing between pressure and flow signals. The remaining results can be interpreted accordingly.

In conclusion, taking all these considerations into account, I believe that the readers have the appropriate tools in this issue of *Intensive Care Medicine* to decide themselves whether PEEPi,dyn and the concept of minimum PEEPi are still of some physiologic and clinical interest or should be rejected as mere artefacts.

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