Intensive Care Med (2020) 46:2381–2384
https://doi.org/10.1007/s00134-020-06105-3

WHAT'S NEW IN INTENSIVE CARE

What's new about pulmonary hyperinflation in mechanically ventilated critical patients

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Pulmonary hyperinflation is the increase in the relaxation volume of the respiratory system at the end of a tidal expiration (end-expiratory volume). This can occur due to a number of factors, acting alone or in combination, such as increased expiratory resistance impeding lung emptying (more pronounced in the presence of expiratory flow limitation in obstructive airway diseases, but also in acute respiratory distress syndrome (ARDS) and obesity), reduced lung recoil pressure (emphysema), increased minute ventilation and ventilatory demand, insufficient expiratory time, or over-support during the preceding inspiration leading to increased end-inspiratory volume and thus larger tidal volume to exhale [1].

In a seated normal subject quietly breathing, at the end of an expiration, alveolar and airway pressures are zero relative to atmosphere, and pleural pressure (as assessed by measuring the esophageal pressure with a dedicated air-filled balloon catheter placed at the distal part of the esophagus) is negative (around—5 cmH_2O). However, in the presence of pulmonary hyperinflation the alveolar pressure remains positive throughout expiration [leading to development of intrinsic end-expiratory positive pressure (PEEPi)] and is transmitted to the pleural space to varying degrees depending on the compliance of the lung and chest wall. For instance, in the case of emphysema the lungs are highly compliant, so most of the positive alveolar pressure is transmitted to the pleural space, unless severe hyperinflation is present leading to overdistension and lower lung compliance.

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The consequences of pulmonary hyperinflation during controlled mechanical ventilation are increased transpulmonary pressure at end inspiration and increased delivered mechanical power [2] with its associated injurious effects and risk of barotrauma, due to increased strain (volume change) of the lung and hemodynamic compromise [1, 3]. The more positive is the mean intrathoracic pressure, the more pronounced are its hemodynamic effects which are the result of a complex interaction between changes in preload secondary to changes in the venous return, right–left ventricle interactions, direct effects of lung inflation and mean alveolar pressure (together with any regional differences in PEEPi), increase in right ventricle and decrease in left ventricle afterload increased pulmonary vascular resistance and effects on ventilation/perfusion ratio [1, 3] . At moderate degrees of hyperinflation decreased venous return is the main mechanism leading to decreased cardiac output. Furthermore, the hyperinflated lung compresses the pericardium (especially the pericardial fossa) increasing their pressure (pericardial and juxtacardial, respectively) which is transmitted to the right atrial cavity increasing the right atrial pressure, the downstream pressure for venous return [1]. However, pulmonary hyperinflation with the resulting PEEPi elevates the upstream pressure driving venous return (i.e., the mean systemic pressure) by both reflex and mechanical means independent of the abdominal pressure [1]. The positive intrathoracic pressure may also change the resistive and elastic properties of peripheral veins and may increase venous resistance depending on the amount applied and the collapsibility of the veins. The net effect of all these phenomena is a decrease in the venous return [4, 5].

In the spontaneously breathing mechanically ventilated patient (assisted ventilation), the inspiratory effort of the patient decreases the mean inspiratory pressure and thus the mean intrathoracic pressure. The respiratory

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consequences of hyperinflation during assisted mechanical ventilation are overdistension, increased effort–work of breathing, and wasted/ineffective efforts. The work performed per breath is mathematically expressed as $\int$ Pressure × dVolume, i.e., the area on a pressure–volume diagram [6] [7]. The higher is the end-expiratory lung volume (hyperinflation), the higher is the recoil pressure of the respiratory system (PEEPi). At the very beginning of inspiration, the inspiratory muscles have to develop enough negative pressure to overcome this positive alveolar pressure (elastic threshold load) and render airway pressure negative so that the ventilator will be triggered. Consequently, with a constant tidal volume the higher the hyperinflation, the larger is the pressure development by the inspiratory muscles (i.e., the elastic component of the work of breathing) and thus the total work of breathing [4, 8]. From an "energy" point of view, even a low amount of PEEPi is a substantial amount of work: Moving 1L volume across a 10 cmH_2O pressure gradient is 1 Joule of energy. This means that for a breath of 500 mL and PEEPi 5 cmH_2O, the patient has to dissipate 0.25 J of energy per breath, only to compensate for this extra elastic load, which is enormous given that a normal subject dissipates 0.2–0.3 J per breath [7].

Wasted–ineffective efforts are inspiratory efforts failing to trigger the ventilator. This is usually due to inability of the inspiratory muscles to overcome the sum of PEEPi and the pressure needed to trigger the ventilator due to hyperinflation which not only increases PEEPi but also renders the respiratory muscles weaker, due to a sub-optimal length tension relationship [1, 5]. A low respiratory drive (for instance, when a patient is under the effects of sedative drugs) may also contribute to the inadequate pressure generation by the respiratory muscles [9]. Sometimes, during assist volume or pressure control, prolonged imposed inspiratory time (machine inspiratory time) greater than the patient's neural inspiratory time results in a situation where the ventilator is inflating the patient long after the inspiratory muscles have stopped their contraction, i.e., during the neural expiration. This results in high tidal volumes with increased end-inspiratory lung volume and a shorter time available for expiration, both of which increase end-expiratory lung volume and thus predispose to wasted efforts [1, 10]. Wasted efforts can be detected on the airflow over time signal of the ventilator display as transient decreases of expiratory flow toward zero flow, or when the patient's inspiratory effort rate (determined by clinical examination) is higher than the ventilator delivered respiratory rate (available on the ventilator display). A new improvement in care is that modern monitors can incorporate algorithms to detect ineffective efforts [11–13]. The consequences of wasted efforts were not adequately explored until recently, when it was shown that clusters of ineffective efforts are often present in mechanically ventilated critically ill patients and more important are associated with worse outcomes [12, 14] (Fig. 1).

To reduce the amount of wasted efforts, one should decrease the level of excessive ventilator assistance [15]. Since mean expiratory flow is one of the major determinants of hyperinflation, during volume or pressure assist-control modes, reducing machine inspiratory time may reduce wasted efforts [10]. Similarly, during pressure support increasing the expiratory trigger threshold (i.e., the cycling-off criterion) will stop the breath earlier, and thus at a lower end-inspiratory volume, and will allow for more expiratory time and thus reduced end-expiratory volume and PEEPi. Both will decrease wasted efforts [15]. Reducing the minute volume will also lower PEEPi. The addition of an external PEEP level lower than the PEEPi offers to the inspiratory muscles part of the pressure required to overcome PEEPi plus the trigger sensitivity [6]. The inspiratory effort may then become adequate to trigger the ventilator [1, 6, 15]. For this, an accurate measurement of PEEPi is needed. In passive mechanically ventilated patients, the actual positive end-expiratory pressure is measured under static conditions as the plateau in airway pressure during a prolonged end-expiratory airway occlusion (PEEPtot). This PEEPtot may be due to externally applied PEEP or PEEPi depending on which is larger. In case PEEPi is larger than the applied external PEEP, the PEEPtot is the average pressure after equilibration of lung areas with different regional PEEPi (due to different regional resistances and compliances). However, the externally applied PEEP may be exceeding some regional critical opening pressures and thus may be hyperinflating regions of the lung with lower regional PEEPi than the applied PEEP [4, 8]. Of course if the set PEEP is higher than any regional PEEPi, the PEEPtot equals the set PEEP. In highly heterogeneous lungs, however, some alveolar units may close before end-expiration and thus have higher regional PEEPi that cannot be measured by the conventional end-expiratory airway occlusion [3]. For these reasons, in passively ventilated patients, the end-inspiratory plateau airway pressure is a useful clinical surrogate of the degree of pulmonary hyperinflation.

In spontaneously breathing patients, the decrease in Pes needed to abruptly bring expiratory flow to zero during unoccluded breathing is taken as dynamic $PEEP_i$ ($PEEP_i$,dyn), which has to be corrected for expiratory muscle activity [8]. Thus, in assisted ventilation pulmonary hyperinflation induces an increase in inspiratory muscle effort and facilitates the appearance of wasted inspiratory efforts. The hyperinflation and its consequences can be minimized by decreasing excessive levels of inspiratory

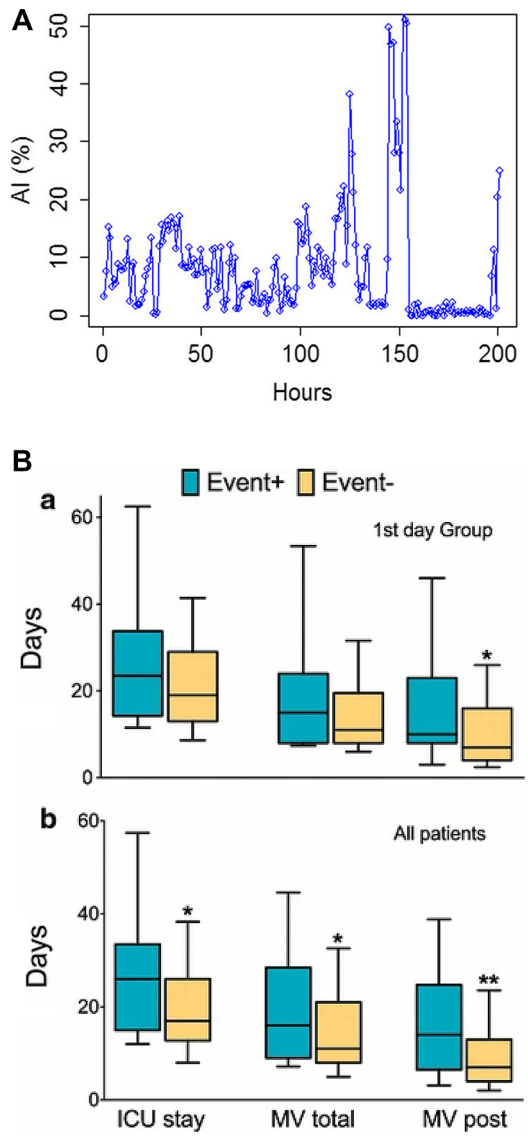

Fig. 1 **a** Asynchrony index (AI), percentage (%) per h, continuously recorded over several days in a representative patient. Recordings show that periods of almost no asynchronies alternated with periods of high level of asynchronies. From Intensive Care Med (2015) 41:633–641 with permission. **b** Duration in days of ICU stay, and mechanical ventilation, in total (MV-total), and after the first recording (MV-post), for patients with events (teal), and without (orange). **a** 1st day group (n = 79), **b** all patients (n = 110). Due to study design and instability of critically ill patients, the recording periods were expected to vary between patients. To overcome the issue of potential selection bias due to either short or long recordings, apart from the analysis of all the patients' data, an additional analysis was performed. This analysis, which aimed at patients with relatively similar observation periods, included data obtained only during the 1st day, from patients having a recording period of at least 16 h (1st day group). From Intensive Care Med (2017) 43:184–191, with permission

assistance and hence reducing the mean expiratory flow, and by using external PEEP to counterbalance intrinsic PEEP in order to decrease its elastic load.

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Compliance with ethical standards

Conflicts of interest
The author(s) declare that they have no conflict of interest.

Publisher's Note

Received: 20 February 2020 Accepted: 11 May 2020
Published online: 29 May 2020

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