Diaphragmatic ultrasound as a monitoring tool in the intensive care unit

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Critically ill patients are a group of patients with special needs during hospitalization. The vast majority of them is mechanically ventilated and requires continuous assessment of vital parameters. Intensive care unit (ICU) is the environment that renders this monitoring feasible. A lot of parameters characterizing cardiac function, hemodynamic status, pulmonary function—oxygenation, acid base balance, renal function, nutrition and gastrointestinal function are continuously or repetitively monitored. It is quite impressive that assessment of respiratory muscles, and specifically of the diaphragm, is lacking in the daily practice of ICUs. This is the case despite the fact that there is robust evidence about diaphragmatic dysfunction in ICU patients under mechanical ventilation.

It is in the ICU where the diaphragm-the main inspiratory muscle-becomes so important. A lot of the time in ICUs is spent on weaning patients from mechanical ventilation. Although weaning from mechanical ventilation can be a rapid and uneventful process for the majority of the patients, it can be difficult in as many as 20–30% of them (1). It is during weaning that the diaphragm becomes the major pathophysiological determinant of weaning failure or success. Weaning failure is usually caused by the inability of the respiratory muscle pump to tolerate the load imposed upon it. Consequently, weaning a patient from the ventilator will be successful whenever an appropriate relationship exists between ventilatory needs and neuromuscular capacity of the respiratory muscles and will ultimately fail whenever this relationship becomes inappropriate-imbalanced (2).

Various insults can render the diaphragm weak in ICU patients such as sepsis, electrolyte disturbances, hyperinflation, critical illness polyneuropathy and/or myopathy to name a few out of a long list (2). Diaphragmatic dysfunction can even be already evidenced at the time of admission to the ICU in recently intubated patients; this is correlated with sepsis and disease severity and renders a bad prognosis. Diaphragmatic dysfunction can evolve early in the course of sepsis in the same way as septic myocardial dysfunction or nerve conduction abnormalities develop early within 48–72 h of sepsis. In that way diaphragmatic dysfunction may be considered a sepsis-related organ failure, for which we don't know if it is just a marker of disease severity or it has causal effect on mortality (3).

Controlled mechanical ventilation (CMV)—the most commonly used mode of ventilation in the initial phase of ICU admission—that is the mode of ventilation that the ventilator assumes all the work of breathing leaving the respiratory muscles totally unloaded, can also cause dysfunction of the diaphragm, an entity named ventilator-induced diaphragm dysfunction (VIDD) (4). VIDD is characterized by diaphragmatic weakness resulting from both atrophy and impairment of force generating capacity of the muscle (specific force production) (4). VIDD develops during partial support modes as well, when the support is excessive, but at a later time point (5). VIDD is a rapid and progressive phenomenon i.e., the longer the

duration of CMV, the greater the degree of atrophy and contractile impairment (6,7).

The question that arises is why we don't monitor diaphragmatic function in critically ill patients. Diaphragm is a striated muscle, "hidden" inside the body with complex anatomy that changes during each breath. Measuring its pressure generating capacity requires placement of esophageal and gastric balloons (transdiaphragmatic pressure) or even more, magnetic stimulation of phrenic nerves (twitch transdiaphragmatic pressure) (8). These require certain expertise (both on technical aspects and on interpretation) and overall make the assessment of diaphragmatic function demanding and technically difficult for everyday clinical practice. Even assessing diaphragmatic movement, in case of suspected paralysis or dysfunction, e.g., following cardiac or upper abdomen operations, the available methodology (fluoroscopy, X-rays, pulmonary function tests) is not easily applicable to ICU patients (8).

Over the recent years there has been an explosion in the use of ultrasounds in critical care medicine. The more the intensivists are becoming familiar with ultrasound, the more they use it in every day practice, switching from invasive to non-invasive monitoring (e.g., cardiac echo and inferior vena cava size and inspiratory variation as part of shock evaluation). Recent studies have provided us with promising results of the use of ultrasounds for monitoring diaphragm function as well (9-12).

In a recent issue of intensive care medicine Zambon and colleagues present a systematic review of the existing literature addressing the usefulness of ultrasound in assessing diaphragmatic dysfunction in critically ill patients. Two different approaches are discussed. The first approach assesses diaphragmatic inspiratory excursion using liver and spleen as acoustic windows with a convex (cardiac or abdominal) low frequency probe. The diaphragm moves downwards during the normal inspiration so either an upward motion during inspiration or immobility indicate paralysis. The second approach assesses diaphragm thickness and thickening during inspiration as well as the thickening fraction [TF = (thickness at end inspiration – thickness at end expiration)/thickness at end expiration] at the zone of apposition with a linear high frequency probe (the diaphragm thickens as it shortens during inspiration). The authors show that diaphragmatic ultrasound in the ICU setting is feasible, easy to apply in daily practice with excellent intra- and inter-observer reproducibility. Although it is proposed to have a fast learning curve, in reality there is a lack of studies addressing this issue.

In the ICU setting diaphragmatic ultrasound has been used successfully to evaluate diaphragm dysfunction. Using excursion in deep unassisted breathing as modality, one can discriminate between diaphragmatic paralysis-paradoxical upward movement or immobility of the diaphragm and paresis usually defined as ≤10 mm excursion with M-mode (10,13). Kim *et al*. (10) found a 29% prevalence of diaphragmatic dysfunction in mechanically ventilated patients (>48 h) undergoing weaning trials. Furthermore, a preliminary study by Valette *et al*. (13) showed that diaphragmatic dysfunction was evidenced at the time of ICU admission in a subgroup of patients with hypercapnic respiratory failure of unknown cause. This raises the possibility that diaphragmatic dysfunction can be an underdiagnosed cause of hypercapnic respiratory failure and intubation.

Diaphragmatic ultrasound using either excursion or thickening fraction has been demonstrated to perform at least equally (10) or even better (14) to other established weaning indices (rapid shallow breathing index-RSBI, maximum inspiratory pressure-$P_{I,max}$, etc.). Till now the indices used to predict weaning outcome assess diaphragmatic function rather indirectly. RSBI, or $P_{I,max}$ are an indirect (RSBI) or direct ($P_{I,max}$) assessment of all respiratory muscles acting together-meaning that in case of diaphragmatic weakness tidal volume or pressure generation can be preserved with the compensatory recruitment-increased work of the other inspiratory and accessory inspiratory muscles. In contrast, ultrasound permits direct assessment of diaphragm function *per se*. Furthermore thickening fraction but not excursion correlates well with indices of respiratory muscle workload—(diaphragm and esophageal pressure-time product) (11,15,16), suggesting that diaphragmatic ultrasound can be used as a direct assessment of respiratory muscle workload. PTPdi and diaphragmatic thickening fraction decrease in parallel with increasing levels of pressure support (11,16). Using ultrasound to facilitate weaning in a pre-specified group of patients is not expected to complicate the weaning trial process. Actually ultrasound is already used to facilitate weaning in the group of patients with suspected cardiac dysfunction as a cause of weaning failure. Indices of diastolic dysfunction before spontaneous breathing trial in patients with preserved systolic fraction (17), or deterioration of indices of diastolic dysfunction during the weaning process (18) can predict weaning outcome.

Another vital question is if diaphragm ultrasound can be used to assess and detect diaphragmatic atrophy in mechanically ventilated patients. This is an important

question as the real incidence and prevalence of VIDD is unknown. The evidence for VIDD originated mainly from studies in previously healthy animals subjected to CMV (19), and in brain dead patients free of infection and other derangements so as to be eligible for organ donation (6,7). These paradigms of course are not the "typical" ICU patient. The actual impact of the ventilator on the diaphragm in the ICU, where each patient is usually suffering multiple insults is as far not established. The systematic review by Zambon *et al*. shows that using diaphragmatic thickness as index of atrophy, several groups showed that CMV results in progressive loss of diaphragmatic thickness. Initially, Grosu and colleagues (12) in a small study described a decline in diaphragmatic thickness of 6% per day in MV patients. In a following study by Goligher *et al*. (15) nearly half (44%) of mechanically ventilated patients had evidence of more than 10% decline in diaphragmatic thickness within a weak and this correlated well with increased ventilatory support (i.e., low diaphragm contractile activity was associated with rapid decreases in diaphragm thickness). Schepens *et al*. (20) showed that the atrophy occurs quickly after onset of CMV-decline in diaphragmatic thickness is already evidenced after 24 h of CMV and reaches its maximum level at day 3. Finally Zambon *et al*. (21) (using diaphragmatic thickness as variable) established a linear relationship between ventilator support and diaphragmatic atrophy rate, providing evidence of a daily atrophy rate ranging from –7.5% under CMV and slower rates with variable levels of pressure support (the higher the support the greater the rate of atrophy). These findings are in accordance with the few studies that used different approaches to assess diaphragmatic dysfunction, measuring either transdiaphragmatic twitch pressure (PdiTw) or the change in endotracheal tube pressure induced by application of bilateral magnetic twitch stimulation of the phrenic nerves during airway occlusion (TwPtr): Jaber *et al*. (6) showed a rapid-progressive decline in TwPtr with time spent under CMV—mean decline by 32% after 6 days, whereas Supinski and Callahan (22) using PdiTw reported reduced diaphragmatic contractility in the vast majority of mechanically ventilated patients they studied.

The systematic review by Zambon *et al*. shows that diaphragmatic ultrasound can be a reliable, easily applicable method to evaluate diaphragm function and atrophy in daily practice in the ICU. Thus, diaphragmatic ultrasound is a promising tool that can fill the gap of monitoring diaphragmatic function routinely in critically ill patients. The availability of ultrasound can change the way intensivists think about their patients. Till now all the effort is focused on the lung to implement lung protective strategies. However, apart from the lung there is a vital pump, the ventilator pump of which the diaphragm is the main component that exhibits plasticity and vulnerability. The diaphragm as a skeletal muscle atrophies in response to unloading (the degree of ventilator support). The degree of diaphragm loading we should aim in order to prevent or reverse VIDD is not known. The degree of pressure support that facilitates rest from fatigue without imposing injury to the diaphragm is not known either. We need to establish diaphragm-protecting ventilator strategies in the same way we established lung protective strategies. For that we need large-scale studies and diaphragmatic ultrasound may be the tool that will make that feasible.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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