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Advanced Point-of-care Bedside Monitoring for Acute Respiratory Failure

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ABSTRACT

Advanced respiratory monitoring involves several mini- or noninvasive tools, applicable at bedside, focused on assessing lung aeration and morphology, lung recruitment and overdistention, ventilation–perfusion distribution, inspiratory effort, respiratory drive, respiratory muscle contraction, and patient–ventilator asynchrony, in dealing with acute respiratory failure. Compared to a conventional approach, advanced respiratory monitoring has the potential to provide more insights into the pathologic modifications of lung aeration induced by the underlying disease, follow the response to therapies, and support clinicians in setting up a respiratory support strategy aimed at protecting the lung and respiratory muscles. Thus, in the clinical management of the acute respiratory failure, advanced respiratory monitoring could play a key role when a therapeutic strategy, relying on individualization of the treatments, is adopted.

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Acute respiratory failure is one of the leading causes of mechanical ventilation initiation and intensive care unit (ICU) admission.[1] Since the early stages of acute respiratory failure management, in establishing the respiratory support strategy, it is essential to be aware of the potential damage to the lung and respiratory muscles resulting from improper regulation of mechanical ventilation. Injuries to these structures can either happen during spontaneous breathing or be triggered by inadequate ventilator settings.[2,3] To date, however, despite the identification of specific targets for diaphragm-protective ventilation and the proposal for potential strategies for an integrated protection of the lung and diaphragm,[4] there are sparse data on the clinical impact of such an approach.

Advanced respiratory monitoring involves several noninvasive or minimally invasive technologies, safely applicable at the bedside, to conduct an in-depth evaluation of the lung and respiratory muscles.[5] The assessment of the esophageal pressure and electrical activity of the diaphragm, electrical impedance tomography, and ultrasound of the lung and respiratory muscles are potentially useful to support physicians in the daily management of acute respiratory failure, specific to the protection of the lung and respiratory muscles (fig. 1). Despite the information conveyed by advanced respiratory monitoring tools and the technology implementation available in the clinical practice, their clinical use is still limited, probably due to the numerous skills required in their application.

In recent years, several articles providing new insights on the application of these technologies in clinical and research fields have published.[6–13] Thus, we prepared the current review focused on rendering an updated description of the tools employed at bedside for advanced respiratory monitoring. In particular, we shed light on how these technologies work and what measures they provide, discuss their clinical usefulness, and review the current evidence supporting their application in acute respiratory failure when part of a personalized strategy for lung and respiratory muscles protection.

Esophageal Pressure

Esophageal pressure is used as a surrogate for pleural pressure, and variations in esophageal pressure are indicative of pleural pressure changes on the lung surface.[14] The assessment of esophageal pressure is obtained through a dedicated esophageal catheter equipped with an air-filled or liquid-filled esophageal balloon and connected to a pressure

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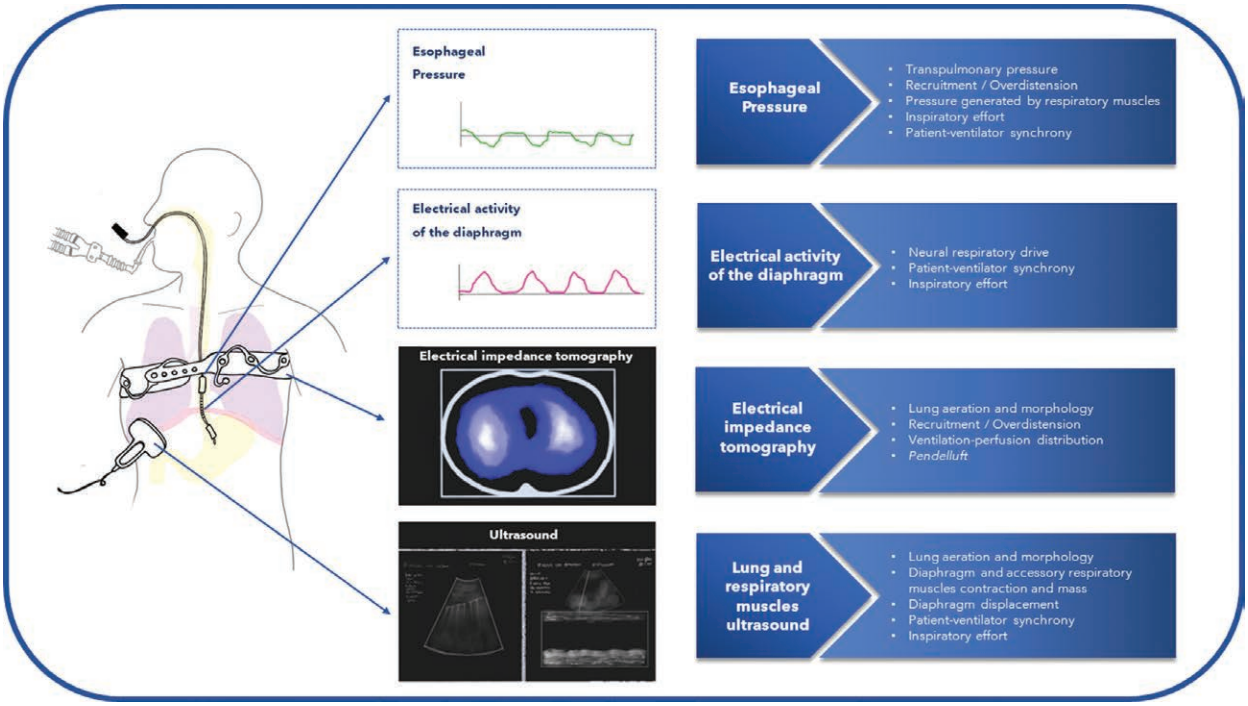

Fig. 1. Advanced respiratory monitoring in acute respiratory failure. These technologies can be used from the early stage of the disease, with patient in spontaneous breath or noninvasive respiratory support, and during invasive mechanical ventilation in passive and active conditions. In these contexts, advanced respiratory monitoring provides useful information on the cause of acute respiratory failure and the characterization of lung involvement. Also, these tools allow the assessment of intratidal gas distribution and lung aeration in terms of overdistention and collapse as well as pulmonary perfusion and ventilation–perfusion matching. In recovering from acute respiratory failure, advanced respiratory monitoring technologies offer an in-depth evaluation of patient–ventilator interaction in terms of inspiratory effort and respiratory muscles activation, respiratory drive, and patient–ventilator synchrony.

transducer at its proximal tip.[15] The procedure for catheter placement allows the positioning of the esophageal balloon midway between the apex and the base of the lung, generally at 35 to 45 cm from the nostrils.[15]

In clinical and research contexts, the esophageal pressure assessment is used for the partitioning of respiratory mechanics into chest wall component and pulmonary component[16] and the computation of transpulmonary pressure, the real pressure distending the lung. The computation of transpulmonary pressure is obtained through different approaches, the most used of which are the direct method and elastance-derived method.[17,18] According to the direct method, transpulmonary pressure is obtained by subtracting esophageal pressure from airway pressure,[11] while the elastance-derived method accounts for lung stress induced by ventilation.[19] However, the reliability of absolute values of esophageal pressure in reflecting absolute values of pleural pressure is controversial. Indeed, the absolute values of esophageal pressure can be influenced by respiratory system mechanical properties, lung volume, weight of the mediastinum, abdominal pressure, body position, esophageal wall reaction, and the elastic recoil of the esophageal balloon as well as lung disease distribution and asymmetry.[16] Pleural pressure is not homogenously distributed in the chest, and esophageal pressure cannot represent the pleural pressure acting on the whole lung surface. Indeed, in the supine position, pleural pressure develops along a vertical gradient from the nondependent to the dependent chest,[20] which is magnified in acute respiratory distress syndrome (ARDS) patients.[21] Accordingly, transpulmonary pressure diminishes from nondependent to dependent lung. In supine position, the esophagus is exposed to mediastinal weight, with a hypothesized increase in esophageal pressure on average of 5 cm H_2O above pleural pressure.[22] Also, it has been demonstrated that the two methods for transpulmonary pressure computation yield conflicting results, definitively questioning the accuracy of the esophageal manometry in representing regional pressure across the lung.[23] To correct the artifacts related to esophageal wall contraction in response to balloon inflation and balloon elastic recoil, an *ad hoc* procedure of balloon calibration has been proposed in both invasive controlled mechanical ventilation and assisted breathing.[24–27] This procedure relies on the identification of the optimal esophageal balloon filling volume

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able to optimize the transmission of the esophageal pressure tidal swings, and removal of the artifacts responsible for an incorrect increase in esophageal pressure above the pleural pressure, *i.e.*, esophageal wall and balloon elastance, respectively.[24–27] By insufflating the esophageal balloon with the optimal filling volume, a validation occlusion test has been demonstrated to be passed *a posteriori* in a higher percentage of cases compared to uncalibrated volume, with which the test was passed in 57% and 52% of the cases in passive and active conditions.[26]

Recent findings support the validity of esophageal manometry, provided a proper calibration of the esophageal balloon is assured.[6] In experimental conditions of lung-injured pigs and human cadavers subjected to direct pleural and esophageal pressure monitoring in the supine position,[6] the vertical gradient of pleural pressure was confirmed. The directly measured transpulmonary pressure reflected the pressure acting on the dependent and midlung adjacent to the esophageal balloon during both inspiration and expiration (fig. 2). The overestimation of pleural pressure due to mediastinal weight on the esophageal balloon was not confirmed, probably due to the suspension of the heart by pericardial ligaments and the wide distribution of atelectasis. In the same setting,[6] the end-inspiratory transpulmonary pressure computed through the elastance-derived method matched the end-inspiratory pressure acting on the nondependent lung regions (fig. 2). Indeed, in contrast with mid- and dependent lung regions, transpulmonary pressure was close to 0 at a low positive end-expiratory pressure (PEEP) in nondependent lung zones when lung volume approximated functional residual capacity.

As a clinical implication, in acute respiratory failure patients undergoing invasive mechanical ventilation, transpulmonary pressure assessment is potentially useful to recruit collapsed lung by counterbalancing negative directly measured end-expiratory transpulmonary pressure and avoiding overdistension by reducing end-inspiratory elastance-derived transpulmonary pressure.[19] However, a personalized ventilatory strategy setting PEEP to overcome negative expiratory transpulmonary pressure has been suggested in patients with ARDS with conflicting results.[28,29] In a randomized trial conducted in intubated ARDS patients,[28] PEEP adjusted according to measurements of esophageal pressure was superior to a ventilatory strategy with PEEP set according to low PEEP/fractional inspired oxygen tension table[30] in improving oxygenation

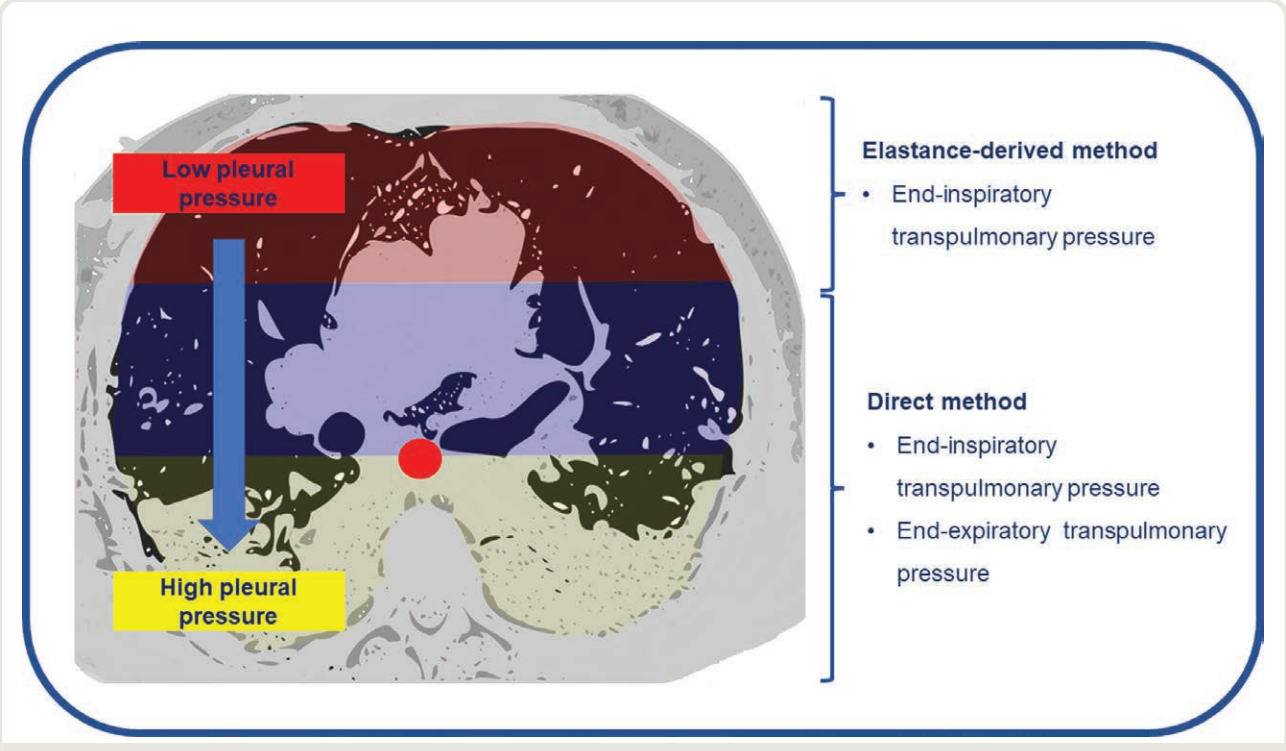

Fig. 2. Transpulmonary pressure. The vertical pleural pressure gradient along with the methods suggested for computation of transpulmonary pressure are represented. In supine patients, pleural pressure varies according to a vertical gradient, lower in nondependent lung and higher in dependent lung. As a consequence, the pressure developed across the lung, namely transpulmonary pressure, is higher in nondependent lung compared to dependent lung. The directly measured transpulmonary pressure reflects the pressure acting on the dependent and midlung adjacent to the esophageal balloon (*red solid circle*) during both inspiration and expiration. The end-inspiratory transpulmonary pressure computed by the elastance-derived method represents the end-inspiratory pressure acting on the nondependent lung regions.

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and mechanics. Conversely, esophageal pressure–guided PEEP provided no benefits in terms of a composite outcome including mortality and ventilator-free days at 28 days compared to an empirically set high PEEP-fraction of inspired oxygen, in a larger and multicenter randomized trial conducted in ARDS patients.[29] Despite these findings, the survival of patients subgroup characterized by a less severe multiple organ dysfunction was higher in the arm with an esophageal pressure-guided positive end-expiratory pressure in a secondary analysis of the EPVent-2 trial.[31] On the other hand, ventilator-induced lung injury is sustained by regional overdistention occurring during tidal ventilation.[32] Limiting the elastance-derived inspiratory transpulmonary pressure under 20 to 25 cm H_2O seems a reasonable approach to avoid overdistention in the nondependent lung regions (table 1).[19] Consistent with previous results,[33] a transpulmonary driving pressure 12 cm H_2O or greater, rather than an elastance-derived inspiratory transpulmonary pressure of 24 cm H_2O or more, has been demonstrated to be a risk factor for mortality at 60 days (table 1).

In spontaneously breathing patients and in those subjects undergoing appropriate noninvasive respiratory support or assisted invasive mechanical ventilation for severe acute respiratory failure, vigorous inspiratory efforts may cause an excessive drop in pleural and esophageal pressure as well as an increase in dynamic inspiratory transpulmonary pressure, not homogeneously distributed across the lung.[36] In these conditions, the atelectatic dependent lung regions in direct contact with diaphragm are exposed to deeper pleural pressure swings compared to the aerated nondependent lung regions. This leads to the pendelluft phenomenon, *i.e.*, the movement of alveolar gas from nondependent to dependent lung at the beginning of inspiration, a well-recognized risk factor for patient self-inflicted lung injury.[37] In patients with acute respiratory failure, keeping the esophageal pressure swing in the range of 3 to 15 cm H_2O and dynamic inspiratory transpulmonary pressure below the upper limit of 15 to 20 cm H_2O should help avoid harmful inspiratory efforts during active or assisted breath.[34]

The main indication for esophageal manometry during acute respiratory failure is assessment of transpulmonary pressure in all those conditions characterized by an increase in chest wall elastance.This has been frequently described in extrapulmonary ARDS as the consequence of an increased intra-abdominal pressure due to abdominal disease or obesity.[38] In obese patients with a body mass index 30 kg/m^2 or more intubated for ARDS, a ventilatory strategy counterbalancing negative expiratory transpulmonary pressure has been associated with an improved survival.[33] Also, a mechanical ventilation driven by transpulmonary pressure rather than airway pressure targets has been useful in improving oxygenation and eliminating the need for extracorporeal membrane oxygenation application in patients intubated for influenza A (H1N1) with an increased chest wall elastance.[39]

The main pitfall of esophageal manometry can be identified in the assessment of the esophageal pressure in patients who are spontaneously breathing or under noninvasive respiratory support. In these conditions, the calibration procedures previously described are not applicable, and

Table 1. Esophageal Pressure and Derived Parameter Descriptions and Significances with Related Targets for Protective Ventilation

Parameter	Description	Significance	Target
Static condition—passively ventilated patient			
Inspiratory elastance-derived transpulmonary pressure	Inspiratory pressure acting in nondependent lung	Overdistention of nondependent lung	20–25 cm H_2O [33]
Inspiratory esophageal-computed transpulmonary pressure	Inspiratory pressure acting in middependent lung	Overdistention of dependent lung	—
Expiratory esophageal-computed transpulmonary pressure	Expiratory pressure acting in middependent lung	Negative value: tendency to atelectasis	≥ 0 cm H_2O[33]*
Transpulmonary driving pressure	Real distending pressure acting on the lung	Lung stress	< 12 cm H_2O[33]
Chest wall driving pressure	Real distending pressure acting on the chest wall	Chest wall stress	—
Dynamic condition—actively breathing patient			
Inspiratory dynamic transdiaphragmatic pressure	Dynamic pressure distending the lung	Dynamic lung stress	< 15–20 cm H_2O[34]
Inspiratory esophageal pressure swing	Drop of the pressure generated during active inspiration	Inspiratory effort	3–15 cm H_2O[34]
Pressure generated by respiratory muscles	Inspiratory pressure generated by respiratory muscles	Inspiratory effort	5–10 cm H_2O[34]
Esophageal pressure-time product	Pressure time integral over inspiration	Inspiratory effort	50–150 cm H_2O*s*min^{-1}
Transdiaphragmatic pressure	Inspiratory pressure generated by diaphragm	Inspiratory diaphragmatic effort	–15 cm H_2O[34]

Esophageal pressure and derived parameters description and significance are reported along with target to provide protective ventilation, according to current suggestions and evidence, in passive patient—static condition and active patient—dynamic condition.

*The target reported refers to obese patients with body mass index 30 kg/m^2 or greater.

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the esophageal pressure evaluation could lose its validity due to the impossibility of correcting for esophageal wall and balloon reaction.

To date, esophageal pressure monitoring is available at bedside thanks to the implementation of systems for esophageal pressure signal acquisition in some ventilator machines or in dedicated portable devices offering the possibility of an automated *in vivo* calibration procedure.[40] However, despite this increased availability and the interesting applications of esophageal manometry in the clinical and research fields, this tool is still limited to expert physicians and researchers, due to the numerous technical skills required for its application.

Electrical Activity of the Diaphragm

Electrical activity of the diaphragm is the signal closest to output of the respiratory center, so it may be a sensitive and reliable method to monitor the patient's neural respiratory drive at the bedside.[41] Specifically, electrical activity of the diaphragm monitoring relies on the assumption that sensed activity of the crural diaphragm is representative of the total muscle activity, as demonstrated in patients intubated for acute respiratory failure.[42] The correct position of the nasogastric catheter is determined by verifying the electrocardiographic aspect of the P and QRS waves and the synchrony of the diaphragm electromyographic signal with the negative deflection of the airway pressure curve during an inspiratory effort against an occluded artificial airway.

Diaphragmatic electrical activity is a useful tool to assess neuromuscular respiratory drive in critically ill patients. Indeed, there is a correlation between the diaphragmatic electrical activity variation over time and the drop in airway pressure 100 ms after the onset of inspiration during an end-expiratory occlusion of the airway (P0.1), the reference method for respiratory drive assessment[43] (table 2).

In critically ill patients, wide heterogeneity in electrical activity of the diaphragm has been documented.[45] Diaphragmatic electrical activity signal varies according to the patient's level of assistance, and its peak values tightly correlate to esophageal pressure and pressure generated by respiratory muscles during inspiration.[46] This means that diaphragmatic electrical activity evaluation provides quantification of inspiratory effort,[46] in the presence of a preserved neuro-mechanical coupling.[42]

Assessing patient–ventilator interactions is crucial to minimize ventilator-induced lung injury and diaphragmatic dysfunction. Growing evidence suggests that the integration of the electrical activity of the diaphragm waveform to the "standard" ventilator curves (flow and airway pressure) improves the ability to detect patient–ventilator asynchronies (table 2)[47,48] during invasive mechanical ventilation or noninvasive respiratory support, and has been demonstrated to be useful to evaluate the impact of sedation on patient–ventilator interaction in acute respiratory failure patients and a mixed ICU population undergoing assisted breathing.[49,50] Indeed, oversedation may be the cause of a depressed respiratory drive and a poor patient–ventilator synchrony[49,50] during invasive mechanical ventilation. The main limitations ascribed to diaphragmatic electrical activity assessment are related to positioning of the dedicated catheter, as in the case of inability to follow the P and QRS waves size reduction criterion.

In summary, diaphragmatic electrical activity assessment provides potentially useful clinical information to guide protective assisted ventilation in patients assisted by invasive mechanical ventilation or noninvasive respiratory support for acute respiratory failure, due to the estimation of patient's neural respiratory drive, inspiratory effort, and patient–ventilator interaction.[45,51] To date, the patient–ventilator asynchrony assessment is the only application of electrical activity of the diaphragm monitoring supported by some evidence.[7]

Table 2. Electrical Activity of the Diaphragm, Description, Application in Acute Respiratory Failure, and Limitations

Parameter	Description	Application	Advantage Compared to Conventional Monitors	Limitations Compared to Conventional Monitoring	Reference
Peak of electrical activity for the diaphragm Diaphragmatic electrical activity tidal change	Maximal electric signal of diaphragm activation during tidal breathing Tidal variation on neural inspiratory time	Inspiratory effort during tidal breathing, patient–ventilator synchrony Neuromuscular respiratory drive, inspiratory effort during tidal breathing	Signal closest to output of the respiratory center	Minimally invasive, dedicated catheter and ventilator, catheter positioning, wide heterogeneity between patients, integrity of respiratory centers–to–diaphragm pathway, influenced by sedation and ventilator settings	7 μV, minimally acceptable inspiratory diaphragmatic activity after intubation[44] Compared to P0.1, where a threshold of 3.5 cm H_2O is associated with a high inspiratory effort, no target has reported for diaphragmatic electrical activity[43]

Diaphragmatic electrical activity with description, application in the setting of the acute respiratory failure, and advantages and limitations compared to conventional monitoring are reported.

P0.1, drop in airway pressure 100 ms after the onset of inspiration during an end-expiratory occlusion of the airway.

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Electrical Impedance Tomography

Electrical impedance tomography is a noninvasive, radiation-free, dynamic, real-time monitoring system that provides data on global and regional changes in lung volumes, ventilation distribution, and lung perfusion. Electrical impedance tomography examination is obtained by placing a silicon belt with 16 to 32 electrodes between the fourth and sixth intercostal space, connected to a dedicated machine.[52,53]

Pulmonary ventilation monitoring is based on the global and regional functional electrical impedance tomography assessment that also allows for an in-depth spatial and temporal analysis of ventilation distribution[54] (table 3). The global changes from minimum end-expiratory to maximum end-inspiratory impedance values correlate with global tidal breath. On the other hand, the global changes in end-expiratory impedance reflect the end-expiratory lung volume modifications. Also, the regional impedance variations are correlated with regional air content changes.[54]

In acute respiratory failure, electrical impedance tomography permits the identification of patients at risk of atelectrauma during invasive mechanical ventilation, through the estimation of regional opening and closing pressure (fig. 3) as well as regional hysteresis.[56,57]

The evaluation of the distribution of the intratidal changes in lung impedance along with end-expiratory lung impedance modifications allows the assessment of overdistended and recruited lung volume in response to PEEP changes during invasive mechanical ventilation.[58] Several procedures have been proposed to set a protective ventilation achieving the best compromise between lung overdistention and lung collapse. During a decremental PEEP trial after a maximal recruiting maneuver, the "optimal" PEEP value is defined by the intercept point of cumulated collapse and overdistension percentage curves.[59] Another method consists of choosing the "optimal" PEEP as that value able to stabilize end-expiratory lung impedance after the application of a recruiting maneuver.[60] If the end-expiratory lung impedance decreases more than 10% within 10 min after recruitment, PEEP needs to be increased by 2 cm H_2O and the recruitment reapplied.[60] According to this approach, the "optimal" PEEP value is defined as the lowest one avoiding an end-expiratory lung impedance decrease of less than 10%.[60]

The application of the "optimal" PEEP improves the homogeneity of tidal ventilation distribution.[61] Indeed, when a patient is afflicted by acute respiratory failure, the distribution of tidal volume within the lung is inhomogeneous because of the altered mechanical properties and the asymmetry of lung involvement.[61] Based on this assumption, "optimal" PEEP has been demonstrated to correspond to the lowest global inhomogeneity index, indicating the spatial heterogeneity and distribution of the ventilation, during a PEEP trial.[61]

In patients intubated for ARDS, PEEP personalized trough electrical impedance tomography to achieve a silent space, namely the hypoventilated area, less than or equal to 15% did not correlate with PEEP chosen to positivize end-expiratory transpulmonary pressure.[62] However, PEEP guided by electrical impedance tomography induced a homogenization of ventilation and an improvement of lung recruitment, whereas PEEP set on transpulmonary pressure was associated with a reduced lung stress.[62]

Electrical impedance tomography has been employed to assess global and regional lung aeration modifications induced by the prone position[63] in awake patients supported by high-flow nasal cannula[64] and in sedated and paralyzed patients with invasive mechanical ventilation for acute respiratory failure.[65] Prone position induces a more homogenous distribution of lung aeration as suggested by the uniform improvement in end-expiratory impedance across the lung.[64,65]

Electrical impedance tomography can also detect the gas distribution and pendelluft phenomenon in patients undergoing assisted mechanical ventilation.[66] In acute respiratory failure patients, occult pendelluft increasingly occurs with progressive reduction of ventilatory support[66] and increase of spontaneous breathing effort.[67] Thus, in the presence of this anomalous alveolar gas distribution detected through electrical impedance tomography at bedside, clinicians are facilitated in the timely application of the corrective measures aimed at abolishing vigorous inspiratory effort and pendelluft and, consequently, at preventing patient self-inflicted lung injury.[36]

Electrical impedance tomography can also measure the perfusion of the lung. Compared to positron emission tomography as a reference method, electrical impedance tomography underestimates relative pulmonary perfusion in dependent lung region and overestimates relative pulmonary perfusion in nondependent lung regions with small differences (less than 10%) in animal models.[68] Also, in the same setting,[68] electrical impedance tomography and positron emission tomography have detected the change of relative lung perfusion in the same direction in 69 to 96% of the measurements.

Perfusion electrical impedance tomography is based on the administration of a 10-ml bolus of hypertonic (5 to 10%) saline during an expiratory hold maneuver.[9] The injection of hypertonic fluid induces a modification of the lung impedance that is translated into a perfusion image. Perfusion electrical impedance tomography could be an adjunctive bedside tool to identify patients with pulmonary embolism[69] or to assess the modification of the ventilation/perfusion mismatch after PEEP changes[8] or prone positioning.[9] From this perspective, in a small cohort of ARDS patients subjected to invasive mechanical ventilation, the percentage of lung units with an unmatched ventilation-to-perfusion ratio was an independent risk factor for mortality, having been higher in nonsurvivors compared to survivors.[70]

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Table 3. Electrical Impedance Tomography

Parameter	Description	Application	Advantage Compared to Conventional Monitors	Limitations Compared to Conventional Monitors	Reference
End-expiratory lung impedance	Global and regional quantification of functional residual capacity	Assessment of lung aeration	Radiation-free, feasibility, applicability at bedside, accuracy	Affected by patient's movements and by presence of pneumothorax or pneumomediastinum or chest skin lesions, availability	—
End-expiratory lung impedance variation	Variation of global and regional quantification of functional residual capacity between two timepoints	Assessment of lung aeration after modifications of ventilator settings (*i.e.*, positive end-expiratory pressure)	Radiation-free, feasibility, applicability at bedside, accuracy	Affected by patient's movements and by presence of pneumothorax or pneumomediastinum or chest skin lesions, availability, sensitive to modifications of intrathoracic fluid volumes (*i.e.*, fluid challenge, dialysis)	—
Tidal impedance variation	Global and regional assessment of impedance change generated by inspired gas during a tidal breath	Evaluation of tidal volume distribution within the entire lungs and between different regions of interest	Radiation-free, feasibility, applicability at bedside, accuracy	Affected by patient's movements and by presence of pneumothorax or pneumomediastinum or chest skin lesions, availability	Global tidal impedance variation strictly correlates with the tidal volume of the patient; the distribution among different lung regions depends on the mechanical properties of the lung and the region of interest set by the operator
Inhomogeneity index	Distribution of tidal volume within the lung	Assessment of the homogeneity of distribution of the tidal volume within the lung to set an individualized positive end-expiratory pressure	Radiation-free, feasibility, applicability at bedside, good interpatient comparability	Affected by patient's movements and by presence of pneumothorax or pneumomediastinum or chest skin lesions, availability, offline computation with dedicated software	In a control group (sedated patients with healthy lungs) of the validation study by Zhao *et al.*,[55] the global inhomogeneity index was reported to be 0.40 ± 0.05
Center of ventilation	Ventral-to-dorsal shifts in distribution of lung ventilation	Assessment of the ventral to dorsal distribution of the tidal volume within the lung of the patient induced by different modes of ventilation and amount of inspiratory support	Radiation-free, feasibility, applicability at bedside, good interpatient comparability	Affected by patient's movements and by presence of pneumothorax or pneumomediastinum or chest skin lesions, availability, offline computation with dedicated software	When center of ventilation is expressed as percentage, a value of 50% represents equal distribution between the ventral and dorsal regions; a lower value indicates a shift of ventilation distribution toward the dorsal region; in case of dorsal atelectasis, the center of ventilation shift to the ventral part of the lung and the value increased more than 50%, indicating less ventilation in the dorsal region
Regional ventilation delay	Temporal delay in distribution of inspired air to reach a certain impedance change	Assessment of lung recruitability and individualization of the positive end-expiratory pressure level	Radiation-free, feasibility, applicability at bedside, good interpatient comparability	Affected by patient's movements and by presence of pneumothorax or pneumomediastinum or chest skin lesions, availability, offline computation with dedicated software	A smaller value indicates a more homogeneous distribution; in lung-injured patients, the different lung properties among lung regions increases the regional ventilation delay; when optimal positive end-expiratory pressure is applied to a recruitable lung, regional ventilation delay decreases

Electrical impedance tomography parameters in the setting of the acute respiratory failure along with advantages and limitations of the technology compared to conventional monitoring are reported.

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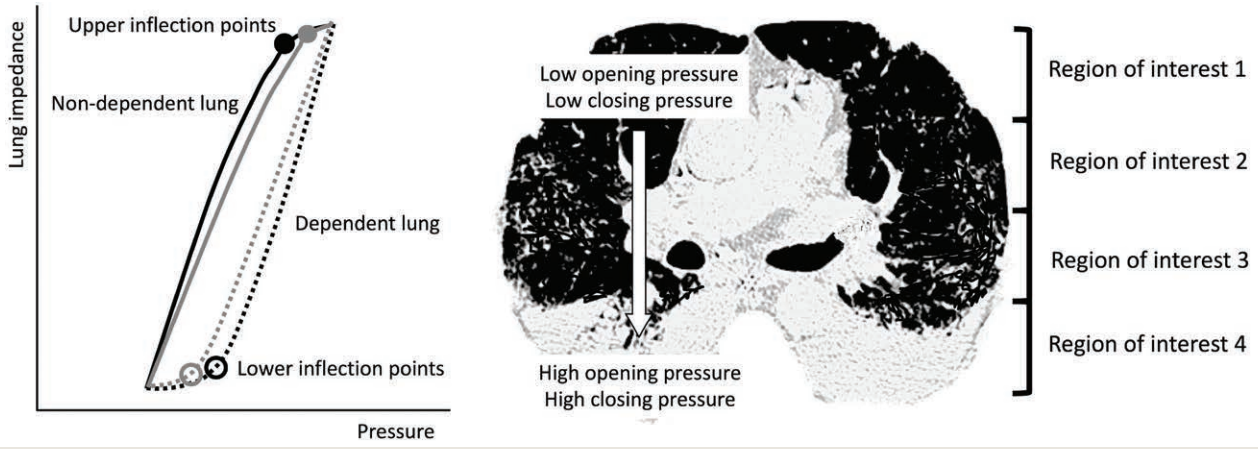

Fig. 3. Lower and upper inflection point distribution. Lower and upper inflection points distribution moving from nondependent (*region of interest 1, black continuous line*) to dependent lung (*region of interest 4, black dotted line*) at electrical impedance tomography examination. At pressure-impedance/volume curve, the lower inflection point of dependent lung (*black hollow circle*) is higher compared to the lower inflection points of the remaining regions of interest, while the upper inflection point of nondependent lung (*black solid circle*) is lower compared to the upper inflection points of the other regions of interest. The opening and closing pressure are lower in nondependent lung compared to the opening and closing pressure in dependent lung. *Black line*, Pressure-impedance/volume curve of region of interest 1; *gray line*, pressure-impedance/volume curve of region of interest 2; *gray dotted line*, pressure-impedance/volume curve of region of interest 3; *black dotted line*, pressure-impedance/volume curve of region of interest 4.

Although it is well known that lung protective ventilation improves clinical outcomes of ARDS patients, robust evidence is currently lacking for or against the use of electrical impedance tomography to individually set the ventilator. Encouraging experimental data have been reported in animals. In 12 Yorkshire swine, electrical impedance tomography–guided ventilation resulted in improved respiratory mechanics and gas exchange and reduced the histopathological findings of ventilator-induced lung injury compared to ARDS network[30] indications.[71]

A single-center randomized controlled trial has investigated whether setting PEEP with electrical impedance tomography or low PEEP/fractional inspired oxygen tension table from the ARDS network[30] improved clinical outcomes in 126 mild-to-severe ARDS patients. The authors reported similar PEEP values set in the two cohorts of patients without any difference in clinical outcomes (28-day mortality, ventilator-free days at day 28, ICU length of stay, successful extubation, and need for tracheostomy).[72] It should be mentioned that the all-cause mortality was 21% in the electrical impedance tomography group, compared to 27% in the low PEEP/fractional inspired oxygen tension table group. Although not significantly different, the population sample should be considered too small, and 35% of randomized patients were affected by mild ARDS.[72] Another randomized controlled trial including 87 moderate-to-severe ARDS patients compared PEEP settings guided by electrical impedance tomography or pressure-volume curve.[73] Patients randomized to the electrical impedance tomography group had an improved survival (69% *vs.* 50%).[73] Therefore, it seems that electrical impedance tomography–guided PEEP titration may improve the clinical outcome in more severe ARDS patients, although further investigation is required.

Besides these potential clinical advantages, electrical impedance tomography has some limitations that should be acknowledged. First, this technology suffers from a low resolution compared to other imaging techniques, such as lung ultrasound or computed tomography scan.[74] However, computer tomography does not assess lung ventilation directly but only the physical density of the lung, namely the static aeration, expressed in Hounsfield units.[75] Positron emission tomography is a noninvasive technology with a high accuracy in quantifying pulmonary ventilation and volume distribution,[76] also in response to PEEP and prone position.[77] In healthy and injured pigs, electrical impedance tomography has allowed accurate measurement of regional lung ventilation and volume in comparison to positron emission tomography,[78] the accepted standard in quantification of the regional ventilation of the lung.[76,77]

Electrical impedance tomography cannot be used for monitoring patients with an implanted pacemaker or cardioverter-defibrillator because of possible interference.[74] Fluid overload or sudden increase in urine output alters measurement of end-expiratory lung impedance, mimicking a reduction or increment in end-expiratory lung volume, respectively.[79] Finally, perfusion electrical impedance tomography also has the limit of requiring a short time (8 s) of apnea during the infusion of the hypertonic solution.[9] Although the expiratory hold is easily obtained in intubated patients receiving controlled invasive mechanical ventilation or in healthy volunteers, it is not so in the case of dyspneic patients with acute respiratory failure with a spontaneous respiratory activity.[80]

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In acute respiratory failure patients, electrical impedance tomography should be exploited as an adjunctive tool to optimize regional distribution of ventilation. Moreover, electrical impedance tomography permits the identification of anomalous gas distribution during active tidal breath, as in the case of the pendelluft phenomenon. Regardless of research interest, the application of perfusion electrical impedance tomography remains limited, and further studies are required to define its clinical application.

Ultrasound for the Evaluation of the Lung and Respiratory Muscles

Lung ultrasound is a versatile, radiation-free tool to assess the real-time lung aeration at the bedside.[10] With this aim, two main approaches to lung ultrasound evaluation are described: a *qualitative* approach, focused on lung morphology assessment, and a *quantitative* approach that is directed to monitoring purpose.[10,81,82] The *qualitative* approach consists of the formulation of an ultrasound diagnosis by evaluating the pleural line, presence of pleural effusion, lung consolidation, interstitial syndrome, and presence of pneumothorax.[81] The *quantitative* approach relies on the aeration scoring system computation that, in turn, provides a global and/or regional score of lung aeration. Global lung ultrasound scores range from a minimum of 0 (best aeration) to a maximum of 36 (total loss of aeration)[10] (table 4). Regional scores are well correlated to lung density evaluated by quantitative computer tomography scan.[86]

In acute respiratory failure, lung sonography is helpful in assessing the cause and the extent of lung aeration compromise, in following the progression of the disease over time, and in evaluating the response to therapies.[86,87] First, in the presence of a lung consolidation, lung sonography permits its characterization into inflammatory consolidation (Supplemental Digital Content 1, http://links.lww.com/ALN/D2, and bronchogram video, http://links.lww.com/ALN/D3) or atelectasis in the presence or absence of dynamic bronchogram, respectively, with a close correlation with computed tomography scan.[88] In diagnosis and discrimination of noncardiac interstitial syndrome in ICU patients, lung ultrasound has showed a moderate-to-high accuracy (area under the curve = 0.86) with the pleural abnormalities being highly specific (100%) but poorly sensitive (31%), according to recent findings.[89]

Lung ultrasound allows the assessment of intratidal lung recruitment (Supplemental Digital Content 2, http://links.lww.com/ALN/D4, and intratidal recruitment video, http://links.lww.com/ALN/D5) and lung recruitment after PEEP application (Supplemental Digital Content 3, http://links.lww.com/ALN/D6, and PEEP recruitment video, http://links.lww.com/ALN/D7)[86] in real time, at bedside. Due to its characteristics, lung ultrasound is promptly and repeatably applicable whenever clinicians need to evaluate the reaeration, defined as an improvement of the local ultrasound findings in response to a specific maneuver.[90] However, it is worth considering that in assessing lung recruitment through ultrasound, global lung ultrasound score involves any improvement in lung aeration irrespective of the initial condition. Indeed, a global reaeration lung ultrasound score is not closely correlated with the reopening of the collapsed areas because a substantial portion of the recruited volume derives from the already, albeit poorly, aerated lung.[91] Conversely, quantitative lung computed tomography scan is unquestionably useful in following the specific reaeration of a previously collapsed zone. From this perspective, the computation of regional lung ultrasound score is potentially more useful than global score in the evaluation of response to the maneuvers executed.

Lung sonography helps in the identification of patients potentially responding to prone positioning according to focal distribution of the disease.[92] Indeed, patients with a focal distribution of the lung involvement may benefit from prone positioning as a rescue ventilatory therapy. Conversely, when the lung involvement is characterized by a nonfocal distribution, a high PEEP ventilatory strategy should be preferred to enhance lung recruitment.[10] Also in this case, a regional lung ultrasound score, focused on the quantification of the aeration in posterior lung regions, seems more useful in following the response to prone positioning.

Lung ultrasound may also be useful in predicting noninvasive respiratory support outcome. In patients with acute respiratory failure related to COVID-2019, a worsening in global lung ultrasound score is predictive of noninvasive respiratory support failure at 24 h from its commencement.[93]

Overall, in keeping with recent findings,[94] lung ultrasound alone or as a part of thoracic ultrasound has a relevant impact on the decision-making process by changing diagnosis and therapy in the emergency department, ICU, and general ward. In critically ill patients undergoing invasive mechanical ventilation, the management was changed in 47% of the cases after lung ultrasound examination, with more than 65% of the modifications adopted involving invasive interventions.[95]

In the ICU, routine use of lung ultrasound for diagnosis and monitoring is effective in reducing the number of ionizing procedures without affecting patient outcome.[96] However, lung ultrasound and chest x-ray examination should be considered as complementary to each other due to the specific clinical information provided. Thus, in daily clinical practice, lung ultrasound could be employed as a first level examination thanks to its repeatability and the absence of radiation. In the case of clinical uncertainty, chest x-ray examination should be employed. Also, lung sonography does not provide data on the deep lung, for which computed tomography scan is the reference examination.[10] Thus, in acute respiratory failure, computed tomography scan is the standard radiological examination to evaluate lung morphology and to assess the specific aeration changes resulting from PEEP and prone positioning application.[97] However, the use of radiation and the nonapplicability at bedside, with the consequent necessity to move the patient outside the ICU, definitively limit computed tomography scan execution.

Another important limitation of the lung ultrasound is that it does not allow the evaluation of overdistension

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Table 4. Ultrasound for the Lung and Respiratory Muscles

Parameter	Description	Application	Advantage Compared to Conventional Monitors	Limitations Compared to Conventional Monitors	Reference
Ultrasound for the lung					
Lung ultrasound score	Global and regional quantification of the lung aeration	Assessment of lung aeration	Radiation-free, feasibility, applicability at bedside, repeatability over time, availability, accuracy	Dependency on operator skills, learning curve not defined for quantitative approach, not possible to assess overdistention, not possible to assess deep lung, not possible to assess lung perfusion (compared to computed tomography scan)	Lung ultrasound score varying from 0 (best aeration) to 36 (total loss of aeration). Normal aeration (A-pattern–score 0), characterized by the reverberation of a sliding pleural line at regular intervals (lines A), eventually associated with B-lines < 3; moderate loss of aeration (B1-pattern–score 1) with well-spared B-lines ≥ 3 at regular interval or coalescent B-lines originating from < 50% of the pleural line; severe aeration loss (B2-pattern–score 2) with multiple coalescent B-lines originating from > 50% of the pleural line; total loss of aeration (C-pattern–score 3)[10]
Ultrasound for the respiratory muscles					
Diaphragm displacement	Tidal excursion of a hemi-diaphragm during tidal breathing	Inspiratory diaphragmatic effort only during spontaneous breath, patient–ventilator synchrony	Radiation-free, feasibility, applicability at bedside, repeatability over time, availability, accuracy	Evaluation of a hemi-diaphragm, affected by meteorism and subcutaneous emphysema Under assisted breath, diaphragmatic displacement has demonstrated no modifications at varying inspiratory support as well as no correlation with inspiratory effort, assessed by esophageal pressure time product and transdiaphragmatic pressure time product[83]	Quiet breathing 1.6–1.8 ± 0.3 cm (right); 1.6–1.8 ± 0.4 cm (left)[84]
Diaphragmatic thickness and inspiratory thickening fraction	Muscle thickness during respiratory cycle and percent change in diaphragm thickness during inspiration	Expiratory diaphragmatic muscle mass Inspiratory diaphragmatic effort Patient–ventilator synchrony	Radiation-free, feasibility, applicability at bedside, repeatability over time, availability, accuracy	Affected by parallax error and gain setting, affected by subcutaneous emphysema, need of a cutaneous marker for the ultrasound assessment over time	Expiratory thickness lower limit: 1.2–1.3 mm Thickening fraction: 169–204%. Cardenas diaphragmatic ultrasound correlates with inspiratory muscle strength and pulmonary function in healthy subjects
Parasternal intercostal muscle thickness and inspiratory thickening fraction	Muscle thickness during respiratory cycle and percent change in parasternal muscle thickness during inspiration	Inspiratory effort of intercostal muscle	Radiation-free, feasibility, applicability at bedside, repeatability over time, availability, accuracy	Lack of supporting evidence, affected by parallax error and gain setting, affected by subcutaneous emphysema, need of a cutaneous marker for the ultrasound assessment over time	Thickening fraction: 3%[85]
Ultrasound assessment for expiratory muscles					
Abdominal wall muscle thickness and expiratory thickening fraction	Thickness of abdominal wall muscles (external oblique, internal oblique, transversus, and rectus abdominis) during respiratory cycle and percent change in muscle thickness during expiration	Expiratory effort during active expiration	Radiation-free, feasibility, applicability at bedside, repeatability over time, availability, accuracy	Lack of supporting evidence, affected by parallax error and gain setting, affected by subcutaneous emphysema, need of a cutaneous marker for the ultrasound assessment over time	Median thickness of the expiratory muscles was 13.1 [10.2–16.1] mm[13]

Ultrasound for the lung and respiratory muscles: parameters, descriptions, applications, advantages and disadvantages compared to conventional monitoring, and reference values are reported.

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during mechanical ventilation,[97] even if the loss of lung sliding in the nondependent lung zone may be suggestive of hyperinflation, especially if pleural line movements reappear after PEEP reduction.[98] An integrated approach involving other advanced respiratory monitoring technologies, *i.e.*, electrical impedance tomography, could overcome ultrasound limits.

In summary, lung ultrasound is useful to speed up the diagnosis of acute respiratory failure as well as start the *ad hoc* treatment and follow over time the response to the therapy established since the early stages of the disease. In those patients with a bilateral lung involvement, the characterization of the disease according to its focal and nonfocal distribution allows the personalization of ventilatory strategy with the application of prone position rather than high PEEP. Unfortunately, data are scarce on the role of lung ultrasound in lung protection during mechanical ventilation, mainly because it is impossible to assess overdistention in the ventilated lung.

Ultrasound provides easily accessible information to many of the muscles involved in the respiratory cycle at the bedside (table 4; fig. 4).[12] In acute respiratory failure, the ultrasound of respiratory muscles may be useful to assess diaphragmatic dysfunction, a condition described in 2.2% of patients admitted to the ICU with acute respiratory failure and responsible for poor prognosis.[99] In the presence of a diaphragmatic dysfunction, different ultrasonographic patterns can be observed, varying from a paradoxical cranial displacement,[100] namely diaphragmatic paralysis, to diaphragmatic weakness defined as a diaphragmatic excursion less than 10 to 15 mm or thickening fraction less than 20% during inspiration.[100] Conversely, in patients with acute respiratory failure related to COVID-19, an increased thickening fraction of the diaphragm has been observed in those subjects who have failed noninvasive respiratory support.[11]

Diaphragmatic ultrasound has recently been proposed for the identification of asynchronous events during noninvasive respiratory support at bedside.[101] However, although this method has high performance, it has a limitation.[101] To obtain asynchronies assessment, it is necessary to import ventilator waveforms in the ultrasound machine while the physician assesses the diaphragm displacement.

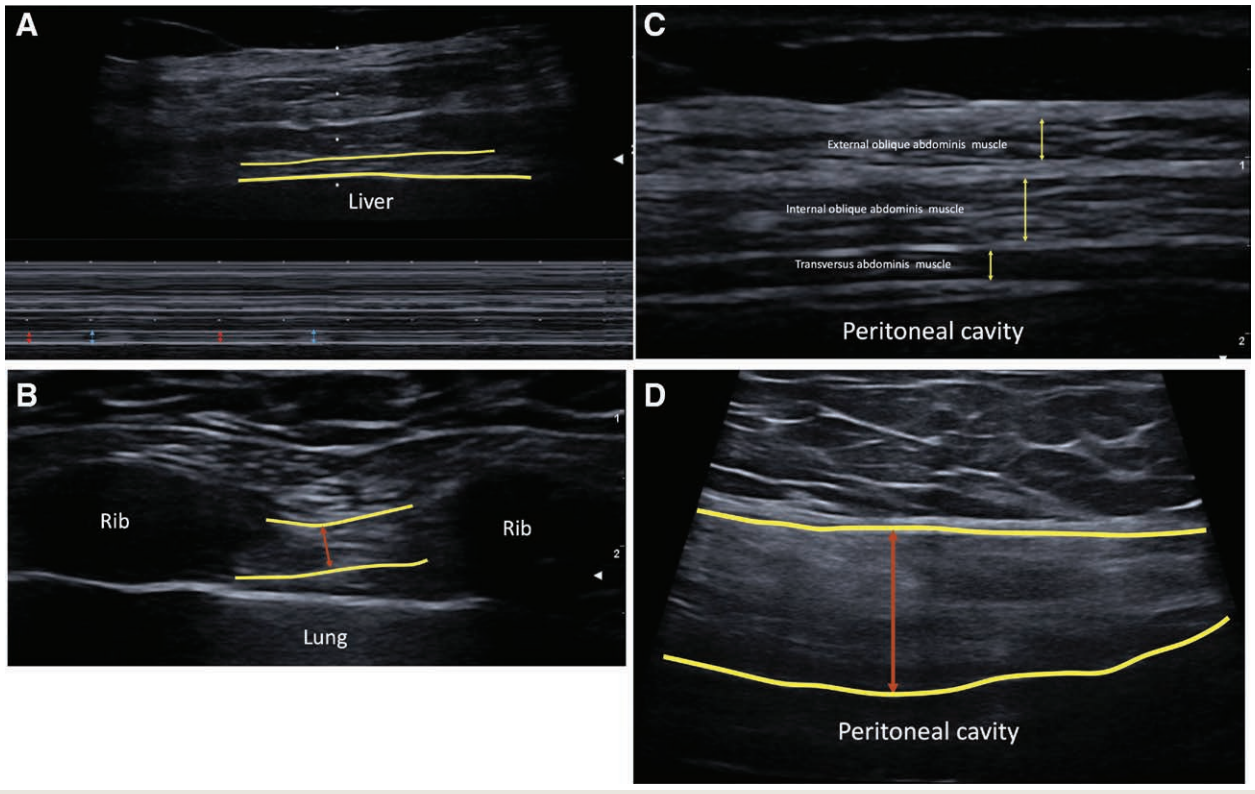

Fig. 4. Respiratory muscles ultrasound. The ultrasound of respiratory muscles is depicted. (*A*) Diaphragmatic ultrasound for thickness during inspiration (*red arrows*) and expiration (*blue arrows*) in M-mode. (*B*) Intercostal muscles ultrasound. (*C*) Abdominal wall muscles ultrasound for thickness of external and internal oblique abdominis muscles and transversus abdominis muscle. (*D*) Rectus abdominis ultrasound for thickness. External and internal boundaries of the muscles are traced in *yellow*. The *orange arrows* refer to thickness of the muscles.

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In recent years, ultrasound evaluation of accessory respiratory muscles has gained evidence (table 4).[12] Inspiratory accessory muscles comprise the parasternal intercostal muscles, which are easily accessible to ultrasound assessment.[12] In healthy subjects, the thickening fraction of this muscle shows very low values, around 3%.[85] In patients with documented diaphragmatic dysfunction, the parasternal thickening fraction increases significantly in response to the increased respiratory load imposed.[85] Ultrasound has also been proposed for the evaluation of appearance and modification of abdominal wall muscles during the respiratory cycle in critically ill patients,[13] although their role in acute respiratory failure requires further investigation. Of course, an increased expiratory thickening fraction of the abdominal wall muscles suggests an active expiration, that, in some cases, could be a protection against excessive tidal volumes delivered during assisted mechanical ventilation.

Limitations to respiratory muscles ultrasound are mainly related to the acoustic window quality. In particular, left diaphragmatic function is difficult to assess by ultrasound due to the poor quality of the splenic window affected by gastroenteral content.[102] In performing respiratory muscles ultrasound, it is worth placing the probe as perpendicularly as possible to the chest and abdominal wall surface to reduce parallax error.[103] Also, it is necessary to exclude the hyperechoic boundaries of the muscular structures in measuring muscular thickness to avoid the artifacts deriving from fascial edema. The application of a cutaneous marker has been demonstrated to enhance intra- and interoperator agreement during diaphragmatic ultrasound.[102]

Ultrasound has proven useful in assessing respiratory muscles during invasive mechanical ventilation and noninvasive respiratory support for acute respiratory failure. However, its impact in management and treatment of acute respiratory failure is still a matter of discussion due to the lack of robust data in support of it.

The main limitation for all the ultrasound examinations is related to the skill of the ultrasound operator. However, according to previous data obtained while assessing the performance of an instrument to evaluate lung ultrasound competence, an interrater agreement of 0.85 among novice and expert operators was observed.[104]

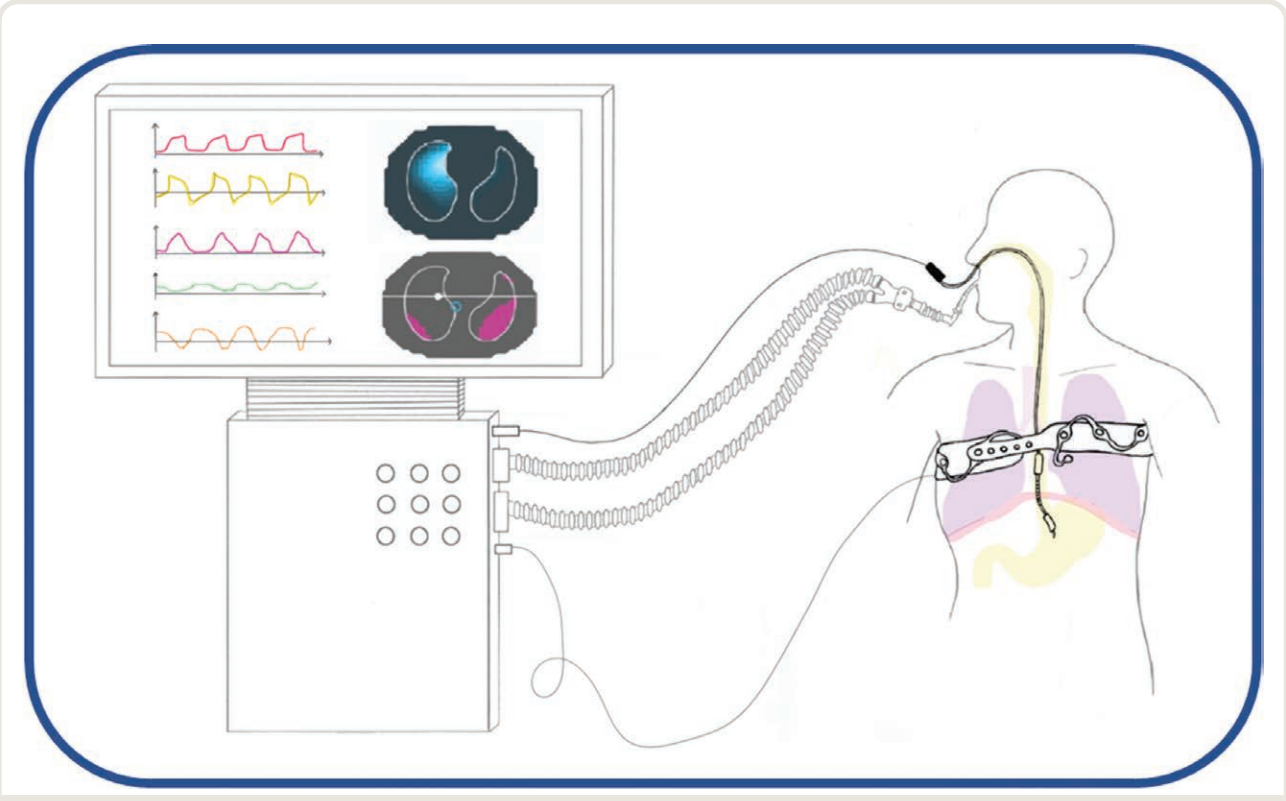

Fig. 5. Implementation of the advanced respiratory monitoring technologies at the bedside. An example of the implementation of some advanced respiratory monitoring technologies on mechanical ventilator at the bedside is depicted. The integration of the signals continuously acquired by ventilator machine is potentially useful in the personalization of the respiratory assistance, also in terms of mechanical ventilation automation. *Red curve*, airway pressure; *yellow curve*, flow; *purple curve*, electrical activity of the diaphragm; *green curve*, transpulmonary pressure; *orange curve*, esophageal pressure; electrical impedance tomography.

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Conclusions

In patients with acute respiratory failure, despite the lack of a robust evidence from multicenter trials, advanced respiratory monitoring tools, more or less integrated with each other (fig. 5), have the potential to provide insights on the respiratory system modifications induced by underlying disease as well as to support clinicians in setting up a mechanical ventilation focused on the protection of the lung and respiratory muscles. Hypothetically, an advanced respiratory monitoring assisted approach could be useful to tailor mechanical ventilation on the patient rather than on the disease.

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Competing Interests

Dr. Cammarota and Dr. De Robertis declare speaking honoraria from MSD (Rome, Italy) and Getinge (Gothenburg, Sweden) outside of the current work. Dr. De Robertis received speaking honoraria from Baxter (Deerfield, Illinois) outside of the current investigation. Dr. Longhini contributed to the development of a new device (not discussed in the current study). The patent is in progress (European Patent application No. EP20170199831). He also received speaking fees from Intersurgical (Wokingham, Berkshire), Draeger (Lubeck, Schleswig-Holstein), and Fisher & Paykel (Auckland, New Zealand). The other authors declare no competing interests.

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Supplemental Digital Content

Supplementary Material 1. Dynamic bronchogram, http://links.lww.com/ALN/D2
Supplementary Material Video. Bronchogram, http://links.lww.com/ALN/D3
Supplementary Material 2. Intra-tidal lung recruitment, http://links.lww.com/ALN/D4
Supplementary Material Video. Intra-tidal recruitment, http://links.lww.com/ALN/D5
Supplementary Material 3. Lung recruitment, http://links.lww.com/ALN/D6
Supplementary Material Video. PEEP recruitment, http://links.lww.com/ALN/D7

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