Colombo *et al. J Anesth Analg Crit Care* (2025) 5:90
https://doi.org/10.1186/s44158-025-00315-1

Journal of Anesthesia,
Analgesia and Critical Care

CONSENSUS ARTICLE

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Monitoring of invasive assisted mechanical ventilation: a good clinical practice document by the Italian Society of Anesthesia, Analgesia, Resuscitation, and Intensive Care (SIAARTI)

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Abstract

The Italian Society of Anesthesia, Analgesia, Resuscitation, and Intensive Care (SIAARTI) developed a good clinical practice document providing consensus-based statements on the monitoring of respiratory variables during weaning from invasive mechanical ventilation in adult patients. The aim was to summarize key parameters and available monitoring techniques to support healthcare professionals in daily clinical practice. The statements and supporting rationales were drafted by a panel of 10 experts to assist clinicians in selecting appropriate monitoring tools for the various respiratory functions involved during assisted ventilation. A total of 13 statements were issued, grouped into 8 items (rationale for monitoring, choice of the level of assistance, monitoring of respiratory patterns, respiratory effort, diaphragm functionality, respiratory drive, patient-ventilator synchrony, discontinuation of invasive assisted ventilation). The panel's work offers a practical bedside tool designed to optimize monitoring while acknowledging the heterogeneity of practices and equipment across Italian intensive care units.

Keywords Monitoring, Assisted mechanical ventilation, Weaning, Inspiratory efforts, Inspiratory drive, Good clinical practice

Introduction

In patients with acute respiratory failure (ARF), the transition from controlled to assisted modes of mechanical ventilation is associated with potential advantages: reduced need for sedation, less hemodynamic impact, a more homogeneous ventilation distribution, a better ventilation/perfusion matching, and prevention of respiratory muscle atrophy [1]. On the other hand, assisted ventilation may be associated with the risk of lung damage induced by excessive transpulmonary pressure oscillations [2, 3], especially in patients with increased respiratory drive generating high inspiratory efforts [4, 5].

The Italian Society of Anesthesia, Analgesia, Resuscitation, and Intensive Care (SIAARTI) developed a good clinical practice document providing consensus-based statements on the monitoring of respiratory variables during weaning from mechanical ventilation in adult patients. The aim was to summarize key parameters and available monitoring techniques to support healthcare professionals in daily clinical practice.

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The panel evaluated the various technologies available in the field, alongside the supporting evidence for their application, taking also into account the need for local expertise and resources within each intensive care unit. Ultimately, the objective was to develop a clinical tool intended for use at the bedside to facilitate and improve patient monitoring.

Methods

SIAARTI has established rules for good clinical practice documents with a consensus process. The methodological path was in line with the principles of rapid review of the literature and the modified Delphi method. The document was issued considering adult critically ill patients (i.e., age ≥ 18 years) as target population of interest and anesthesiologists and intensivists as target readers and users. The study has been performed in accordance with the Declaration of Helsinki.

The process can be summarized as follows:

- The Executive Board of the Society ranked the topic of the present document as of high priority;
- An anesthesiologist-intensivist with documented expertise in methodology was nominated (A.C.) as the project methodologist and coordinated the process;
- A panel of 10 experts was nominated along with two coordinators (G.G. and D.C.). The experts were identified based on their clinical and scientific expertise. Two anesthesiologists-intensivists with expertise in evidence assessment (M.I. and R.S.) joined the panel as search specialists, created the search strategy with the input of the methodologist, and performed the inclusion/exclusion process of relevant scientific records;
- As first step, a scoping workshop took place as an online remote meeting. All the proposals of clinical questions (or "items") that emerged from the discussion were collected and rationalized by the coordinators of the panel. Then, the panelists were asked to express their opinions on the appropriateness and priority of the proposed clinical questions through an online form [6]. Specifically, the assessment was classified as follows: 1–3 refusal/disagreement ("Not appropriate"); 4–6 "uncertainty"; 7–9 sharing/support ("appropriateness"). Consensus was considered reached when at least 75% of the experts, except the methodologist and the literature search specialists, assigned a score in the same interquartile range (i.e., 1–3, 4–6, or 7–9). In case of lack of agreement, a second voting round was possible, and afterwards, the panel could decide to exclude the questions from further voting rounds and from the document.
- The items approved by the panel were subsequently shared with the two expert search specialists who conducted a systematic review of the literature on the PubMed database. The review and its reporting were conducted according to the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [7] and the results were made available to the panelists. The search strategy, methods, and results of the systematic review are presented in Fig. 1.
- The panel was grouped into working subgroups. Each subgroup had to draft statements and rationales on 2 clinical questions, based on the available evidence [6]. The overall list of statements was then submitted to blind voting. The assessment followed the same methods adopted for the clinical questions.
- Draft of the document and internal revision.
- The final version of the Good Clinical Practice document, once approved by the panel, has been sent to 3 external reviewers who independently reviewed the clinical and scientific content of the document.

Results

The panel considered a total of 12 clinical questions (items). Among these, 8 items reached consensus and were further subjected to the process of statement production and voting rounds. A total of 13 statements were finally issued on 8 items (Table 1).

The detailed results of the original voting rounds in Italian language are available as Supplementary Material 1.

Rationale for the monitoring of assisted mechanical ventilation

Statement 1.1

The objective of assisted ventilation monitoring is to ensure protective ventilation of the lung and diaphragm.

Statement 1.2

Monitoring during assisted ventilation should not be limited to the simple control of the respiratory pattern and gas exchange, but it must also include the monitoring of respiratory drive and effort, diaphragmatic function, respiratory mechanics, and patient-ventilator synchrony.

Rationale

Compared to fully controlled mechanical ventilation, assisted modes are associated with potential advantages:

a) Improvement of ventilation-perfusion matching
b) Less hemodynamic impact
c) Greater variability of the respiratory pattern
d) Preservation of the activity of the respiratory muscles
e) Less need for sedation

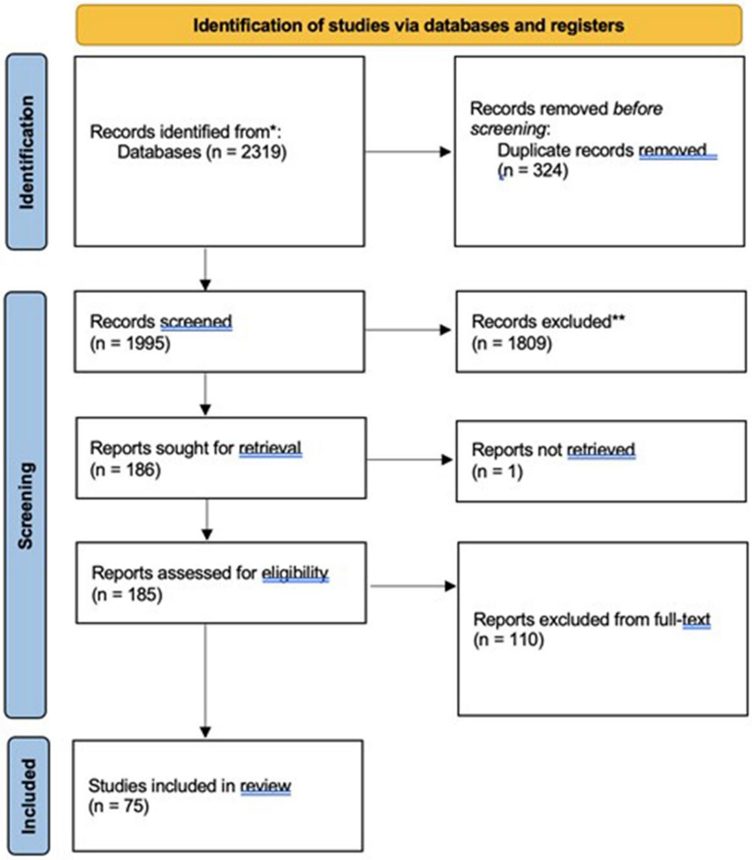

Fig. 1 Flow-diagram

On the other hand, a too-fast transition to assisted ventilation or its improper setting can be associated with the following problems:

a) Less control of ventilatory pattern and spontaneous effort, with risk of ventilation-associated lung injury caused by the development of excessive tidal volumes and transpulmonary pressure swings (Patient Self-Inflicted Lung Injury, P-SILI)
b) Bad patient-ventilator interaction with risk of asynchronies
c) Impairment of diaphragmatic function (myotrauma) that can become clinically manifest as muscular exhaustion if the respiratory assistance is insufficient or as disuse atrophy in case of over-assistance [8].

During assisted ventilation, the patient metabolic demands, and consequently oxygen consumption and carbon dioxide (CO_2) production, are increased, leading to an increased respiratory load. While during controlled ventilation, permissive hypercapnia and hypoxia can be accepted; during assisted ventilation, pH and arterial partial pressure of oxygen (PaO_2) should be maintained closer to physiological values. In the presence of conditions associated with increased respiratory drive (e.g., severe hypoxia, acidosis, agitation, fever), patients may generate high inspiratory efforts, resulting in excessive transpulmonary pressure swings and non-protective tidal volumes. In these conditions, alveolar pressure can reach markedly negative absolute values that reflect the important reduction of inspiratory airway pressure and favor the movement of fluids from the interstitial space to the alveoli, thus worsening alveolar oedema and triggering a vicious circle that causes P-SILI [3, 9].

With regard to the effects of mechanical ventilation on diaphragmatic function, even short periods of controlled (passive) ventilation can cause an alteration of contractility of the diaphragm and atrophy (i.e., the so-called ventilator-induced diaphragmatic dysfunction, VIDD), which can be prevented by preservation of diaphragmatic inspiratory contraction during assisted ventilation [10, 11]. However, even during assisted

Table 1 Items and statements approved by the panel of experts

1. Rationale for the monitoring of assisted mechanical ventilation
The objective of assisted ventilation monitoring is to ensure protective ventilation of the lung and diaphragm Monitoring during assisted ventilation should not be limited to the simple control of the respiratory pattern and gas exchange, but it should also include the monitoring of respiratory drive and effort, diaphragmatic function, respiratory mechanics, and patient-ventilator synchrony
2. Choice of the level of assistance in assisted invasive mechanical ventilation modes
2.1 During assisted invasive mechanical ventilation, the inspiratory support should aim to control the inspiratory effort, protect the lung and the diaphragm, maintain patient-ventilator synchrony, and preserve gas exchange and patient's comfort, limiting the degree of dyspnea
3. Monitoring of respiratory patterns during assisted invasive mechanical ventilation
3.1 Based on the available evidence, the panel suggests performing a careful monitoring of respiratory pattern in all acute respiratory failure (ARF) patients switched to an assisted invasive mechanical ventilation mode after a prolonged period of controlled mechanical ventilation, independently of the etiology of respiratory failure. Moreover, it is suggested to monitor the respiratory pattern of patients with difficult or prolonged weaning 3.2 The panel of experts suggests that respiratory rate, tidal volume, minute ventilation, and the analysis of both ventilator and patients' respiratory cycles should be monitored during assisted invasive mechanical ventilation
4. Monitoring of respiratory effort during assisted invasive mechanical ventilation
4.1 Monitoring of respiratory effort during partial ventilatory support is of pivotal importance to avoid providing over or under-assistance to the patients, causing respectively atrophy or muscular lesions. A high inspiratory effort is the pathophysiological mechanism leading to patient self-inflicted lung injury (P-SILI). Promptly recognizing an increase of inspiratory effort can allow preventing of a chain of events leading to the P-SILI
5. Monitoring of diaphragm functionality during invasive assisted ventilation
5.1 Based on the available evidence, the panel believes that monitoring of diaphragmatic function should be considered in patients undergoing invasive assisted mechanical ventilation, especially after a prolonged period of controlled mechanical ventilation. The panel considers of pivotal importance the monitoring of diaphragmatic function in cases of difficult or prolonged weaning 5.2 Diaphragmatic function can be effectively monitored through invasive and non-invasive techniques. Among the invasive techniques, there are the monitoring of esophagal (Pes) and transdiaphragmatic (Pdi) pressure, and the monitoring of electrical activity of the diaphragm (EAdi)
6. Monitoring of respiratory drive during invasive assisted ventilation
6.1 Monitoring of respiratory drive is extremely helpful for the proper setting of the level of ventilator assist during partial ventilatory support, preventing muscle atrophy or fatigue, and ultimately interrupting the cascade of events leading to patient self-inflicted lung injury (P-SILI) 6.2 Variations in respiratory drive, when appropriate neuro-mechanical coupling is present, result in proportional increases in inspiratory effort. Dysregulation of respiratory drive is a cause of patient self-inflicted lung injury (P-SILI). Prompt recognition of increased respiratory drive allows the identification and management of the cascade of events leading to P-SILI
7. Monitoring patient-ventilator synchrony during invasive assisted ventilation
7.1 The panel recommends close monitoring of patient-ventilator synchrony in patients with acute respiratory failure (ARF) undergoing assisted ventilation after a period of controlled mechanical ventilation or in those experiencing difficult and/or prolonged weaning. Additionally, the panel advises monitoring of ventilator waveforms (pressure, flow, and volume) when evaluating patient-ventilator synchrony. In cases of challenging evaluation and/or assisted ventilator settings difficult to manage, advanced monitoring methods, such as diaphragmatic electrical activity or esophagal pressure measurements, should be employed
8. Monitoring for the discontinuation of invasive assisted ventilation
An integrated approach combining monitoring of respiratory parameters, gas exchanges, neuro-ventilatory "drive," respiratory workload, clinical lung, and diaphragmatic ultrasound, can provide pivotal information for the process of weaning from assisted ventilation The use of assisted ventilation with proportional modes can be useful to lower the risk of respiratory muscle disfunction and to favor the weaning from invasive assisted mechanical ventilation

ventilation, diaphragmatic dysfunction may occur, due to an improper setting of the level of inspiratory assistance provided by the ventilator. If the inspiratory support is insufficient, the diaphragm will develop fatigue/muscular exhaustion, and if it is excessive, muscular atrophy can occur due to disuse of the diaphragm.

For all these reasons, it is important to set up careful respiratory monitoring, independently from the mode of ventilation, especially in patients who require prolonged periods of mechanical ventilation. Monitoring should not be limited only to gas exchanges and respiratory pattern (tidal volume and respiratory rate), but it should also include respiratory drive, inspiratory effort, diaphragmatic function, and patient-ventilator synchrony.

Choice of the level of assistance in assisted invasive mechanical ventilation modes

Statement 2.1

During assisted invasive mechanical ventilation, the inspiratory support should aim to control the inspiratory effort, protect the lung and the diaphragm, maintain patient-ventilator synchrony, and preserve gas exchange and patient's comfort, limiting the level of dyspnea.

Rationale

Assisted ventilation modes may have a significant impact on gas exchange, risk of ventilator-induced lung injury, and patient comfort. By definition, assisted ventilation modes require a certain degree of interaction between the patient and the ventilator. Appropriate setting of the level of inspiratory support, of the sensitivity of inspiratory trigger, of the pressurization ramp and of the cycling between the inspiratory phase and expiratory of the mechanical breath are paramount importance.

The inspiratory support setting determines the amount of pressure added to positive end-expiratory pressure (PEEP) during inspiration. It is important to set a level of inspiratory pressure that preserves gas exchange within the physiological range, ensures a sufficient degree of comfort, controls dyspnea, and provides protective ventilation of the lung and the diaphragm. An absent or too low respiratory effort promotes diaphragmatic dysfunction, resulting in weaning difficulty, atelectasis, and hypoxia. Several studies have shown that patients admitted to intensive care unit (ICU) due to acute respiratory failure develop diaphragmatic weakness in 64% of cases and difficult weaning in 80% already after 24 h of mechanical ventilation [12, 13]. This leads to worse clinical outcomes, in particular prolonged mechanical ventilation, increased length of ICU stay, and higher risk of morbidity and mortality [14].

When setting the level of pressure support taking into account patient respiratory drive and effort, the decrease of airway pressure (Paw) observed in the first 100 ms during an end-expiratory occlusion (P0.1) should be >1 cmH_2O and $<3.5-4$ cmH_2O to avoid both under- and over-assistance [15].

The peak variation of the Paw obtained during an end-expiratory hold (ΔPocc) allows to obtain an estimate of the pressure developed by respiratory muscles (Pmusc) ($Pmusc = \frac{3}{4}\ \Delta Pocc$) and of the dynamic transpulmonary pressure swings (ΔPLdyn) ($\Delta PLdyn = \Delta Paw — \frac{2}{3}\ \Delta Pocc$) [16]. The inspiratory support should then be set to maintain a $Pmusc < 13-15$ cmH_2O OR or a $\Delta PLdyn < 16-17$ cmH_2O [16].

An alternative method to estimate the pressure developed by the respiratory muscles is represented by the Pmusc.index (PMI), calculated as the difference between the plateau airway pressure (Paw_{plat}) obtained during a tele-inspiratory pause, and the sum of PEEP and inspiratory support pressure ($PMI = Paw_{plat} - (PS + PEEP)$). It has been shown that this method may help to identify conditions of inadequate assistance [17]: a $PMI > 6$ cmH_2O suggests an excessive inspiratory effort, possibly indicating an insufficient inspiratory support [17].

The control of patient-ventilator interaction is also fundamental. Indeed, an excessive level of inspiratory support during assisted ventilation is associated with injurious tidal volumes (> 8 ml/kg) and high driving pressures (≥ 12 cmH_2O), exposing the patients to a high risk of asynchronies and high values of mechanical power [18]. Targeting a tidal volume between 6 and 8 ml/kg and an airway driving pressure (static method [19]) < 11 cmH_2O during assisted ventilation have been associated with a reduced risk of mortality in patients with ARDS [19]. Particular attention should be conferred to achieving an individualized and optimal level of ventilatory assistance, precisely tailored to the patient's specific respiratory demands. Indeed, available evidence [20] indicates that both insufficient and excessive support may promote patient–ventilator asynchronies and increase dyspnea. Therefore, maintaining an optimal ventilator "comfort zone" of ventilatory support is crucial to balance patient comfort and synchrony.

Also, ultrasound may be employed to evaluate the amount of assistance: the variation in diaphragm thickness over the days can help to recognize excessive or reduced mechanical support.

In conclusion, setting inspiratory support in assisted ventilation modes requires a thorough understanding of respiratory mechanics and of the patient's physiology. A careful regulation of the level of pressure support, of the trigger sensitivity, of cycling on- and off-criteria, and rise time can contribute to improve patient comfort and gas exchange and to facilitate weaning from mechanical ventilation. Continuous monitoring and individualized adjustments are fundamental to guarantee optimal results in patients requiring assisted ventilation.

Monitoring of respiratory pattern during assisted invasive mechanical ventilation

Statement 3.1

Based on the available evidence, the panel suggests performing a careful monitoring of respiratory pattern in all ARF patients switched to an assisted invasive ventilation mode after a prolonged period of controlled ventilation, independently of the etiology of respiratory failure. Moreover, it is suggested to monitor the respiratory pattern of patients with difficult or prolonged weaning.

Statement 3.2

The panel of experts suggests that respiratory rate, tidal volume, minute ventilation, and the analysis of both ventilator and patients' respiratory cycles should be monitored during assisted invasive mechanical ventilation.

Rationale

As previously described, if neuromuscular transmission is preserved, a high respiratory drive may translate in excessive inspiratory efforts that in turn may result in P-SILI [21–23].

Allowing the maintenance of spontaneous ventilation, with an optimal effort and respiratory pattern, and obtaining a rapid weaning from invasive mechanical ventilation, should be a priority in patients with acute respiratory failure.

Therefore, monitoring of the respiratory pattern becomes necessary to meet the goal of lung- and diaphragm-protective ventilation [24].

As described by Scott et al. [25], clinical examination of the patient is essential, but some parameters are often overlooked. In 2019, Tobin emphasized the pivotal role of a thorough clinical examination in evaluating a patient's respiratory effort [26]. Even simple bedside observations can provide valuable information: for instance, palpable activation of the sternocleidomastoid muscle serves as a reliable marker of increased inspiratory load, while a visible downward displacement of the trachea with each inspiratory effort reflects heightened work of breathing and inspiratory muscle recruitment.

Respiratory rate (RR), for example, is often underestimated, although it is an early indicator of clinical deterioration that may precede the modifications of other vital parameters.

The normal value of RR in an adult patient is 12 − 20 breaths/min and it varies during physical activity and sleep [27]. In patients with ARF, an increased RR may indicate conditions such as hypoxia, pain, heart failure, or metabolic disorders such as lactic acidosis [28, 29] It has been shown that a RR above 35 bpm is one of the main parameters that predicts failure of spontaneous breathing trials during weaning [28, 29]. Furthermore, RR is incorporated into the "Rapid Shallow Breathing Index" (RSBI), which is the most used index for assessing the risk of failure of a spontaneous breathing trial. The RSBI is calculated as the ratio between RR and tidal volume (Vt), and during a spontaneous breathing trial, an RSBI superior to 105 is considered highly predictive of failure [30]. During the weaning phase, an increase in RR may indicate respiratory fatigue due to insufficient ventilator assistance. However, the changes in RR can also be related to the ventilatory support. For example, an excessive level of ventilator assistance may induce dynamic hyperinflation and promote ineffective efforts, which may diminish or disappear with the reduction of the level of ventilatory assistance. In this scenario, the reduction of the level of assist will lead to an increase in RR not due to respiratory distress, but simply to the fact that each inspiratory effort of the patient will trigger the ventilator. Similarly, a RR higher than 35 bpm does not necessarily indicate a high respiratory drive, as it may simply represent the "unstressed" rate that is the rate selected by respiratory centers located in the brainstem [31, 32]. The "unstressed" RR varies significantly between healthy and sick individuals, and it is, on average, 10 bpm higher in critically ill patients [31, 32].

A decrease in RR (i.e., bradypnea, defined as a RR < 12 bpm) may instead indicate a neurological depression, a ventilatory over-assistance [18, 33], excessive sedation or sleep apnea (more difficult to identify during invasive ventilation) [27, 34].

During the prolonged weaning phase, the presence of a persistently low Vt may lead to the onset of dyspnea even in the absence of objectively increased respiratory effort. This paradoxical dissociation suggests that the sensation of breathlessness in such patients is not solely determined by mechanical load or muscle recruitment, but may also arise from altered respiratory drive or impaired neuromechanical coupling. Consequently, continuous monitoring of Vt becomes essential to identify this subtle yet clinically significant manifestation. Failure to recognize low Vt–associated dyspnea could delay liberation from ventilatory support and contribute to patient discomfort or respiratory failure recurrence [35].

"Minute ventilation," defined as the amount of gas moving into and out of the lungs over a minute, is the product of RR and Vt [36]. Like RR, increase or decrease in minute ventilation has also been shown to be an early indicator of respiratory failure [37].

In addition to minute ventilation, several studies [38, 39] have demonstrated the importance of respiratory cycle analysis in terms of duration of the respiratory phases and speed at which the gas is inspired and expired [40]. The two most frequently evaluated parameters are the ratio between tidal volume and inspiratory time (Vt/Ti) and the ratio between inspiratory time and respiratory time (Ti/Ttot).

The Vt/Ti has been widely used to measure respiratory drive, even though it has limits compared to P0.1, as it tends to underestimate respiratory drive in case of marked alterations of the respiratory mechanics [41].

The Ti/Ttot, instead, indicates the relationship between the duration of inspiration and expiration and provides a rough evaluation of the degree of airway obstruction [27]. As the respiratory muscles are usually normally active only during the inspiration, Ti/Ttot has also been defined as the respiratory work cycle. Therefore, the stress level to which respiratory muscles are subjected is proportional to the Ti/Ttot ratio [42, 43].

Today, several "tools" are available to monitor respiratory pattern. In particular, the electrical activity of the diaphragm (EAdi). EAdi is obtained using a modified nasogastric catheter equipped with a series of electrodes positioned at the level of the distal esophagus. It is the closest measure to the output of the respiratory centers [44]. EAdi does not have well-defined reference values, making it useful primarily for evaluating trends within the same patient. However, it does not assess the activity of extra-diaphragmatic respiratory muscles. Overall, values between 5 and 15 μV can generally be considered adequate. A limitation of this technique is that EAdi measurement is available only on one commercially available mechanical ventilator.

EAdi is easy to monitor, and it has proven to be a good surrogate of respiratory drive and has a strict correlation with transdiaphragmatic pressure (Pdi), an index of respiratory effort [45]. However, EAdi variations are useful to monitor the changes of respiratory drive and effort of the patients and to identify patients at risk of over-assistance by the ventilator.

The combination of EAdi with the analysis of breathing pattern provides an index capable of evaluating the contribution of the diaphragm to Vt generation. In particular, the Vt/EAdi ratio represents the "neuroventilatory efficiency" of the diaphragm that reflects the capacity of the diaphragm to convert respiratory drive into ventilation. When the Vt/EAdi ratio is high, the patient generates a high Vt with a low EAdi value, while when it is low, the patient generates a small Vt despite a high EAdi. A low Vt/EAdi indicates severe neuroventilatory coupling impairment and may help identify patients at high risk of weaning failure [42, 43].

In conclusion, the expert panel recommends careful monitoring of the respiratory pattern (i.e., RR, minute ventilation, Vt, and respiratory cycle analysis) in patients with ARF undergoing assisted mechanical ventilation, to prevent the onset of P-SILI and to facilitate weaning from the mechanical ventilator.

Monitoring respiratory effort during assisted invasive mechanical ventilation

Statement 4.1

Monitoring respiratory effort during partial ventilatory support is of pivotal importance to avoid providing over or under-assistance to the patients, causing respectively atrophy or muscular lesions. A high inspiratory effort is the pathophysiological mechanism leading to P-SILI. Promptly recognizing an increase of inspiratory effort can prevent a chain of events leading to the P-SILI.

Rationale

Monitoring respiratory effort during assisted ventilation can provide useful information to the clinician. In case of adequate neuro-mechanical coupling, patients with high inspiratory efforts will also have a high respiratory drive [46]. In a smaller percentage of patients, usually characterized by respiratory muscles weakness, there is a neuromuscular decoupling, characterized by high respiratory drive that does not translate into high effort (Fig. 2).

As previously described, a high inspiratory effort, associated with high transpulmonary pressures, may lead to P-SILI. Despite [47] this, measurement of respiratory effort is still rarely used in clinical practice, although it may be non-invasively estimated at the bedside [48].

In recent study, Telias and colleagues provide important physiological insights into the impact of patient breathing effort during acute hypoxemic respiratory

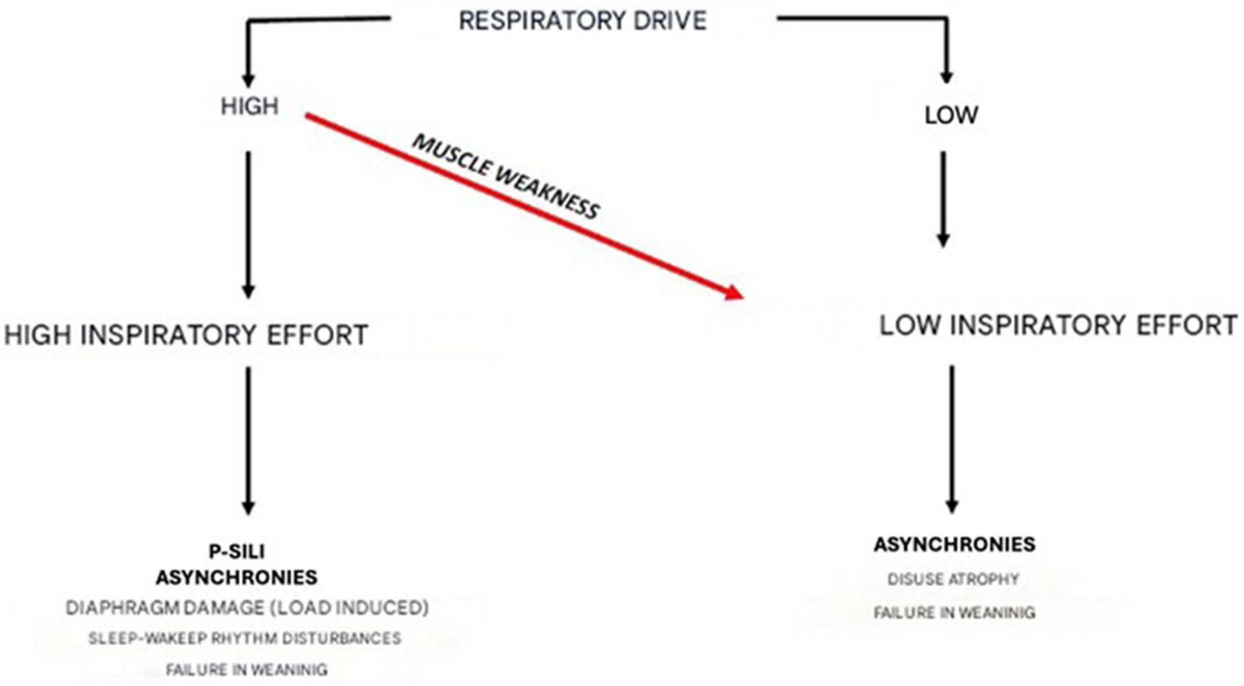

Fig. 2 Pathophysiological pathways leading to P-SILI and/or asynchronies based on respiratory drive and inspiratory effort

failure [49]. The authors demonstrate that vigorous inspiratory effort is associated with increased indices of lung stress and strain, greater transpulmonary pressure swings, and more pronounced alveolar pressure drops—effects that differ across modes of assisted ventilation. These findings suggest that, while spontaneous effort may support gas exchange and diaphragm activity, excessive effort can exacerbate lung injury through P-SILI.

The reference method for the measurement of respiratory muscle effort is represented by the negative oscillations of esophageal pressure. This method is characterized by some drawbacks, which limit its diffusion in the clinical practice; in particular, it requires the use of dedicated catheters and a certain level of expertise in calibration and interpretation of the tracings [50].

To obtain an accurate measure, a careful calibration of the esophageal balloon is needed [51]. Different calibration methods have been proposed for paralyzed patients under controlled ventilation [52] and for patients with different degrees of spontaneous activity [50, 53]. Reliable indices for monitoring the inspiratory effort are the variation of the Pes oscillations, also known as delta Pes (ΔPes) [54], the work of breathing (WOBes) [55], the pressure–time product (PTPes) [56], and the pressure-frequency product respiratory (PRPes) [56, 57]. The panel agrees on considering Pes the gold standard method for the measurement of the inspiratory effort [58] also in pediatric patients [59] but the calibration procedures require a certain level of experience and familiarity with the technique.

The negative deflection of airway pressure detected on the airway tracing (ΔPocc) during a single inspiratory effort against an occluded airway (i.e., during an end-expiratory hold) is a simple, rapid, non-invasive, and reliable indicator of respiratory effort. This index is based on the principle that the negative pressure generated during an expiratory pause represents a reliable estimate of the pressure developed by the respiratory muscles to expand the lungs and the chest wall during an assisted breath [16, 60–62].

The measurement of the activity electric of the diaphragm (EAdi) allows an estimation of inspiratory effort during assisted ventilation without the need for an esophagal balloon catheter by measuring the Pmus/EAdi ratio (PEI), also known as the index of “neuromuscular efficiency” [45] (i.e., the amount of pressure developed by the respiratory muscles per microvolts of diaphragm electrical activity).

1. Diaphragmatic ultrasonography allows to measure the displacement (excursion) and the thickening fraction of the diaphragm [63]. In subjects under spontaneous, unassisted breathing, values of excursion < 1 cm, and diaphragmatic thickening fraction (Dt_{di}) < 30% are suggestive of diaphragmatic dysfunction. Recent studies have shown that, during partial ventilatory support, displacement is not very specific as it is influenced by the positive pressure generated by the ventilator, while a significant correlation was found between inspiratory effort and thickening fraction. Monitoring of diaphragm function during invasive assisted ventilation.

Statement 5.1

Based on the available evidence, the panel believes that monitoring of diaphragmatic function should be considered in patients undergoing invasive assisted mechanical ventilation, especially after a prolonged period of controlled mechanical ventilation. The panel considers pivotal importance monitoring of the diaphragmatic function in cases of difficult or prolonged weaning.

Statement 5.2

Diaphragmatic function can be effectively monitored through invasive and non-invasive techniques. Invasive techniques are the monitoring of Pes and Pdi pressure, and the monitoring of EAdi. Diaphragm ultrasound is the most common non-invasive monitoring technique.

Rationale

A growing body of evidence shows that both lung and diaphragm function are crucial for the success of weaning from mechanical ventilation [64, 65]. Despite this, diaphragmatic function monitoring is still not adequately implemented in the clinical practice [66]. The goals of diaphragmatic function monitoring can be summarized as follows:

i) To reduce P-SILI during assisted ventilation
ii) To reduce the risk of patient-ventilator asynchronies
iii) To monitor the process of weaning and prevent its failure [66].

Compared to Pes, the measurement of Pdi allows a more accurate measurement of the inspiratory effort [35] and the overall quantification of the contribution of respiratory muscles to respiratory work [67, 68]. In daily clinical activity, Pdi and its derivative PTPdi require a longer time for the operations of calibration at the bedside [50, 53].

Diaphragm ultrasound can be used to monitor diaphragmatic function over time [69]. Different studies have proposed techniques and indexes: diaphragm thickness (Dt) and the Dt_{di} seem to correlate with the force detected through the Pdi and with EAdi [70]. For this reason, they have been proposed as indexes to monitor assisted ventilation, prevent fatigue, facilitate a recovery of diaphragmatic contractility, and evaluate the effect of sedation on diaphragmatic function [70–72]. Other indices have been proposed, both by exploiting the M-Mode [73, 74], and by using the Doppler [75] or by employing algorithms [68, 75]. However, some studies have highlighted the limits of these parameters and a poor correlation with the Pdi, imposing caution in its use, especially in unexperienced hands [34, 76]. Recently, the same ultrasound approaches adopted for the diaphragm have also been proposed for the evaluation of the intercostal and abdominal (expiratory) muscles, expanding the potential of ultrasound monitoring of respiratory muscle function [77]. The panel recommends using these non-invasive techniques at the integration of other invasive assessment techniques and after an adequate learning curve [78, 79].

EAdi is the last technique of invasive monitoring introduced in the market [80]. It is sensitive to the variations in patient drive effort both with its peak values ($EAdi_{peak}$) [80] and with the integral under the EAdi curve ($EAdi_{AUC}$) [81]. EAdi has shown excellent correlation with the Pes measures, resulting in a reliable quantification of the inspiratory effort [45], although with a high degree of individual variability. In the literature, various Eadi-derived indexes have been described, among which some deserve interest for the monitoring of diaphragmatic functionality: (a) the neuro-ventilatory efficiency (NVE) [81], i.e., the ratio between tidal volume and $EAdi_{peak}$; (b) the neuro-muscular efficiency index (NME), calculated as the ratio between delta airway pressure and delta $EAdi_{peak}$ ($\Delta Paw/\Delta EAdi_{peak}$) during an expiratory occlusion maneuver [82, 83]. This $\Delta Paw/\Delta EAdi_{peak}$, however, is characterized by an extreme inter- and intra-patient variability imposing the execution of more than one maneuver to obtain a reliable result [84]. The ability to monitor both neural activity and the generated force has generated the concept of neuro-muscular-coupling that allows to detect discrepancies between alterations in the neural drive and its capacity to generate muscular work [85]. The possibility to monitor diaphragmatic function and to guide the ventilator proportionally to the patient's drive, as provided by neurally adjusted ventilatory assist (NAVA) mode, has permitted a combined use of the EAdi traces to perform a monitored training of the diaphragm [85, 86]. Surface electromyography is a recently developed noninvasive technique that seems as reliable as EAdi for diaphragm activity monitoring [77, 87]. In addition, it allows the assessment of extra-diaphragmatic muscles function [77, 87, 88], but further research is needed to fully validate its use.

The panel underlines that these monitoring tools are commonly employed during weaning tests: unfortunately, the difference in weaning test settings across the studies made comparison and unified interpretation quite hard [89]. The panel reiterates the crucial importance of monitoring diaphragmatic function with at least one of the proposed monitoring methods (preferably at least 2) and using a predefined weaning protocol to guarantee a standardized approach.

Monitoring of respiratory drive during invasive assisted ventilation

Statement 6.1

Monitoring of respiratory drive is extremely helpful for the proper setting of the level of ventilator assist during partial ventilatory support, preventing muscle atrophy or fatigue, and ultimately interrupting the cascade of events leading to P-SILI.

Rationale

Respiratory drive refers to the stimulus sent by the respiratory centers located in the brainstem to the respiratory muscles, determining the intensity of their contraction [90]. These centers also regulate the timing of respiratory muscle activation, thus defining the RR. Respiratory drive is primarily modulated by blood gases through central and peripheral chemoreceptors, mechanoreceptors located in muscle fibers and within the lung parenchyma, and stimuli associated with psychological alterations such as anxiety and agitation originating from the central nervous system. The activity of the respiratory centers is also influenced by medications, mainly sedatives, and by the level of ventilator support provided during mechanical ventilation [91].

Statement 6.2

Variations in respiratory drive, in the presence of appropriate neuro-mechanical coupling, result in proportional increases in inspiratory effort [46] (Fig. 1). Prompt recognition of increased respiratory drive allows the identification and management of the cascade of events leading to P-SILI [47].

Rationale

Two techniques are available to assess respiratory drive in the clinical setting: integrated EAdi [44], which allows breath-by-breath measurement of respiratory drive; and the change in airway pressure measured during the first 100 ms of the inspiratory phase with an occluded airway (P0.1) [92]. EAdi guarantees the possibility of monitoring both the neural RR and the amount of the neural drive via the $EAdi_{peak}$ [80] and/or the $EAdi_{AUC}$ [81].

P0.1 is automatically or semi-automatically measured by most commercially available mechanical ventilators, although it cannot be assessed breath-by-breath. The optimal target for respiratory drive remains uncertain, but currently, a $P0.1 > 4$ cmH_2O is considered high and predictive of excessive inspiratory effort by the patient, with a sensitivity of 92% and a specificity of 89% [15, 93, 94].

Monitoring patient-ventilator synchrony during invasive assisted ventilation

Statement 7.1

The panel recommends close monitoring of patient-ventilator synchrony in patients with ARF undergoing assisted ventilation after a period of controlled mechanical ventilation or in those experiencing difficult and/or prolonged weaning. Additionally, the panel advises monitoring of ventilator waveforms (pressure, flow, and volume) when evaluating patient-ventilator synchrony. In cases of challenging evaluation and/or assisted ventilator settings difficult to manage, advanced monitoring methods, such as EAdi or Pes measurements, should be employed.

Rationale

The primary aim of mechanical ventilation is to assist or take over the patient's respiratory function, enabling recovery from the underlying illness and enhancing clinical outcomes. However, optimizing ventilator settings, tailored to individual patients, can often be challenging, as [90, 95–97]. Significant inter- and intra-patient variability in respiratory mechanics and subsequent adaptation to MV [98–101] may lead to suboptimal care and outcomes.

Specifically, suboptimal ventilator settings during assisted ventilation modes can cause a temporal discrepancy between the patient's respiratory effort and the ventilator's support. This discrepancy is referred to as "patient-ventilator asynchrony." More specifically, patient-ventilator asynchrony represents a lack of coordination between the patient and the ventilator, caused either by a mismatch between the patient's neural respiratory timing and the mechanical timing set on the ventilator or by a disparity between the ventilator's support and the patient's demands [102–105]. Unfortunately, this is a very common issue among mechanically ventilated patients, with an incidence as high as up to 80% [106].

As demonstrated by de Haro et al. [107], asynchronies were detected in 97% of mechanically ventilated patients, including also those under deep sedation or neuromuscular blockade, with a median asynchrony index of 3.41% (IQR 0.96–8.39). These findings highlight that asynchronies are pervasive, even in supposedly fully controlled conditions, underscoring the importance of continuous monitoring and ventilator optimization to minimize their occurrence.

Several studies [108, 109] have demonstrated that significant patient-ventilator asynchrony (defined as an asynchrony index > 10%) [53] is associated with worse clinical outcomes, such as prolonged mechanical ventilation, prolonged ICU and hospital stays, increased ICU and in-hospital mortality, and higher risks of pneumonia and tracheostomy [109].

The ability to accurately identify and monitor asynchronies in real-time provides critical information to guide and personalize the respiratory support in critically ill patients.

Recent advances in artificial intelligence and machine learning have significantly improved the automated detection and characterization of patient–ventilator asynchronies. Contemporary reviews provide comprehensive overviews of AI-driven algorithms capable of accurately identifying asynchrony patterns, supporting real-time monitoring, and facilitating personalized ventilatory management [110, 111].

Patient-ventilator asynchronies are categorized into major types (e.g., ineffective efforts, auto-triggering, double-triggering, and reverse triggering) and minor types (e.g., premature or short cycling, prolonged or delayed cycling, and inspiratory or expiratory trigger delays) [112] (Table 2).

Currently, visual assessment of ventilator waveforms (pressure and/or flow) is one of the main methods used to identify patient-ventilator asynchronies at the bedside, especially major types [113, 114]. However, this highly subjective method requires specific training and experience. Studies have shown that less than 25% of ICU healthcare providers can correctly identify all types of patient-ventilator asynchronies [115, 116]. Furthermore, each type requires specific therapeutic strategies to reduce the asynchrony itself and mitigate the risk of prolonged weaning [117].

To address the subjectivity of waveform analysis and the lack of continuous patient-ventilator interaction monitoring, research has focused on developing real-time automated asynchrony detection systems using machine learning approaches, not influenced by "noise" due to secretions or patient movements [118–122].

Chen et al. [123] evaluated and designed a software able to detect ineffective efforts using a computerized algorithm based on flow waveform characteristics and pressure deflections. They applied this software to 14 mechanically ventilated adults and showed a sensitivity and specificity of > 90% for detecting ineffective efforts.

Table 2 Patient-ventilator asynchronies

Asynchrony	Type	Definition	Possible solutions
Ineffective efforts	Asynchrony between respiratory drive and inspiratory trigger	The ventilator is unable to detect the neural effort of the patient despite the presence of an inspiratory effort	Optimizing the sensitivity of the inspiratory trigger Reducing sedation or use of drugs with little or no effect on the respiratory drive Reducing respiratory support Correcting metabolic alkalosis Increasing PEEP or counterbalancing the intrinsic PEEP Reducing mechanical inspiratory time, optimizing expiratory trigger in case of COPD patient If the asynchronies persist, consider a neural trigger
Auto trigger	Asynchrony between respiratory drive and inspiratory trigger	Mechanical act not activated by the inspiratory neural effort of the patient	Optimizing sensitivity of the inspiratory trigger Reducing the noises present in the circuit Eliminating the leaks
Double trigger	Asynchrony between neural inspiratory time and ventilator variables	Two mandatory acts that can or cannot be separated by a brief expiratory time	Increasing the inspiratory time, in time cycled act Increasing the inspiratory flow Optimizing the expiratory trigger threshold in PSV Optimizing the pressurization ramp in PSV Removing the causes of reverse triggering
Reverse triggering	Asynchrony in variables of the cycle of the ventilator	The insufflation of the ventilator activates the diaphragm	Reducing the assistance of the ventilator Reducing sedative medications Myoresolution
Cycling asynchrony	Asynchrony between the patient's neural inspiratory time and the cycling variables of the ventilator	A mismatch between brainstem respiratory center output and ventilator inspiratory time	Optimizing inspiratory time and threshold of the expiratory trigger in PSV Avoiding excessive assistance Using proportional modes

Younes et al. [124] developed a system to improve patient-ventilator interaction monitoring using signals generated from the equation of motion. This system integrates signals from volume, airway pressure, flow, and esophageal pressure waveforms, and estimates the patient's respiratory system elastance and resistance. It provides a real-time visual trace reflecting the patient's respiratory muscle pressure output, alongside airway pressure and flow, enabling visual detection of asynchronies, such as excessive inspiratory and expiratory trigger delays and ineffective efforts.

Recently, Blanch et al. [125] validated a software capable of detecting major asynchronies during invasive mechanical ventilation, such as ineffective efforts, double-triggering, and short and prolonged cycling. Similarly, Mojoli et al. [126] demonstrated the effectiveness of ventilator waveform analysis conducted by three experienced physicians and one resident specifically trained, showing that waveform interpretation can reliably evaluate patient activity and patient-ventilator interaction at the bedside when a standardized analysis method is adopted after specific training.

For patients who are difficult to ventilate using standard assisted modes (i.e., pressure support ventilation, PSV) or who experience difficult or prolonged weaning, proportional ventilation modes like NAVA and proportional assist ventilation plus (PAV+) have proven effective in improving patient-ventilator interaction and reducing respiratory work [80, 127–129].

However, a recent multicenter randomized trial by Bosma and colleagues demonstrated that PAV$^+$ did not significantly reduce the time to successful liberation from mechanical ventilation compared with pressure-support ventilation. Although PAV$^+$ is based on a physiologically sound rationale by proportionally adjusting assistance to patient effort, the negative primary outcome highlights that theoretical advantages do not necessarily translate into clinical benefit. These findings suggest that, in heterogeneous critically ill populations, the potential advantages of proportional modes require further confirmation before widespread clinical adoption [130].

Nevertheless, during difficult weaning, invasive monitoring of respiratory drive and mechanics, through an esophagal probe to assess Pes or a dedicated gastric probe to measure EAdi, can be useful. Studies on patient-ventilator synchrony have shown that Pes monitoring, when integrated with airway flow and pressure waveforms, can help assess and monitor patient-ventilator synchrony

[131]. For example, Pes monitoring has allowed the identification of an otherwise undetectable type of asynchrony that is reverse triggering [132]. However, while this technique is a potential standard for evaluating and monitoring patient-ventilator synchrony, it is rarely used in clinical practice due to its technical complexity and the expertise required for positioning and calibrating the esophagal probe [119, 132].

EAdi measurement, on the other hand, is relatively simple and can be continuously monitored using dedicated software [118]. As a direct measure of the patient's neural respiratory drive, EAdi signals can be used to regulate the initiation and termination of mechanical inspiration during NAVA, or to monitor the patient's effort, to detect patient-ventilator asynchrony, and to optimize neuro-ventilatory coupling during other assisted modes [42, 129, 133–135]. Several studies have shown that EAdi is useful not only to monitor patient-ventilator synchrony (the gold standard method [46]) but also to adjust ventilator settings during PSV, thereby improving patient-ventilator interaction [135].

In conclusion, the panel of experts recommends monitoring patient-ventilator synchrony in all patients who are difficult to ventilate in standard invasive assisted modes (e.g., PSV), following a period of controlled mechanical ventilation, or experiencing difficult and/or prolonged weaning. Monitoring can be performed visually after adequate training, using automated ventilator waveform analysis systems, or through Pes or EAdi monitoring.

Monitoring for the discontinuation of invasive assisted ventilation

Statement 8.1

An integrated approach combining the monitoring of respiratory parameters, gas exchanges, neuro-ventilatory "drive," respiratory workload, lung, and diaphragmatic ultrasound, can provide pivotal information for the process of weaning from assisted ventilation.

Statement 8.2

The use of assisted ventilation with proportional modes can be useful to lower the risk of respiratory muscle dysfunction and to favor weaning from invasive assisted mechanical ventilation.

Rationale

Several studies have shown that monitoring ventilatory parameters such as Vt, RR, and oxygenation is relevant for clinical decisions about weaning from invasive ventilatory support, although they may be insufficient to predict the risk of re-intubation [136]. Over time, alternative methods have been proposed. Among these, the RSBI, calculated as the ratio between RR and Vt (RR/Vt), and the integrative weaning index (IWI), which is calculated as the product of respiratory system compliance and the ratio of arterial oxygen saturation to RSBI ($IWI = Crs \times SaO_2/RSBI$), have shown moderate predictive power for successful extubation [30, 137, 138].

Although these indices are simple to apply in clinical practice, recent evidence highlights the need for a multifactorial approach towards the weaning process, considering also the mode of ventilatory support. Compared to PSV, which delivers constant support irrespective of the patient's physiological demands, methods such as NAVA or PAV + are associated with better adaptation to assisted ventilation, reduced asynchrony index, and improved respiratory muscle tropism.

Although conclusive evidence is lacking, preliminary studies suggest that proportional modes may accelerate the weaning process and reduce the risk of re-intubation [139–141]. Monitoring the central neuro-ventilatory drive and respiratory muscle workload has proven crucial in making clinical decisions about discontinuing ventilatory support [142].

Currently, EAdi is considered the reference method to assess neuro-ventilatory drive (normal values 5–15 μV) [143]. P0.1 is also a readily interpretable measure of the neuro-ventilatory drive (normal values 1–4 cmH_2O) [15, 92]. Similarly, the measurement of maximum negative deflection during an expiratory occlusion maneuver (ΔPocc) provides a reliable estimate of Pmus without requiring esophageal pressure monitoring, which remains the gold standard but is rarely used in routine clinical practice [16, 144]. Ultrasound, a non-invasive method widely adopted in intensive care, can also provide pivotal information for the weaning timing. Several studies have demonstrated that an integrated approach between lung, cardiac, and diaphragmatic ultrasound may reduce the risk of premature or delayed extubation [145–147]. Data from critically ill patients under assisted ventilation suggest that $Dt_{di} < 20\%$ during respiratory cycles correlates with an increased risk of extubation failure [147]. In the immediate post-extubation phase, the diameter of the inferior vena cava and the presence of B-lines on lung ultrasound are also associated with a higher risk of re-intubation within 48 h from extubation [145, 146]. Electrical impedance tomography (EIT), although less widespread than ultrasound, allows non-invasive, bedside patient monitoring during the process of weaning from mechanical ventilation [148]. Evidence suggests that a heterogeneous distribution of tidal volume between the non-dependent (ventral) and dependent (dorsal) lung regions negatively affects the success of extubation [149]. Finally, prospective observational studies have highlighted that the use of electroencephalography (EEG) and peripheral perfusion index (derived from

Table 3 Monitoring parameters and their role in the different items. In bold and gray background parameters that the authors agreed on defining as standard of practice/gold standard for that specific items

			Items						
Source/Technique	**Parameter**	**Reference Value**	Choice of the level of assistance (2)	Monitoring of respiratory patterns (3)	Monitoring of respiratory effort (4)	Monitoring of diaphragm function (5)	Monitoring of respiratory drive (6)	Monitoring patient-ventilator synchrony (7)	Monitoring for the discontinuation of invasive assisted ventilation (8)
Ventilator Parameters	Vt	6-8 ml/Kg	X	X					X
	RR	12 - 20 /min		X			X		X
	V_E			X					
	Ventilator waveforms							X	
Calculated from the ventilator	RSBI	<105		X					X
	Vt/Ti			X					
	Ti/T_{TOT}			X					
	ΔP	<11 cmH_2O	X						
Manouver on Ventilator	P0.1	1-4 cm H_2O	X				X		
	ΔP_{occ}	10-12 cm H_2O	X		X				X
	PMI	<6 cm H_2O	X						
Oesophageal/Gastric balloon	P_{es}				**X**	X		X	
	WOBes				X				
	PTPes				X				
	P_{di}					X			
EAdi Catheter	$Eadi_{peak}$	5-15μV		X	X	X	**X**	**X**	X
	$EAdi_{AUC}$					X	X		
	Vt/Eadi			X					
	$Paw/EAdi_{peak}$				X	X			
Ultrasound	Ex_{di}	>1 cm			X				
	T_{di}					X			
	Dt_{di}	>30%	X		X	X			X
Impedence	EIT								X

pulse oximetry) can provide important information on the chance of weaning success [150, 151].

In conclusion, the discontinuation of invasive assisted ventilation requires an integrated approach that accounts for the ventilatory pattern and supports the use of proportional methods, monitors the neuro-ventilatory drive and respiratory workload, employs lung and diaphragmatic ultrasound to optimize weaning timing, and reduces the risk of re-intubation.

Limitations

This consensus is not based on a systematic literature review, and this limitation has to be clearly acknowledged. We opted for a consensus based on clinical expertise, well aware that this approach has weaknesses.

Conclusions

At the conclusion of the consensus process, the panel emphasized the importance of comprehensive patient monitoring during assisted ventilation, encompassing all relevant physiological variables (see Table 3). The authors also recommended developing standardized local protocols and procedures to ensure that all team members acquire adequate proficiency with the various techniques and adopt a consistent, evidence-informed clinical approach.

Abbreviations

Crs	Respiratory system compliance
Dt_{di}	Diaphragm thickening fraction
EIT	Electrical impendence tomograph
EAdi	Electrical activity of the diaphragm
$EAdi_{peak}$	Peak of the electrical activity of the diaphragm
$EAdi_{AUC}$	Area under the curve of electrical activity of the diaphragm
EX_{di}	Diaphragm excursion
IQR	Interquartile range
ΔP	Driving pressure (pressure support–positive end expiratory pressure)
ΔPocc	Variation of occlusion pressure (the maximum negative deflection during an expiratory occlusion maneuver)
MV	Mechanical ventilation
NAVA	Neurally adjusted ventilatory assist
NME	Neuro-muscular efficiency index
NVE	Neuro-ventilatory efficiency
PAV+	Proportional assist ventilation plus
Paw	Airway pressure
Paw/EAdi	Airways pressure on electrical activity of the diaphragm ratio
Pdi	Trans-diaphragmatic pressure
Pes	Esophageal pressure
PEEP	Positive end expiratory pressure
Pmus	Respiratory muscle pressure
PMI	Pressure-muscular index (the difference between the plateau airway pressure obtained during a tele-inspiratory pause, and the sum of PEEP and pressure support)
P0.1	Inspiratory negative pressure during the first 100 ms of the effort
Pplat	Plateau pressure
P-SILI	Patient self-inflicted lung injury
PSV	Pressure support ventilation
PTPes	Esophageal pressure time product
RR	Respiratory rate
V_E	Minute ventilation

RSBI	Rapid shallow breathing index (RR/Vt)
WOBes	Esophageal work of breathing
T_{di}	Diaphragm thickening
Ti/T_{TOT}	Inspiratory time on total respiratory time ratio
VIDD	Ventilator-induced diaphragmatic dysfunction
Vt	Tidal volume
Vt/Ti	Tidal volume on inspiratory time ratio

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s44158-025-00315-1.

Supplementary Material 1.

Acknowledgements
We would like to thank Dr. Cristina Cacciagrano (SIAARTI Research Office) for the support of this activity and document.

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Funding
The document was issued thanks to the not conditioning support of Getinge.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 3 September 2025 Accepted: 5 November 2025

References

1. Marini JJ (2011) Spontaneously regulated vs. controlled ventilation of acute lung injury/acute respiratory distress syndrome. Curr Opin Crit Care 17:24–9
2. Grieco DL, Menga LS, Eleuteri D, Antonelli M (2019) Patient self-inflicted lung injury: implications for acute hypoxemic respiratory failure and ARDS patients on non-invasive support. Minerva Anestesiol 85(9):1014–1023
3. Carteaux G, Parfait M, Combet M, Haudebourg A-F, Tuffet S, Mekontso Dessap A (2021) Patient-self inflicted lung injury: a practical review. J Clin Med 10(12):2738
4. Vetrugno L, Guadagnin GM, Brussa A et al (2020) Mechanical ventilation weaning issues can be counted on the fingers of just one hand: part 1. Ultrasound J 12:9
5. Quickfall D, Sklar MC, Tomlinson G, Orchanian-Cheff A, Goligher EC (2024) The influence of drugs used for sedation during mechanical ventilation on respiratory pattern during unassisted breathing and assisted mechanical ventilation: a physiological systematic review and meta-analysis. EClinicalMedicine 68:102417
6. The RAND/UCLA appropriateness method user's manual. CA: RAND Corporation 2001.
7. Page M, McKenzie J, Bossuyt P, The PRISMA et al (2020) statement: an updated guideline for reporting systematic reviews. BMJ 2021:372
8. Yoshida T, Uchiyama A, Matsuura N, Mashimo T, Fujino Y (2013) The comparison of spontaneous breathing and muscle paralysis in two different severities of experimental lung injury*. Crit Care Med 41:536–545
9. Marongiu I, Slobod D, Leali M, Spinelli E, Mauri T (2024) Clinical and experimental evidence for patient self-inflicted lung injury (P-SILI) and bedside monitoring. J Clin Med 13:4018
10. Demoule A, Molinari N, Jung B et al (2016) Patterns of diaphragm function in critically ill patients receiving prolonged mechanical ventilation: a prospective longitudinal study. Ann Intensive Care 6:75
11. Vaporidi K, Akoumianaki E, Telias I, Goligher EC, Brochard L, Georgopoulos D (2020) Respiratory drive in critically ill patients. Pathophysiology and clinical implications. Am J Respir Crit Care Med 201:20–32
12. Demoule A, Jung B, Prodanovic H et al (2013) Diaphragm dysfunction on admission to the intensive care unit. Prevalence, risk factors, and prognostic impact—a prospective study. Am J Respir Crit Care Med 188:213–219
13. Dres M, Dubé B-P, Mayaux J et al (2017) Coexistence and impact of limb muscle and diaphragm weakness at time of liberation from mechanical ventilation in medical intensive care unit patients. Am J Respir Crit Care Med 195:57–66
14. Dres M, Demoule A (2018) Diaphragm dysfunction during weaning from mechanical ventilation: an underestimated phenomenon with clinical implications. Crit Care 22:73
15. Telias I, Damiani F, Brochard L (2018) The airway occlusion pressure (P0.1) to monitor respiratory drive during mechanical ventilation: increasing awareness of a not-so-new problem. Intensive Care Med 44:1532–1535
16. Bertoni M, Telias I, Urner M et al (2019) A novel non-invasive method to detect excessively high respiratory effort and dynamic transpulmonary driving pressure during mechanical ventilation. Crit Care 23:346

17. Foti G, Cereda M, Banfi G, Pelosi P, Fumagalli R, Pesenti A (1997) End-inspiratory airway occlusion. Am J Respir Crit Care Med 156:1210–1216
18. Cammarota G, Verdina F, De Vita N et al (2022) Effects of varying levels of inspiratory assistance with pressure support ventilation and neurally adjusted ventilatory assist on driving pressure in patients recovering from hypoxemic respiratory failure. J Clin Monit Comput 36:419–427
19. Bellani G, Grassi A, Sosio S et al (2019) Driving pressure is associated with outcome during assisted ventilation in acute respiratory distress syndrome. Anesthesiology 131:594–604
20. Vitacca M, Bianchi L, Zanotti E et al (2004) Assessment of physiologic variables and subjective comfort under different levels of pressure support ventilation. Chest 126:851–859
21. Carteaux G, Parfait M, Combet M, Haudebourg A-F, Tuffet S, Mekontso Dessap A (2021) Patient-self inflicted lung injury: a practical review. J Clin Med 10:2738
22. Yoshida T, Grieco DL, Brochard L, Fujino Y (2020) Patient self-inflicted lung injury and positive end-expiratory pressure for safe spontaneous breathing. Curr Opin Crit Care 26:59–65
23. Brochard L, Slutsky A, Pesenti A (2017) Mechanical ventilation to minimize progression of lung injury in acute respiratory failure. Am J Respir Crit Care Med 195:438–442
24. Cornejo R, Telias I, Brochard L (2024) Measuring patient's effort on the ventilator. Intensive Care Med 50:573–576
25. Scott JB, Kaur R (2020) Monitoring breathing frequency, pattern, and effort. Respir Care 65:793–806
26. Tobin MJ (2019) Why physiology is critical to the practice of medicine. Clin Chest Med 40:243–257
27. Respiratory care: patient assessment & care plan development. David C. Shelledy, Jay I. Peters. Jones & Bartlett Publishers, 2016 :715 pages.
28. Esteban A, Alia I, Gordo F, Fernandez R, Solsona JF, Vallverdu I (1997) Extubation outcome after spontaneous breathing trials with T-tube or pressure support ventilation. Am J Respir Crit Care Med 156:459–465
29. Esteban A, Alia I, Tobin MJ, Gil A, Gordo F, Vallverdu I (1999) Effect of spontaneous breathing trial duration on outcome of attempts to discontinue mechanical ventilation. Am J Respir Crit Care Med 159:512–518
30. Yang KL, Tobin MJ (1991) A prospective study of indexes predicting the outcome of trials of weaning from mechanical ventilation. N Engl J Med 324:1445–1450
31. Marantz S, Patrick W, Webster K, Roberts D, Oppenheimer L, Younes M (1996) Response of ventilator-dependent patients to different levels of proportional assist. J Appl Physiol 80:397–403
32. Younes M. Control of breathing during mechanical ventilation. Mechanical Ventilation Berlin/Heidelberg: Springer-Verlag; p. 63–82
33. Pletsch-Assuncao R, Caleffi Pereira M, Ferreira JG et al (2018) Accuracy of invasive and noninvasive parameters for diagnosing ventilatory overassistance during pressure support ventilation*. Crit Care Med 46:411–417
34. Carrie C, Gisbert-Mora C, Bonnardel E et al (2017) Ultrasonographic diaphragmatic excursion is inaccurate and not better than the MRC score for predicting weaning-failure in mechanically ventilated patients. Anaesth Crit Care Pain Med 36:9–14
35. Jubran A, Laghi F, Grant BJB, Tobin MJ (2025) Air hunger far exceeds dyspnea sense of effort during mechanical ventilation and a weaning trial. Am J Respir Crit Care Med 211(3):323–330
36. Walker K (1976) Clinical methods: the history, physical, and laboratory examinations. Butterworths, Boston
37. Lynn LA, Curry JP (2011) Patterns of unexpected in-hospital deaths: a root cause analysis. Patient Saf Surg 5:3
38. Clark FJ, von Euler C (1972) On the regulation of depth and rate of breathing. J Physiol 222:267–295
39. Milic-Emili J, Grunstein MM (1976) Drive and timing components of ventilation. Chest 70:131–133
40. Barcroft J, Margaria R (1931) Some effects of carbonic acid on the character of human respiration. J Physiol 72:175–185
41. Tobin MJ, Perez W, Guenther SM et al (1986) The pattern of breathing during successful and unsuccessful trials of weaning from mechanical ventilation. Am Rev Respir Dis 134(6):1111–1118
42. Dres M, Schmidt M, Ferre A, Mayaux J, Similowski T, Demoule A (2012) Diaphragm electromyographic activity as a predictor of weaning failure. Intensive Care Med 38:2017–2025
43. Rozé H, Repusseau B, Perrier V et al (2013) Neuro-ventilatory efficiency during weaning from mechanical ventilation using neurally adjusted ventilatory assist. Br J Anaesth 111:955–960
44. Sinderby C, Navalesi P, Beck J et al (1999) Neural control of mechanical ventilation in respiratory failure. Nat Med 5:1433–1436
45. Bellani G, Mauri T, Coppadoro A et al (2013) Estimation of patient's inspiratory effort from the electrical activity of the diaphragm*. Crit Care Med 41:1483–1491
46. Beck J, Gottfried S, Navalesi P et al (2001) Electrical activity of the diaphragm during pressure support ventilation in acute respiratory failure. Am J Respir Crit Care Med 164:419–424
47. Pettenuzzo T, Sella N, Zarantonello F et al (2022) How to recognize patients at risk of self-inflicted lung injury. Expert Rev Respir Med 16:963–971
48. Telias I, Spadaro S (2020) Techniques to monitor respiratory drive and inspiratory effort. Curr Opin Crit Care 26:3–10
49. Telias I, Madorno M, Pham T, et al. Physiological consequences of breathing effort according to the mode of ventilation during acute hypoxemic respiratory failure. Am J Respir Crit Care Med 2025. https://doi.org/10.1164/rccm.202411-2155OC
50. Cammarota G, Verdina F, Santangelo E et al (2020) Oesophageal balloon calibration during pressure support ventilation: a proof of concept study. J Clin Monit Comput 34:1223–1231
51. Cammarota G, Lauro G, Santangelo E et al (2020) Mechanical ventilation guided by uncalibrated esophageal pressure may be potentially harmful. Anesthesiology 133:145–153
52. Mojoli F, Iotti GA, Torriglia F et al (2016) In vivo calibration of esophageal pressure in the mechanically ventilated patient makes measurements reliable. Crit Care 20:98
53. Cammarota G, Santangelo E, Lauro G et al (2021) Esophageal balloon calibration during sigh: a physiologic, randomized, cross-over study. J Crit Care 61:125–132
54. Goligher EC, Dres M, Patel BK et al (2020) Lung- and diaphragm-protective ventilation. Am J Respir Crit Care Med 202:950–961
55. Cabello B, Mancebo J (2006) Work of breathing. Intensive Care Med 32:1311–1314
56. Carteaux G, Mancebo J, Mercat A et al (2013) Bedside adjustment of proportional assist ventilation to target a predefined range of respiratory effort*. Crit Care Med 41:2125–2132
57. Khemani RG, Hotz J, Morzov R et al (2016) Pediatric extubation readiness tests should not use pressure support. Intensive Care Med 42:1214–1222
58. Jonkman AH, Telias I, Spinelli E, Akoumianaki E, Piquilloud L (2023) The oesophageal balloon for respiratory monitoring in ventilated patients: updated clinical review and practical aspects. Eur Respir Rev 32:220186
59. Vedrenne-Cloquet M, Khirani S, Khemani R et al (2023) Pleural and transpulmonary pressures to tailor protective ventilation in children. Thorax 78:97–105
60. Grashoff J, Petersen E, Becher T, Rostalski P. Automatic estimation of respiratory effort using esophageal pressure. 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) IEEE; 2019. p. 4646–9
61. Kallet RH, Phillips JS, Summers TJ et al (2021) Expiratory pause maneuver to assess inspiratory muscle pressure during assisted mechanical ventilation: a bench study. Respir Care 66:1649–1656
62. Natalini G, Buizza B, Granato A et al (2021) Non-invasive assessment of respiratory muscle activity during pressure support ventilation: accuracy of end-inspiration occlusion and least square fitting methods. J Clin Monit Comput 35:913–921
63. Umbrello M, Formenti P, Longhi D et al (2015) Diaphragm ultrasound as indicator of respiratory effort in critically ill patients undergoing assisted mechanical ventilation: a pilot clinical study. Crit Care 19:161
64. Dres M, Goligher EC, Heunks LMA, Brochard LJ (2017) Critical illness-associated diaphragm weakness. Intensive Care Med 43:1441–1452
65. Dres M, Demoule A (2019) Beyond ventilator-induced diaphragm dysfunction. Anesthesiology 131:462–463
66. Dres M, Demoule A (2020) Monitoring diaphragm function in the ICU. Curr Opin Crit Care 26:18–25
67. Shi Z-H, Jonkman A, de Vries H et al (2019) Expiratory muscle dysfunction in critically ill patients: towards improved understanding. Intensive Care Med 45:1061–1071

68. Fossé Q, Poulard T, Niérat M-C et al (2020) Ultrasound shear wave elastography for assessing diaphragm function in mechanically ventilated patients: a breath-by-breath analysis. Crit Care 24:669
69. Zambon M, Greco M, Bocchino S, Cabrini L, Beccaria PF, Zangrillo A (2017) Assessment of diaphragmatic dysfunction in the critically ill patient with ultrasound: a systematic review. Intensive Care Med 43:29–38
70. Goligher EC, Laghi F, Detsky ME et al (2015) Measuring diaphragm thickness with ultrasound in mechanically ventilated patients: feasibility, reproducibility and validity. Intensive Care Med 41:642–649
71. Grassi A, Ferlicca D, Lupieri E et al (2020) Assisted mechanical ventilation promotes recovery of diaphragmatic thickness in critically ill patients: a prospective observational study. Crit Care 24:85
72. Pearson SD, Lin J, Stutz MR et al (2022) Immediate effect of mechanical ventilation mode and sedative infusion on measured diaphragm thickness. Ann Am Thorac Soc 19:1543–1550
73. Palkar A, Narasimhan M, Greenberg H et al (2018) Diaphragm excursion-time index. Chest 153:1213–1220
74. Spadaro S, Grasso S, Mauri T et al (2016) Can diaphragmatic ultrasonography performed during the T-tube trial predict weaning failure? The role of diaphragmatic rapid shallow breathing index. Crit Care 20:305
75. Cammarota G, Boniolo E, Santangelo E et al (2021) Diaphragmatic kinetics assessment by tissue doppler imaging and extubation outcome. Respir Care 66:983–993
76. Poulard T, Bachasson D, Fossé Q et al (2022) Poor correlation between diaphragm thickening fraction and transdiaphragmatic pressure in mechanically ventilated patients and healthy subjects. Anesthesiology 136:162–175
77. Dres M, Dubé B-P, Goligher E et al (2020) Usefulness of parasternal intercostal muscle ultrasound during weaning from mechanical ventilation. Anesthesiology 132:1114–1125
78. Haaksma ME, Smit JM, Boussuges A et al (2022) EXpert consensus on diaphragm ultrasonography in the critically ill (EXODUS): a Delphi consensus statement on the measurement of diaphragm ultrasound-derived parameters in a critical care setting. Crit Care 26:99
79. Capdevila Mathieu, De Jong Audrey, Belafia Fouad, Vonarb Aurelie, Carr Julie, Molinari Nicolas, Choquet Olivier, Capdevila Xavier, Jaber Samir (2025) Ultrasound-guided transcutaneous phrenic nerve stimulation in critically ill patients: a new method to evaluate diaphragmatic function. Randomized controlled trial. Anesthesiology 142(3):522–531
80. Colombo D, Cammarota G, Bergamaschi V, De Lucia M, Corte FD, Navalesi P (2008) Physiologic response to varying levels of pressure support and neurally adjusted ventilatory assist in patients with acute respiratory failure. Intensive Care Med 34:2010
81. Muttini S, Villani PG, Trimarco R, Bellani G, Grasselli G, Patroniti N (2015) Relation between peak and integral of the diaphragm electromyographic activity at different levels of support during weaning from mechanical ventilation: a physiologic study. J Crit Care 30:7–12
82. Di mussi R, Spadaro S, Mirabella L et al (2016) Impact of prolonged assisted ventilation on diaphragmatic efficiency: NAVA versus PSV. Crit Care 20:1
83. Bellani G, Coppadoro A, Pozzi M et al (2016) The ratio of inspiratory pressure over electrical activity of the diaphragm remains stable during ICU stay and is not related to clinical outcome. Respir Care 61:495–501
84. Jansen D, Jonkman AH, Roesthuis L et al (2018) Estimation of the diaphragm neuromuscular efficiency index in mechanically ventilated critically ill patients. Crit Care 22:238
85. Laghi F, Shaikh H, Littleton SW, Morales D, Jubran A, Tobin MJ (2020) Inhibition of central activation of the diaphragm: a mechanism of weaning failure. J Appl Physiol 129:366–376
86. Rozé H, Lafrikh A, Perrier V et al (2011) Daily titration of neurally adjusted ventilatory assist using the diaphragm electrical activity. Intensive Care Med 37:1087–1094
87. Bellani G, Bronco A, Arrigoni Marocco S et al (2018) Measurement of diaphragmatic electrical activity by surface electromyography in intubated subjects and its relationship with inspiratory effort. Respir Care 63:1341–1349
88. AbuNurah HY, Russell DW, Lowman JD (2020) The validity of surface EMG of extra-diaphragmatic muscles in assessing respiratory responses during mechanical ventilation: a systematic review. Pulmonology 26:378–385
89. Boles J-M, Bion J, Connors A et al (2007) Weaning from mechanical ventilation. Eur Respir J 29:1033–1056
90. Morton SE, Knopp JL, Chase JG et al (2019) Optimising mechanical ventilation through model-based methods and automation. Annu Rev Control 48:369–382
91. Navalesi P, Longhini F (2015) Neurally adjusted ventilatory assist. Curr Opin Crit Care 21:58–64
92. Whitelaw WA, Derenne J-P, Milic-Emili J (1975) Occlusion pressure as a measure of respiratory center output cm conscious man. Respir Physiol 23:181–199
93. Rittayamai N, Beloncle F, Goligher EC et al (2017) Effect of inspiratory synchronization during pressure-controlled ventilation on lung distension and inspiratory effort. Ann Intensive Care 7:100
94. Telias I, Brochard L, Goligher EC (2018) Is my patient's respiratory drive (too) high? Intensive Care Med 44:1936–1939
95. Lambermont B, Rousseau A-F, Seidel L et al (2021) Outcome improvement between the first two waves of the coronavirus disease 2019 pandemic in a single tertiary-care hospital in Belgium. Crit Care Explor 3:e0438
96. Mahase E. Covid-19: most patients require mechanical ventilation in first 24 hours of critical care. BMJ 2020;m1201
97. Wunsch H (2020) Mechanical ventilation in COVID-19: interpreting the current epidemiology. Am J Respir Crit Care Med 202:1–4
98. Chiew YS, Chase JG, Shaw GM, Sundaresan A, Desaive T (2011) Model-based PEEP optimisation in mechanical ventilation. Biomed Eng Online 10:111
99. Chiew YS, Pretty C, Docherty PD et al (2015) Time-varying respiratory system elastance: a physiological model for patients who are spontaneously breathing. PLoS ONE 10:e0114847
100. Chiew YS, Pretty CG, Shaw GM et al (2015) Feasibility of titrating PEEP to minimum elastance for mechanically ventilated patients. Pilot Feasibility Stud 1:9
101. Lee JWW, Chiew YS, Wang X et al (2021) Stochastic modelling of respiratory system elastance for mechanically ventilated respiratory failure patients. Ann Biomed Eng 49:3280–3295
102. Sassoon CSH, Foster GT (2001) Patient-ventilator asynchrony. Curr Opin Crit Care 7:28–33
103. Kacmarek RM, Pirrone M, Berra L (2015) Assisted mechanical ventilation: the future is now! BMC Anesthesiol 15:110
104. Tobin MJ, Jubran A, Laghi F (2001) Patient–ventilator interaction. Am J Respir Crit Care Med 163:1059–1063
105. Garofalo E, Bruni A, Pelaia C et al (2018) Recognizing, quantifying and managing patient-ventilator asynchrony in invasive and noninvasive ventilation. Expert Rev Respir Med 12:557–567
106. de Wit M, Pedram S, Best AM, Epstein SK (2009) Observational study of patient-ventilator asynchrony and relationship to sedation level. J Crit Care 24:74–80
107. de Haro C, Xifra-Porxas A, Batlle M, et al. Longitudinal characterization of patient-ventilator asynchronies in acute hypoxemic respiratory failure. Respir Care. 2025. https://doi.org/10.1089/respcare.12673.
108. Blanch L, Villagra A, Sales B et al (2015) Asynchronies during mechanical ventilation are associated with mortality. Intensive Care Med 41:633–641
109. Kyo M, Shimatani T, Hosokawa K et al (2021) Patient–ventilator asynchrony, impact on clinical outcomes and effectiveness of interventions: a systematic review and meta-analysis. J Intensive Care 9:50
110. Tlimat A, Fowler C, Safadi S et al (2025) Artificial intelligence for the detection of patient–ventilator asynchrony. Respir Care 70:583–592
111. Rietveld TP, van der Ster BJP, Schoe A et al (2025) Let's get in sync: current standing and future of AI-based detection of patient-ventilator asynchrony. Intensive Care Med Exp 13:39
112. Longhini F, Colombo D, Pisani L et al (2017) Efficacy of ventilator waveform observation for detection of patient–ventilator asynchrony during NIV: a multicentre study. ERJ Open Res 3:00075–02017
113. Georgopoulos D, Prinianakis G, Kondili E (2006) Bedside waveforms interpretation as a tool to identify patient-ventilator asynchronies. Intensive Care Med 32:34–47
114. Nilsestuen JO, Hargett DH (2005) Using ventilator graphics to identify patient-ventilator asynchrony. Respir Care 50(2):202–234
115. Arellano DH (2017) Identifying patient-ventilator asynchrony using waveform analysis. Palliat Med Care 4:1–4

116. Ramirez II, Arellano DH, Adasme RS et al (2017) Ability of ICU healthcare professionals to identify patient-ventilator asynchrony using waveform analysis. Respir Care 62:144–149
117. Holanda MA, Vasconcelos RdosS, Ferreira JC, Pinheiro BV (2018) Patient-ventilator asynchrony. J Bras Pneumol 44:321–333
118. Dres M, Rittayamai N, Brochard L (2016) Monitoring patient–ventilator asynchrony. Curr Opin Crit Care 22:246–253
119. Doorduin J, van Hees HWH, van der Hoeven JG, Heunks LMA (2013) Monitoring of the respiratory muscles in the critically ill. Am J Respir Crit Care Med 187:20–27
120. Chen C-W, Lin W-C, Hsu C-H, Cheng K-S, Lo C-S (2008) Detecting ineffective triggering in the expiratory phase in mechanically ventilated patients based on airway flow and pressure deflection: feasibility of using a computer algorithm*. Crit Care Med 36:455–461
121. Gholami B, Phan TS, Haddad WM et al (2018) Replicating human expertise of mechanical ventilation waveform analysis in detecting patient-ventilator cycling asynchrony using machine learning. Comput Biol Med 97:137–144
122. Mulqueeny Q, Redmond SJ, Tassaux D, et al. Automated detection of asynchrony in patient-ventilator interaction. 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society IEEE; 2009. p. 5324–7
123. Chen Y, Zhang K, Zhou C, Chase JG, Hu Z (2023) Automated evaluation of typical patient–ventilator asynchronies based on lung hysteretic responses. Biomed Eng Online 22:102
124. Younes M, Brochard L, Grasso S et al (2007) A method for monitoring and improving patient: ventilator interaction. Intensive Care Med 33:1337–1346
125. Blanch L, Sales B, Montanya J et al (2012) Validation of the better care® system to detect ineffective efforts during expiration in mechanically ventilated patients: a pilot study. Intensive Care Med 38:772–780
126. Mojoli F, Pozzi M, Orlando A et al (2022) Timing of inspiratory muscle activity detected from airway pressure and flow during pressure support ventilation: the waveform method. Crit Care 26:32
127. Piquilloud L, Vignaux L, Bialais E et al (2011) Neurally adjusted ventilatory assist improves patient–ventilator interaction. Intensive Care Med 37:263–271
128. Yonis H, Crognier L, Conil J-M et al (2015) Patient-ventilator synchrony in neurally adjusted ventilatory assist (NAVA) and pressure support ventilation (PSV): a prospective observational study. BMC Anesthesiol 15:117
129. Schmidt M, Kindler F, Cecchini J et al (2015) Neurally adjusted ventilatory assist and proportional assist ventilation both improve patient-ventilator interaction. Crit Care 19:56
130. Bosma KJ, Burns KEA, Martin CM et al (2025) Proportional-assist ventilation for minimizing the duration of mechanical ventilation. N Engl J Med 393(11):1088–1103
131. Akoumianaki E, Maggiore SM, Valenza F et al (2014) The application of esophageal pressure measurement in patients with respiratory failure. Am J Respir Crit Care Med 189:520–531
132. Gogineni VK, Brimeyer R, Modrykamien A (2012) Patterns of patient-ventilator asynchrony as predictors of prolonged mechanical ventilation. Anaesth Intensive Care 40:964–970
133. Piquilloud L, Tassaux D, Bialais E et al (2012) Neurally adjusted ventilatory assist (NAVA) improves patient–ventilator interaction during non-invasive ventilation delivered by face mask. Intensive Care Med 38:1624–1631
134. Ducharme-Crevier L, Beck J, Essouri S, Jouvet P, Emeriaud G (2015) Neurally adjusted ventilatory assist (NAVA) allows patient-ventilator synchrony during pediatric noninvasive ventilation: a crossover physiological study. Crit Care 19:44
135. Liu L, Xu X-T, Yu Y, Sun Q, Yang Y, Qiu H-B (2021) Neural control of pressure support ventilation improved patient-ventilator synchrony in patients with different respiratory system mechanical properties: a prospective, crossover trial. Chin Med J (Engl) 134:281–291
136. MacIntyre NR (2001) Evidence-based guidelines for weaning and discontinuing ventilatory support. Chest 120:375S-395S
137. Jia D, Wang H, Wang Q et al (2024) Rapid shallow breathing index predicting extubation outcomes: a systematic review and meta-analysis. Intensive Crit Care Nurs 80:103551
138. Boniatti VM, Boniatti MM, Andrade CF et al (2014) The modified integrative weaning index as a predictor of extubation failure. Respir Care 59:1042–1047
139. Campoccia Jalde F, Jalde F, Wallin MKEB et al (2018) Standardized unloading of respiratory muscles during neurally adjusted ventilatory assist. Anesthesiology 129:769–777
140. Liu L, Xu X, Sun Q et al (2020) Neurally adjusted ventilatory assist versus pressure support ventilation in difficult weaning. Anesthesiology 132:1482–1493
141. Di mussi R, Spadaro S, Volta CA et al (2020) Continuous assessment of neuro-ventilatory drive during 12 h of pressure support ventilation in critically ill patients. Crit Care 24:652
142. Epstein S (2002) Decision to extubate. Intensive Care Med 28:535–546
143. Piquilloud L, Beloncle F, Richard J-CM, Mancebo J, Mercat A, Brochard L (2019) Information conveyed by electrical diaphragmatic activity during unstressed, stressed and assisted spontaneous breathing: a physiological study. Ann Intensive Care 9:89
144. Dianti J, Bertoni M, Goligher EC (2020) Monitoring patient–ventilator interaction by an end-expiratory occlusion maneuver. Intensive Care Med 46:2338–2341
145. Silva S, Ait Aissa D, Cocquet P et al (2017) Combined thoracic ultrasound assessment during a successful weaning trial predicts postextubation distress. Anesthesiology 127:666–674
146. Tongyoo S, Thomrongpairoj P, Permpikul C (2019) Efficacy of echocardiography during spontaneous breathing trial with low-level pressure support for predicting weaning failure among medical critically ill patients. Echocardiography 36:659–665
147. Blumhof S, Wheeler D, Thomas K, McCool FD, Mora J (2016) Change in diaphragmatic thickness during the respiratory cycle predicts extubation success at various levels of pressure support ventilation. Lung 194:519–525
148. Bachmann MC, Morais C, Bugedo G et al (2018) Electrical impedance tomography in acute respiratory distress syndrome. Crit Care 22:263
149. Serpa Neto A, Deliberato RO, Johnson AEW et al (2018) Mechanical power of ventilation is associated with mortality in critically ill patients: an analysis of patients in two observational cohorts. Intensive Care Med 44:1914–1922
150. Lotfy A, Hasanin A, Rashad M et al (2021) Peripheral perfusion index as a predictor of failed weaning from mechanical ventilation. J Clin Monit Comput 35:405–412
151. Welte TM, Gabriel M, Hopfengärtner R et al (2022) Quantitative EEG may predict weaning failure in ventilated patients on the neurological intensive care unit. Sci Rep 12:7293

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